Planning for SCALE:

a <u>S</u>urvey of <u>C</u>limate change and <u>A</u>dirondack <u>L</u>ake <u>E</u>cosystems

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Climate change is the greatest 21st century threat to the natural resources of New York State (NYS), including >3000 lakes and their watersheds in the Adirondacks. Even as the region recovers from a century of acid rain, impacts from climate change and interacting stressors are quickly emerging. In the decades ahead, climate change impacts are expected to drive environmental changes despite the protected status of Adirondack ecosystems. Existing monitoring programs are ill-equipped to quantify and track future climate change impacts.

A new assessment of current ecological conditions is needed. Such work would reveal climate impacts since the 1980s, and also use modern technologies to establish current baseline conditions that enable detection of future climate-driven changes. **We propose the SCALE initiative as a consortium-based model for assessing representative lakes in a cost-efficient manner.**

<u>Citizen benefits of SCALE</u>

Residents of the Adirondacks, and the millions who visit the region annually, rely upon healthy lakes in numerous ways. These ecosystems provide a source of water, recreation, and food for people, but ongoing shifts in lake conditions are creating noticeable impacts on tourists and residents alike. For instance, safe conditions for ice fishing, winter carnivals, and other outdoor recreation have contracted by several weeks in the last 50 years. These changes challenge local economies and deep-rooted cultural traditions. Intense storms are damaging homes and infrastructure, thereby stressing public budgets and making the region feel less livable. The emergence of algal blooms in a growing number of Adirondack lakes could undercut property values and contaminate fisheries.

In order to maintain the beauty and integrity of Adirondack lakes, individuals, government agencies, and other stakeholders must understand and adapt to climate change. Scientific data can help guide management efforts toward lakes where they can make the biggest difference. For instance, warming trends and oxygen depletion are likely to eliminate trout fisheries in some lakes, while stocking efforts could help to fortify fish populations in other lakes against these stressors. Similarly, invasion by harmful species of fish, snails, and weeds is more likely in some lakes than others. At the same time, direct human impacts on Adirondack lakes require greater management effort in some lakes than others, based on their differential susceptibility. For instance, lakes with slow flushing rates are most likely to be degraded by road salt accumulation or septic system leakage of nutrients. Thus, the rigorous surveys undertaken for SCALE will provide essential input for prioritizing responses to climate change. This guidance will boost both the effectiveness and the cost-efficiency of climate adaptation efforts.

Scientific benefits of SCALE

Understanding the impacts of climate change on the Adirondacks requires identifying sentinel ecosystems and response variables. Lying at the lowest point in the landscape, lakes act as both sensitive integrators and indirect regulators of climate change. Most Adirondack lakes are embedded in stream networks, which enable them to integrate environmental change that occurs throughout the region. The rich history of Adirondack lake research and monitoring offers unique opportunities to discern the effects of climate change across this extensive area. For example, long-term temperature measurements demonstrate that lake surface waters have exhibited rapid warming trends for decades. However, the ecological consequences of changes in temperature and precipitation on Adirondack waters remain largely unknown.

Historic and ongoing scientific monitoring programs and surveys were primarily designed to detect the effects of acid deposition. Most prominently, the Adirondack Lakes Survey (ALS) offered an unprecedented snapshot of 1,469 sites between 1984-1987, which provided chemical, physical, and biological data to characterize the profound impacts of acidic precipitation on lake ecosystems. This sampling effort was essential for guiding the 1990 Clean Air Amendments (CAAA). Moreover, the variation among lakes revealed by the ALS offers a strong baseline against which to measure the effectiveness of the CAAA via long-term monitoring efforts, such as the Adirondack Long-Term Monitoring (ALTM) program. While the 1980s survey lacked many of the measurements necessary to understand the impacts of climate and other stressors that could interact with acidification, its extensive records provide a wealth of historical context for assessing climate-induced changes in the Adirondacks.

A new regional effort is urgently needed, leading a consortium of academic researchers and non-profit organizations to develop a vision for the Survey of Climate change and Adirondack Lake Ecosystems (SCALE) initiative. Despite decades-long efforts to protect lakes and streams nationwide, water bodies throughout New York State are showing symptoms of climate change impacts. SCALE will leverage past work to address pressing scientific and management-oriented research needs to protect Adirondack lakes, setting a new standard for environmental research and management.

Results from SCALE will guide science-based management of all Adirondack lakes for decades to come. This systematic assessment will reveal the extent of climate change impacts on habitat quality, climate-sensitive species distributions, carbon accounting, and harmful algal blooms. These threats constitute existential challenges to the long-term health of New York's waters, yet each is amenable to adaptive management that can minimize impact when informed by strong data.

SCALE will build upon the legacy of lake surveys and long-term Adirondack lake monitoring while leveraging the latest technological advances. Newly available methods offer insightful complements to traditional manual survey techniques, requiring fewer survey sites while enhancing understanding of the major drivers of changes across the Adirondacks through time. For instance, remote sensing will allow us to estimate aspects of lake temperatures, ice cover, and water chemistry for nearly all Adirondack lakes, but will require validation from field measurements at a subset of sites. Other tools, such as high frequency sensors and eDNA measurements, will help to characterize the state and dynamics of lake ecosystems with far greater precision than was previously possible.

Defining priorities for SCALE

A baseline assessment of climate change impacts should begin by identifying specific environmental attributes that are (1) sensitive to climate change impacts, (2) integrate impacts to both lakes and their watersheds, and (3) are socially and economically important. To identify research and monitoring priorities for SCALE, we convened a workshop in July 2021 involving representatives from leading academic, not-for-profit, and government organizations (Table 1). Workshop participants were tasked with creating a list of measurements SCALE should undertake, including enumerating and prioritizing assessment metrics.

Table 1. List of organizations represented at the 2021 SCALE planning workshop

	Organizations represented at 2021 SCALE planning workshop
1	Ausable River Association
2	City University of New York - City Tech
3	Cornell University
4	Huntington Wildlife Forest, SUNY College of Environmental Science and Forestry
5	New York Attorney General's Office, Environmental Protection Bureau
6	New York State Museum
7	New York State Department of Environmental Conservation, Dvision of Air Resources
8	New York State Department of Environmental Conservation, Division of Fish and Wildlife
9	New York State Department of Environmental Conservation, Office of Climate Change
10	New York State Energy Research and Development Authority
11	Paul Smith's College
12	Rensselaer Polytechnic Institute
13	SUNY College of Environmental Science and Forestry
14	Syracuse University
15	The Nature Conservancy
16	US Environmental Protection Agency, Office of Air and Radiation, Atmospheric Program, Clean Air Markets Division
17	US Geological Survey

The SCALE planning workshop was a two-day event. The morning of the first day included presentations summarizing past monitoring programs. The 1980's ALS, the Adirondack Long-Term Monitoring (ALTM) program, the Adirondack Effects Assessment Program (AEAP), and the US Environmental Protection Agency's (EPA) programs were featured. Following these presentations, the meeting organizers gave an overview of known climate change impacts on lake habitats and interacting stressors.

Following plenary presentations, meeting participants discussed a series of focal questions in breakout groups. Questions centered on the overarching topic of what measures are needed to advance understanding of climate change and stressor impacts on Adirondack lakes. Participants were asked to identify key metrics, including those that would contribute to actionable science and/or support management or regulatory needs.

This report summarizes the priority topics agreed upon by workshop participants, and offers an initial vision for how SCALE could be structured and funded. We focus on four focal research themes, each of which addresses key environmental management and policy needs. The sections that follow explain the scientific rationale behind each focal theme, and then provide a roadmap for a consortium approach to updating our understanding of the status and trends of Adirondack lakes.

Focal research questions

1. How has the warming climate and increasing severe storms affected baseline conditions of water temperature, oxygen, and nutrients in Adirondack lakes?

> a. At what rate are lake surface temperatures increasing, and are documented long-term clarity losses suppressing deep-water warming or leading to cooling of Adirondack lakes?
>
> b. Is the duration and strength of seasonal stratification increasing, and is this accentuating deep-water oxygen depletion? Has warming shifted non-stratified lakes toward consistent annual stratification?
>
> c. Does increasing temperature, severe storms that flush terrestrial carbon and nutrients inputs into lakes, salinity, or DOC concentration of lake waters increase the likelihood of deep-water anoxia? How important are watershed attributes, such as road and housing density relative to lake attributes, such as depth and trophic status, In explaining deep-water anoxia?
>
> d. If occurring, is increasing deep-water oxygen depletion releasing more phosphorus from sediments, which could exacerbate HABs? Does the chemistry of lakes differ between lakes that exhibit consistent seasonal anoxia versus those that do not?

Oxygen is essential to life on the planet, and all biological processes are temperature-dependent and require nutrients. Climate change is increasing surface water temperatures, severe storms, and contributing to deep-water dissolved oxygen losses in lakes worldwide. The magnitude of these effects in the Adirondacks is unclear, and may be exacerbated by some types of land use. Substantial oxygen losses will threaten many species and reduce water quality, while potentially increasing carbon emissions from lakes. A survey is needed to assess temperature increases, severe storm impacts, dissolved oxygen losses, and nutrient availability in Adirondack lakes in order to interpret and predict potential changes in the biota and ecosystem processes.

2. How is climate change affecting the biota of Adirondack lakes?

> a. Do invasions by warm-water species reflect greater vulnerability of fast-warming lakes?
>
> b. How rapidly are cold-water fishery species being extirpated under climate change, and could stocking offset those losses?
>
> c. Has warming affected the energy sources and trophic level of fishery species in lake food webs?
>
> d. Has warming and deep-water oxygen depletion enhanced mercury bioaccumulation despite regulatory reductions in new mercury entering Adirondack ecosystems?

The underlying biology of all organisms is temperature-dependent. Yet the fate of many species, such as climate-sensitive Adirondack cold-water fisheries (e.g., trout) remain difficult to predict *due to complex feedbacks and interactions between organisms and the environment and between organisms. SCALE will disentangle climate effects on economically and ecologically important species to identify which lakes are most vulnerable to loss of climate-sensitive species, alteration of food webs, and enhanced levels of toxic mercury in fishery species.*

3. How is climate change affecting carbon cycling, including the role of lake sediments as carbon sinks?

> a. What predicts carbon burial rates across the Adirondacks? Is it possible to generate region-scale estimates of lake carbon burial rates, or other carbon flux rates such as carbon dioxide or methane emissions?
>
> b. Do lake methane, carbon dioxide, and nitrous oxide emissions vary with temperature? Does oxygen depletion of bottom waters control greenhouse gas emissions?
>
> c. Are increases in lake dissolved organic carbon (otherwise known as "browning") likely to continue to increase in future decades? What are the implications of these increases for the potential formation of regulated disinfection byproducts (total trihalomethanes, haloacetic acids) in drinking water?
>
> d. Is the ratio of lake carbon burial to emissions likely to decrease as temperatures increase, thereby serving as a positive feedback to climate change?

Lakes serve as important sites of carbon cycling. In order to create local, state, and national carbon budgets that account for both natural and human (anthropogenic) sources and sinks of carbon, it is important to measure carbon burial and dissolved gas concentrations (carbon dioxide and methane) concentrations in lakes. A lake survey represents a key approach to measuring these important carbon fluxes.

4. Are harmful algal blooms (HABs) becoming more prevalent under climate change?

> a. What is the trajectory of lake productivity through time, and what proportion of Adirondack lakes now suffer from algal blooms?
>
> b. Is there historical evidence of HABs (e.g., as revealed in sediment records), and do contemporary HABs leave toxins in food fishes?
>
> c. Are HABs associated with thresholds of watershed land use or local lake conditions (nutrients, stratification, temperature)?
>
> d. Can we predict which Adirondack lakes are most vulnerable to HABs going forward, and what are the risks to humans, pets, livestock, and native species? Can knowledge about HABs provide the ability to create early warning systems, such as for public beaches?

Harmful algal blooms, which can be toxic to humans and wildlife alike, are increasingly observed in lakes across the country and around the world. Reports of algal blooms in Adirondack lakes are rare, but anecdotal reports of increasing algal growth are not unusual.

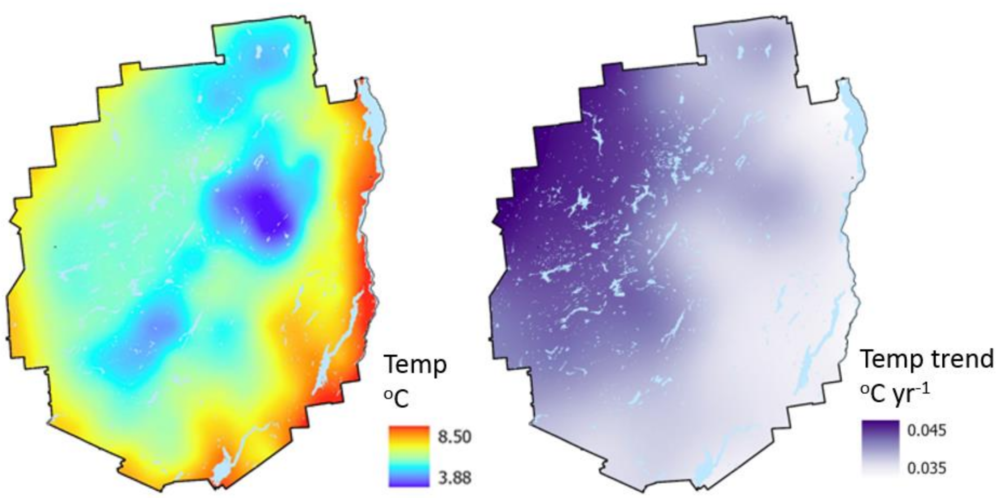
Adirondack Park regulations have spared these lakes from many factors associated with algal blooms (e.g., agricultural and urban development), thereby offering an invaluable reference point for assessing the role of climate change in HABs. This survey will create a much-needed baseline for understanding climate influences on HABs across NYS and nationally.

1. Baseline conditions: temperature, oxygen, and nutrients

1.1. Background and rationale

While lakes occupy less than 3% of Earth's land surface, they are hotspots of biodiversity and biogeochemical cycling. Dissolved oxygen and temperature represent two of the most important characteristics of inland waters; all complex life requires oxygen, and rates of all biological processes depend on temperature. Additionally, dissolved oxygen regulates characteristics such as habitat suitability for biota, nutrient cycling, and metal toxicity. Dissolved oxygen is also sensitive to variations in temperature that govern the mixing of lake waters.

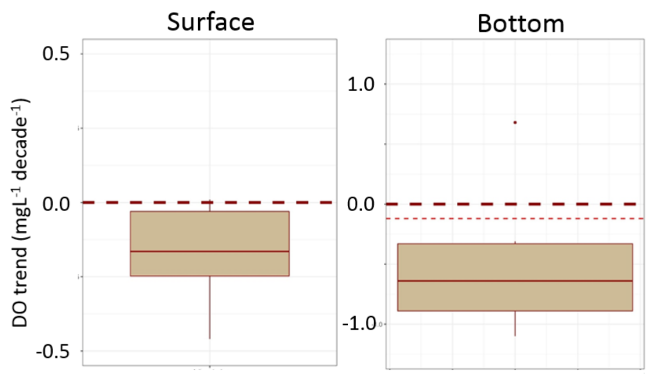
Tracking temperature across depths and throughout the year in a subset of Adirondack lakes can enable calibration and validation of models that predict rates of warming and shifts in mixing patterns arising from climate change. This is a critical step to understanding other climate effects that are mediated by thermal changes, such as changes in dissolved oxygen, species distributions, carbon emissions, and harmful algal blooms.



Adirondack air temperatures are warming. A preliminary analysis of weather station data from the Adirondack region shows that annual mean air temperatures vary widely across the Adirondacks (left map) and have been warming at a rate of ~0.35-0.45 °C per decade (right map). These rates are similar to other regions of the temperate zone. Yet, long-term water temperature measurements from 28 Adirondack lakes measured over the period 1994-2012 reveal warming rates that are substantially faster than these air temperature warming rates. Unfortunately, the coarse sampling from past monitoring efforts means that the calculated lake warming rates have high statistical uncertainty. However, studies of lake summer surface temperature trends in other temperate lakes reveal median warming rates ~0.3-0.4 °C per decade, which are consistent with Adirondack air temperature warming rates.

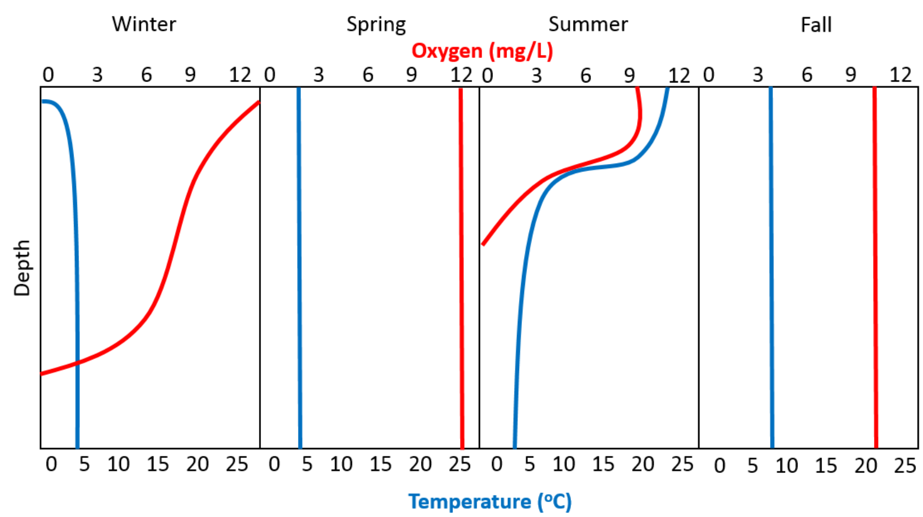
Climate impacts on lakes also involve bottom temperatures, ice cover duration, and mixing patterns, all of which appear to be changing on complex ways. Deep-water temperature trends are highly variable among lakes and regions. Due to widespread increases in dissolved organic carbon (DOC) concentrations in Adirondack lakes, it is possible that many lakes are suffering from declining bottom temperatures despite rising air temperatures. Increases in surface temperatures and declining bottom temperatures can reflect a strengthening density difference between the layers of water, which inhibits exchange of heat, oxygen, and nutrients (called thermal stratification). The duration, depth, and strength of summer thermal stratification regulates many aspects of lake ecosystems.

Recent research demonstrates that dissolved oxygen is declining in lakes around the world. Dissolved oxygen profiles have been collected from some Adirondack lakes as part of AEAP monitoring from 1994-2012 (n=28; see figures to right). These data suggest that dissolved oxygen declined in both surface waters and deep waters at -0.16 mg L^{-1} per decade (left graph) and -0.64 mg L^{-1} per decade (right graph) over that 18 year period. These are rapid losses in dissolved oxygen—considerably faster than global averages. We have no data on whether these rates have been sustained since 2012, or whether the historical data from 28 lakes is representative of all Adirondack lakes. Moreover, it is unclear what factors were contributing to these rapid declines in dissolved oxygen in Adirondack lakes.



Dissolved oxygen in deep waters is often far lower than expected from atmospheric diffusion. However, the deviation is hard to predict using available models. Likely influences include day of the year, temperature and salinity gradients from surface to bottom, time since cessation of ice cover, water clarity, plankton biomass, dissolved organic carbon concentration, and bathymetry (the topography of the lake bottom). Sampling each of these variables regularly will be necessary to formulate a general model that predicts dissolved oxygen in lakes, and can forecast future dissolved oxygen changes. Bathymetric data exist for many Adirondack lakes, and these should be prioritized for surveys that include the other variables alongside dissolved oxygen.

Gradients of temperature and oxygen with depth often vary substantially among seasons of a year. It is important to understand the seasonal variability of dissolved oxygen to quantify the extent and duration of low oxygen (hypoxic) and zero oxygen (anoxic) zones. For instance, dissolved oxygen often becomes depressed in summer (facilitated by thermal stratification) and winter (facilitated by ice cover) (see figure to right). As climate change lengthens the period of thermal



stratification and shortens the period of ice cover, we expect more extreme low oxygen conditions during summer and alleviation of oxygen deficits during winter. Since temperature, oxygen, and ice cover patterns in the world's lakes are all affected by climate change, all three must be assessed in concert. A key requirement for forecasting the future impacts of climate change on Adirondack lakes is the ability to accurately predict warming rates, thermal stratification, and dissolved oxygen concentrations, all of which are important determinants of the biota and ecosystem functioning (e.g., nutrient and carbon cycling).

1.2. Measuring dissolved oxygen and temperature

Modern technology makes measuring dissolved oxygen and temperature relatively simple. Sensors measuring dissolved oxygen and temperature are fairly inexpensive (~$1,000 each), robust and durable for field use, and portable. Often, integrated sensing systems (called sondes) are used that measure dissolved oxygen and temperature along with several other water quality characteristics relevant to understanding dissolved oxygen dynamics, including conductivity, chlorophyll fluorescence, phycocyanin fluorescence, fluorescent dissolved organic matter (FDOM), turbidity, and pH. These integrated sondes are more expensive (~$25,000 each) but offer substantially more data, hence they are used frequently in water quality monitoring.

1.3 Dissolved oxygen, temperature, and nutrient sampling strategy

Field teams should profile dissolved oxygen and temperature throughout the water column whenever an offshore lake visit is made. A full profile from surface to bottom (rather than just at select depths) of a lake of average depth (5-25 m) will take <30 minutes to collect. A sonde that measures a full suite of variables (e.g., conductivity, chlorophyll, etc) should be used whenever possible to understand how other variables relate to vertical patterns of dissolved oxygen.

In a subset of lakes, submerged data loggers should be deployed at various depths through the water column to track seasonality in dissolved oxygen and temperature. Deployments should have at least one sensor in the surface mixed layer, and several others spaced at greater depths to record seasonal depletion of oxygen after thermal stratification sets in. Thus, these focal lakes might require 6-10 dissolved oxygen loggers in order to collect adequate data.

Submerged data loggers should be deployed soon after the ice melts, and be left in place at least until just before ice cover returns in the winter to capture the seasonal dynamics of dissolved oxygen. Ideally, sensors should be left in over winter, too, to better understand dissolved oxygen draw-down rates under ice and how they compare with summer draw-down rates. This will enable assessment of the importance of the winter season relative to the summer season in creating low oxygen conditions that affect the biota and chemistry of lakes. Multiple years of measurements are preferred in order to understand the magnitude of interannual variability in dissolved oxygen. However, if sensors are removed from a lake in the late full after full water column mixing occurs, the sensors could be cleaned, calibrated, and re-deployed in a different lake the following spring. This would increase the number of lakes sampled at the expense of reduced duration of data within each individual lake.

The specific set of lakes targeted for continuous dissolved oxygen and temperature measurements should also be the focus of other kinds of intensive sampling. This suite of lakes must be selected to represent the full ranges of variables that influence lake ecosystem dynamics, biodiversity, and human use value in the Adirondacks. As listed above, these include depth, surface area, and volume, temperature (which in turn is sensitive to lake size/volume, climate, and elevation), water clarity, plankton biomass (using chlorophyll as a proxy), nutrient concentrations, and dissolved organic carbon concentration. Given this diversity of predictor variables, we believe that at least 50 lakes should be prioritized for this intensive sampling.

If characteristics such as temperature and time since ice-out, chlorophyll, and dissolved organic carbon emerge as important predictors of observed oxygen depletion, it may be possible to predict categories of deep-water oxygen behavior for nearly all Adirondack lakes. This is because each of these characteristics can be remotely sensed (water clarity, ice cover, chlorophyll, dissolved organic matter, surface temperature) or modeled using lake bathymetry and meteorological data (stratification, bottom temperature). Thus, submerged data logger deployments in a strategic selection of lakes may enable accurate prediction of seasonal and long-term dissolved oxygen patterns for all Adirondack lakes. Ideally, such insights would set the stage for future modeling of dissolved oxygen in response to scenarios of future warming.

During field visits for profiling using sondes or deployment/retrieval of data loggers, it will be important to collect water samples for measurements of water chemistry (nutrients, DOC, salinity), as well as plankton biomass and other key characteristics. These observations will assist with calibrating remote sensing data, and enable us to understand linkages between warming rates, dissolved oxygen (specifically the presence, volume, and duration of anoxia), and with other metrics recorded in SCALE, such as the fish community composition, greenhouse gas dynamics, and harmful algal blooms. We are particularly interested in nutrient concentrations, which can reflect inputs from surrounding watersheds (especially from wastewater produced by lakeside homes and communities) or oxygen-mediated transformation and release of nutrients from lake sediments.

1.4. Resources needed

Field sampling. The temperature and oxygen research described here depends on collecting profile data with a sonde, and bringing back water for laboratory analyses of additional variables that cannot be measured in the field. Teams should collect water column profiles from offshore locations in order to capture dissolved oxygen and temperature measurements below the surface mixed layer. This will likely require teams of at least two technicians (for both safety and efficiency reasons) conducting work from a portable boat. Using the sonde and processing water samples would likely take less than an hour on the water, enabling each team to collect data from two nearby sites per field day, depending on isolation from the nearest road. However, field visits should also be leveraged to collect other relevant samples and data to address additional research priorities at minimal marginal cost. Preliminary priorities for other important characteristics to measure are indicated under the next three research themes.

Field teams can also use special sampling containers to collect water at specific depths within each lake. Depths will be chosen to reflect surface, transition, and deep-water conditions. Preserved samples will be analyzed for concentrations of nutrients (inorganic and organic nitrogen and phosphorus; silica; sulfate) and dissolved carbon (inorganic and organic). Facilities for these analyses exist at several consortium organizations, so new analytical instruments should not be required. Thus, the primary costs would be consumable materials and analysis fees.

High-frequency sensor deployment. Assuming that an average study lake is 15 m deep and stratifies at 3 m, and a sensor is deployed about every two meters below the surface mixed layer, then about seven dissolved oxygen/temperature sensors with wipers would be needed per lake. For extended deployments, wipers are needed to remove biofouling and obtain high quality data. Integrated sensors measuring dissolved oxygen and temperature with automated wipers cost about $2,000 each, so a sensor network would cost about $14,000 per lake. Assuming 35 sets of this deployment setup were purchased, the total would be about $490,000. If 10 of these 35 setups were removed and redeployed each year, then three years of continuous data would be obtained for 25 lakes while one year of data would be available from an additional 30 lakes (55 lakes in total). Additional equipment renewal expenses would be required in the second and third year of SCALE given the sensitivity of these loggers and the potential for lost equipment. It is likely that a team of two could deploy a temperature and dissolved oxygen sensor string in two hours at each lake. However, this assumes sufficient preparation time, as sensors would need to be cataloged and calibrated prior to deployment. Following collection of equipment in the fall, there would be a substantial quantity of data that would need to be processed and quality checked. In the spring, sensors must be recalibrated and cross-compared before deployment, and may require some maintenance. All of this effort is worthwhile because the temperature and oxygen data are essential inputs to inferences about habitat suitability for the biota, carbon storage and cycling, and HABs.

Remote sensing and modeling. Quantifying long-term trajectories of Adirondack lake temperature can be completed using a combination of remote sensing and hydrodynamic modeling. Both of these approaches require field temperature measurements for model calibration and validation (see above). Hydrodynamic modeling can be used to backcast past temperatures at all depths, or project future temperature, ice cover, and stratification characteristics given various climate change scenarios. Additionally, hydrodynamic modeling can be used to disentangle the effects of changes in water clarity (e.g., due to lake browning) from climate warming. In turn, rates of changes in water clarity can be assessed from remote sensing imagery. Therefore, these two approaches (remote sensing and hydrodynamic modeling) work together to provide a long-term and large-spatial-scale assessment of water temperature, when validated against field measurements. Costs of remote sensing are primarily related to technical personnel, and secondarily with computer hardware and software.

2. Biotic responses to a changing climate

2.1 Background and Rationale

The biota of Adirondack lakes will be profoundly affected by climate change. The climate-induced changes in thermal regimes and dissolved oxygen discussed above are likely to drive shifts at both species and ecosystem levels. The potential outcomes include making lakes less hospitable for species that require cold water year-round, and enhancing the suitability of Adirondack waters for invasive species that thrive under warmer conditions. These shifts in species distributions may modify energy flow pathways that fuel aquatic food webs, and initiate shifts in the bioavailability of legacy pollutants such as mercury.

The basic biology of all organisms depends on temperature, and the metabolism of the microbes, algae, plants, and most animals in Adirondack waters is directly affected by environmental warming because they are unable to regulate their own temperature. Indeed, each species may have a preferred range of both temperatures and dissolved oxygen concentrations to meet its needs, and become stressed if conditions extend much beyond this range. Given this matching of the biota to the environment, shifts in thermal, mixing, and oxygen dynamics can have myriad consequences.

SCALE will focus on high-level outcomes of these environmental changes rather than underlying mechanisms. By systematically re-surveying many lakes, and comparing results to those from the 1980s, we can address four important dimensions of biotic change: declines of cold-water species, invasions by warm-loving species, shifts at the base of the food web that alter energy sources and maximum trophic position supporting fishery species, and potential increases in the accumulation of toxic mercury in fishes.

Cold-water species are being squeezed by the combination of warming temperatures and declining oxygen concentrations in all aquatic ecosystems, but lakes are especially vulnerable. As described earlier, the surface layer of lakes has become considerably warmer during the summer and fall, and even the deep waters are becoming slightly warmer in many cases. The Adirondacks are home to numerous species of cold-loving animals, including the prized brook trout and lake trout as well as species of conservation concern like the round whitefish. These species suffered substantial losses during the 20th century due to acid rain and species invasions, so their present limited ranges reflect many extirpations. Their persistence depends upon access to cold-water refuges in the depths of lakes during the summer, because they become stressed when temperature exceeds ~20°C. At the same time, they require high oxygen concentrations to survive, hence the long-term decreases in bottom-water DO also pose an existential threat. The combined stresses of warming from above and deoxygenation from below are referred to as an oxythermal squeeze, and is a well-documented problem as climate change affects temperate lakes.

The counterpoint to extirpations of sensitive native species is the risk of facilitating invasions by non-native species that prefer warmer temperatures. While some Adirondack lake invaders are cold-loving (e.g. rainbow smelt), most prefer warmer temperatures (e.g. smallmouth bass, northern pike, golden shiner, Eurasian water milfoil). The ALSC surveys of the 1980s greatly increased the documentation of such invasions, as have efforts by the Adirondack Watershed Institute and other monitoring programs. The warming and deoxygenation trends since that time have likely led to further colonization by such unwanted species. Thus, there is a pressing need to re-assess invasions using prior data as baselines for quantifying expansion rates, and to enable identification of the factors that enhance likelihood of further invasion of a particular lake.

Beyond species-level effects, climate change is expected to shift aquatic food web sources of energy and length of food chains. As shallow habitats become warmer, we expect to see higher productivity of both attached and planktonic algae near the surface. The attached algae are a key food supply for macroinvertebrates in lakes, making them the dominant source of energy fueling lake food webs. However, warm water can prevent top predators from accessing these habitats, thereby forcing them to feed on zooplankton and other small prey that lead to reduced growth rates. At the same time, browning creates a shading effect that could reduce algal productivity, while human activities may produce local nutrient fertilization that encourages plant growth. How all of these factors will balance remains an open question, but the two key dimensions of lake food webs are the balance between attached algae, planktonic algae, and terrestrial input as energy sources, and the average number of links in the food chains that support top predators like lake trout. The extensive collections of fish and zooplankton in the 1980s ALS create an opportunity to evaluate shifts in both energy sources and food chain length across Adirondack lakes by analyzing the stable isotope ratios of archived samples.

Separate from such food web shifts, we expect to see warming and deoxygenation enhance the uptake of toxic mercury into fishery species. Mercury contamination accompanied acid deposition throughout the 20th century, leading Adirondack lakes to show some of the highest levels of mercury in food fishes observed in New York. Because mercury is a potent neurotoxin, NYSDEC and NYSDOH have created advisories against consuming many species of fish from numerous Adirondack lakes. Though inputs of new mercury have been sharply reduced for decades, the legacy of historical pollution can persist as mercury cycles within lake ecosystems. The key mediating step is the transformation of mercury into an organic form (methylmercury) that becomes more concentrated with each step in a food chain. The bacteria and Archaea that create methylmercury require low oxygen conditions, and so ongoing deoxygenation of the deep waters overlying sediments that store mercury could substantially enhance the entry of mercury into the food web. To safeguard the health of both human anglers and fish-consuming wildlife (loons, otters), it is important to assess whether shifting environmental conditions have increased mercury levels in fishes of Adirondack lakes.

2.2 Measuring biotic responses to climate change

We will use a combination of traditional and new methods to assess biotic responses to climate change across Adirondack lakes.

Collecting and vouchering organisms was a strength of the ALS approach. This resulted in a rich archive of fish and invertebrates deposited at the NY State Museum in Albany, and the American Museum of Natural History in NYC. We believe that it is important to extend that approach to SCALE, albeit at a subset of lakes due to the laborious nature of deploying fish nets and traps overnight. We plan to use gill nets and minnow traps to collect fish, plankton nets to collect zooplankton and phytoplankton, sediment sampling and dipnets to collect macroinvertebrates, and rake surveys to document macrophytes. Specimens will be preserved and deposited in the NY State Museum in Albany. Fish will be identified and measured by NYSM staff, while plankton will be archived for later identification and enumeration.

Environmental DNA (eDNA) now offers a compelling complement to collecting organisms, whereby a water sample collected in a systematic way can be used to identify species that reside in that ecosystem based on matches to a library of genetic sequences that differ among species. There are many nuances to the field and lab components of eDNA work, but it has emerged as a powerful tool for analyzing a broad array of taxa in a repeatable and time-efficient way. We plan to take a metabarcoding approach, which emphasizes taxonomic breadth during detection of species presences. For instance, with a few water samples from a lake, we will be able to populate a list of fish, macroinvertebrates, and perhaps additional taxa. Repeating the sampling at another time point can boost the robustness of those inferences. Metabarcoding has little capacity to identify species absences (as is true of most field methods), nor does it provide reliable quantification of relative abundance. However, the detection of rare and cryptic species is sufficient to assess the persistence of vulnerable species (brook trout, lake trout, round whitefish). Moreover, eDNA has proven highly sensitive for documenting the early phases of invasion of non-native species (smallmouth bass, smelt, northern pike, golden shiner) well before they are likely to be captured by traditional organismal sampling methods.

Finally, we will analyze muscle tissue from several fish species to quantify food web patterns and mercury contamination. Food web analyses will rely upon stable isotopes of carbon, nitrogen, and hydrogen, which will be compared among fish, zooplankton, and algae-eating benthic invertebrates. Though molluscs are often used to establish isotopic baselines, they are scarce in Adirondack waters so we will likely use crayfish or other large benthic macroinvertebrates. Carbon isotopes reflect energy flow pathways, and work well in lakes to distinguish between use of energy originating from planktonic versus attached algae. Nitrogen isotopes reflect the trophic position of a species in the food web, so that comparing top predator species to zooplankton and macroinvertebrates can reveal whether food chains are relatively long or short (i.e. fish occupy high or low trophic position). Hydrogen isotopes are ideal for disentangling the role of terrestrial energy inputs to lakes, and are an important complement to carbon isotopes because Adirondack lakes receive so much terrestrial-derived carbon.

Mercury analysis indicates how contaminated a fish is with methylmercury. To interpret the causes of differential mercury contamination, we will compare to environmental conditions (e.g. deoxygenation of the deep waters, warming rates), lake variables (size, depth), and food web properties (energy sources, fish trophic position).

Both stable isotopes and mercury will be analyzed from preserved 1980s fish specimens from the ALS, as well as new samples collected for SCALE. These chemical constituents are minimally affected by museum preservation practices. Comparing contemporary and historical results across a wide range of lakes will enable us to quantify changes in food webs and mercury during the last forty years.

2.3 Biotic sampling strategy

Biotic sampling will be stratified across classes of sampling intensity. Fish and macroinvertebrates will be sampled only for high-intensity lakes, while eDNA, plankton, and macrophytes will be sampled from every lake visited during SCALE. Organism collections will follow the ALS protocols from the 1980s. eDNA sampling will follow standard protocols for collecting and filtering large-volume, replicate samples, and will be tailored to Adirondack lakes through pilot work. Stable isotope analyses will focus on fish muscle samples and whole invertebrates (after gut clearance).

Samples of the biota will be collected in the field, then processed in the laboratory prior to further analysis. Fish muscle will be dissected before chemical preservation, while plankton will be chemically preserved whole at the field site after a holding period to allow gut clearance. Macrophytes will be identified and returned in the field. eDNA samples will be dried or chemically preserved. Fish muscle and whole invertebrates will be dried and stored frozen until subsampling.

2.4 Resources needed

Organismal sampling will require considerable labor from field teams who have the taxonomic expertise to identify species of fish, invertebrates, and macrophytes. Fish sampling will require overnight deployments of nets and traps. A variety of common field equipment will be needed.

eDNA sampling has become straightforward, and will require filtering and pumping apparatus, as well as clean storage for samples. Analysis of samples is far more complex, and involves considerable risk of contamination in the lab. Samples will be analyzed in a dedicated eDNA lab where positive pressure, cleaning protocols, and limited entry of materials minimize the risk of contamination. We will quantify inadvertent contamination using both field and lab blanks. The metabarcoding analyses require preparation (i.e., optimizing primers, developing extraction and amplification protocols, developing a reference database) as well as considerable molecular biology and bioinformatics skills to process the results (i.e., statistical identifications of taxa, managing large sequence datasets).

Sample processing for stable isotope analysis is fairly straightforward in the field and lab. Samples will be analyzed using two dedicated mass spectrometers (one for C-N; one for H) in a lab specialized for quantification of light element stable isotope ratios, and will adhere to accepted quality control practices.

Most costs of these biotic inventory and assessment methods arise from field travel and laboratory analyses. Relatively little specialized field equipment is needed, and consortium institutions have all the major equipment require for these analyses.

3. Lake carbon emissions

3.1 Background and rationale

Inland waters are an important component of the global carbon cycle. For example, supported by landscape inputs of terrestrial carbon, global lake CO_2 emissions to the atmosphere rival CO_2 uptake by the world's oceans. Lakes are also globally important hotspots of carbon burial, thereby acting as a carbon sink. Global CO_2 emission rates from inland waters are estimated at 1.8 Pg C / year, and inland waters are also important sources of the greenhouse gases methane (CH_4) and nitrous oxide (N_2O). However, estimates of CO_2 and CH_4 emissions from inland waters are highly uncertain and have frequently been revised upwards. Understanding current and predicting future CO_2 and CH_4 emissions from inland waters is essential for carbon accounting and understanding the overall sources and sinks of CO_2 and CH_4 across New York State's ecosystems.

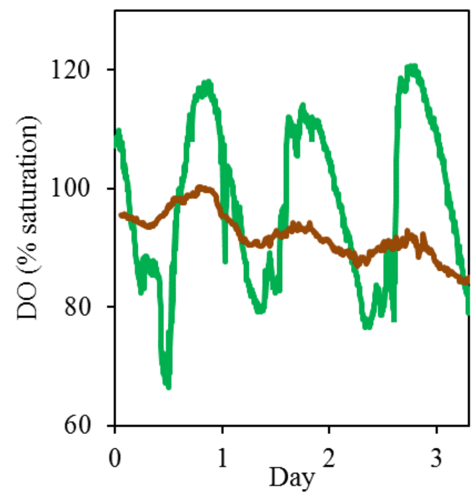
There are several key aspects of lake carbon cycling that dictate their role in the global carbon cycle. First among these is the balance between carbon burial versus emissions to the atmosphere. Burial in sediments removes organic carbon from the water column and is a first step toward the long-term sequestration of carbon in geological reservoirs. While lakes are recognized as hotspots of carbon burial, specific rates and amounts are poorly constrained. *In situ* measurements of carbon burial in inland waters are scarce and variable, with rates varying from 0.2 to 17,392 g C m^{-2} yr^{-1}. Rates of carbon burial have rarely been measured in Adirondack lakes.

Lake carbon emissions act as a source of greenhouse gases, and may offset carbon burial. Emissions can take several forms, with CO_2 and CH_4 emissions being of high importance as these are both important greenhouse gasses. Estimating emissions from lakes and reservoirs is complicated by the fact that multiple pathways must be accounted for, and there can be considerable spatial variability within a single lake. Also, the dynamics of dissolved CO_2 and oxygen are intimately intertwined. The metabolic processing of carbon under aerobic conditions represents an important source of CO_2 emissions from inland waters. In most lakes, ecosystem respiration (ER) exceeds gross primary production (GPP), and thus net ecosystem production (NEP=GPP-ER) is negative, signifying that such lakes are a source of CO_2 to the atmosphere. However, not all CO_2 comes from metabolic sources. Indeed, inorganic carbon loading (e.g., via groundwater), rather than biotic metabolism, may be a primary driver of CO_2 emissions in many lakes. Understanding the importance of metabolic sources of CO_2 to total CO_2 emissions is essential for characterizing the long-term sensitivity of lake carbon emissions to climate.

Elucidating the amount of CH_4 emissions and factors regulating CH_4 emissions across Adirondack lakes is a critical gap in carbon accounting for New York State. Methane emissions from inland waters are poorly constrained but globally important. Anoxic lake sediments are a major natural source of methane, and therefore quantifying the duration and extent of anoxia is a key step toward modeling lake methane emissions. Other important predictors of methane emissions include lake productivity, temperature, surface area, and depth. In turn, lake productivity is often closely associated with nutrient concentrations.

Snapshot profiles of lake CO_2 and CH_4 across lakes will be a key first step toward quantifying lake carbon cycling and greenhouse gas emissions. Emissions of CO_2 and CH_4 exhibit substantial seasonal variability. Surface CO_2 concentrations are lowest during the summer in thermally stratified lakes, when gross primary production (GPP) is consuming CO_2. Additionally, a recent review of 25 studies indicated that the spring ice-melt period, when lakes fully mix, may represent a substantial proportion of total annual lake CO_2 budgets. Yet the ice-melt period is usually not the only period of deep convective mixing. Stratification breaks down at other times of the year, especially in shallower, more wind-exposed lakes. These mixing periods may drive a large fraction of annual CO_2 lake emissions. Severe storms, which are increasing due to climate change, may also present opportunities for deep convective mixing, thereby increasing CO_2 emissions. Furthermore, constrained by light, GPP often can only occur in surface waters, whereas ER is often maintained throughout the water column, and may be highest in deep waters due to settling of labile carbon sources. GPP also exhibits a higher activation energy than ER, therefore decreasing more rapidly at cold temperatures than ER. Meanwhile, methane production is far more sensitive to water temperature than CO_2 production, hence it is expected to increase rapidly with warming.

3.2 Measuring lake carbon burial and emissions



Lake carbon burial rates are commonly estimated by collecting sediment cores and dating them using 210Pb- and/or 137Cs, after correction for sediment focusing. Lake CO_2, CH_4, and N_2O concentrations are typically measured using a greenhouse gas analyzer after water samples are equilibrated with an overlying gas. Lake metabolism characteristics, including GPP, ER, and their imbalance (NEP), are estimated from high-frequency measurements of dissolved oxygen after accounting for thermal stratification and gas exchange with the atmosphere.

Other characteristics must also be measured to understand controls on carbon burial, CO_2 and CH_4 emissions, and ecosystem metabolism across Adirondack lakes. For instance, variability in plankton chlorophyll, dissolved organic carbon concentrations, carbon quality (source and absorbance characteristics), nutrients (N and P), and temperature all affect carbon cycling characteristics. These measurements may enable the forecasting of carbon cycling attributes across many more Adirondack lakes if accurate remote sensing algorithms or process-based models can be generated. For example, NEP (reflected as deviations from 100% saturation of dissolved oxygen (DO) in the figure to right) differs consistently between nutrient-rich eutrophic lakes (green line) and high-DOC dystrophic lakes (brown line). The data from oxygen loggers can be used to estimate rates of GPP, ER, and NEP. Positive NEP (DO>100% saturation) indicates that a lake is a metabolic sink for carbon, while negative NEP (DO<100% saturation) indicates that a lake is a net source of carbon to the atmosphere.

In addition, certain controls on lake carbon cycling such as chlorophyll, DOC, and temperature can be remotely sensed, making historical reconstructions of carbon cycling across Adirondack lakes plausible. It remains to be seen whether three decades of archived imagery can be used to reliably infer shifts in lake carbon cycling. However, remote sensing provides a uniquely rich record that could at least partially compensate for the lack of historical field data.

3.3. Sampling strategy

Sediment cores. Teams with expertise in lake sediment coring will collect and process sediment cores from the high-intensity class of SCALE lakes. These lakes will vary in the characteristics believed to regulate carbon burial rates (see above), and assessing 25 lakes will be a major undertaking that gives substantial insight into regional variability in carbon burial rates. Core lengths will be sufficient to obtain estimates of carbon burial rates for the last ~150-175 years; thus, the length of each core length will be set based on predicted sedimentation rates.

CO_2 ,CH_4, and N_2O. Measuring dissolved greenhouse gases requires intensive manual sampling efforts. Sampling should occur near the deepest point in the lake to obtain data from throughout the water column. Often, surface waters are nearly in equilibrium with the atmosphere, so nearshore samples may not be representative of whole-lake concentrations. Due to heterogeneity in gas concentrations through the water column, measurements should be made at least one depth in the surface mixed layer and approximately every 1-3 meters below the surface mixed layer. For lakes of moderate depth (i.e., >15 m), more than an hour may be required to collect CO_2 and CH_4 measurements in the field. Additionally, CO_2, CH_4, and N_2O concentrations are typically dynamic across the seasons. Therefore, measurements should be made at least monthly during the stratified period. Ideally, several measurements also should be made through the ice, especially later in the winter when dissolved CO_2 and CH_4 concentrations may build up substantially.

Lake metabolism. Metabolic sources (ecosystem respiration) and sinks (gross primary production) of CO_2 can be estimated using models applied to high-frequency dissolved oxygen data, temperature profiles, and estimates of gas flux across the air-water interface (typically estimated using wind speed). Continuous time series of dissolved oxygen and temperature have already been described, and will enable us to understand the seasonal evolution of anoxia in Adirondack lakes. Adding a wind speed sensor, or generating a model of wind speed based on attributes such as lake surface area and wind sheltering, is the only additional variable needed to calculate lake metabolism. These variables will be evaluated for all low- and medium intensity lakes.

3.4. Resources needed

Lake sediment coring requires a gravity corer and processing tools that are available in any paleolimnology lab. Collecting a sediment core can be a time-intensive activity, but will require only a single visit. Most of the cost associated with sediment cores is in the processing of the samples (staff time), and varies based on experience, the length of core, sub-sampling intensity along the chronosequence, and the desire list of analytes.

Portable greenhouse gas analyzers enable accurate measurements of dissolved CO_2, CH_4, and NO_2 in the field. These analyzers are fairly expensive (>$30,000 each), and SCALE will require one for each of three field teams. Teams will collect dissolved gas measurements regularly throughout the year, and most intensively during periods when deep mixing is expected. These measurements will require several hours during each sampling visit.

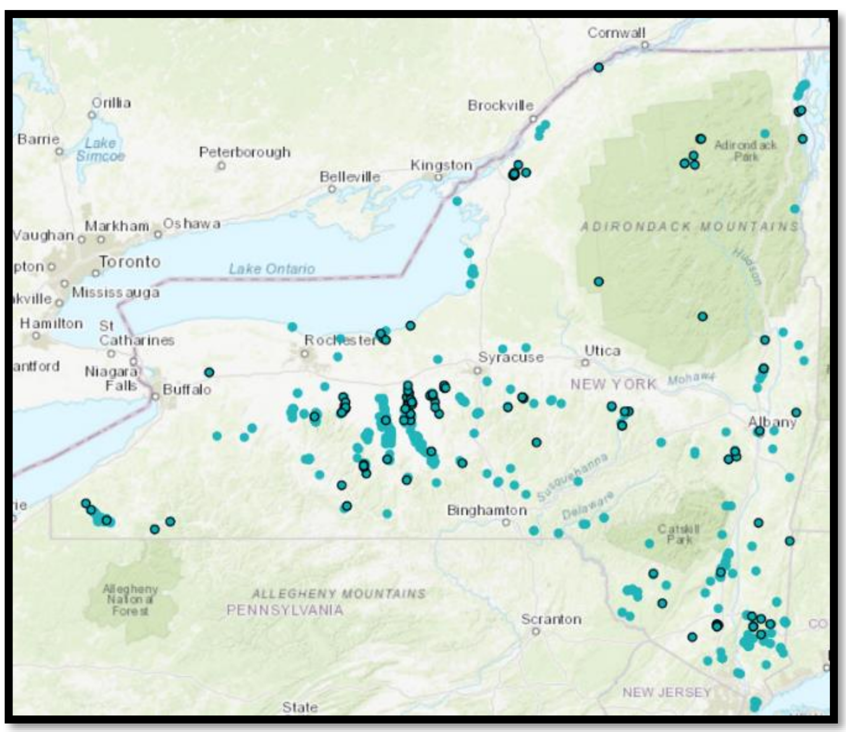
Estimating lake metabolism will involve little additional cost because it uses the same time series data of dissolved oxygen and temperature described earlier. The additional work to produce metabolism estimates would involve measuring or estimating wind speeds at the lake surface, and feeding sensor data into process models after completion of QA/QC.

All carbon measurements (sediment cores, greenhouse gases, lake metabolism) will be made on every lake in the high-intensity class, while metabolism also will be estimated for medium-intensity lakes, and greenhouse gases will be measured even in low-intensity lakes. In each case, the selected lakes will be selected to represent a wide range of carbon inputs (DOC concentration and source), lake productivity (nutrient and chlorophyll concentrations), lake sizes, mixing regimes, and extent of anoxia. Initial data should be reviewed at the end of each sampling season to ensure that SCALE addresses the full range of lake characteristics that contribute to regulating carbon dynamics.

4. Harmful algal blooms

4.1. Background and rationale

Much of the aesthetic, spiritual, and recreational benefits that Adirondack lakes provide to people derive from their clear, cool water. Algal blooms are a direct threat to these ecosystem services, and as well as provisioning of drinking water and food fish. As a consequence, the economic value of lakefront property generally decreases with declining water quality (Nelson et al. 2015), and the 'pea soup' look and 'rotting' smell during and after an intense algal bloom can deter even the hardiest of lake users. For all of these reasons, reports of a global increase in phytoplankton blooms since at least the 1980s are worrying. However, other analyses suggest there has not been a widespread increase in algal blooms through time across the United States. To date, reports of intense algal blooms have been rare in the Adirondacks, however there is widespread sentiment that our lakes are becoming greener through time. Indeed, NYSDEC verified citizen-reported algal blooms in six Adirondack lakes between 1-14 September 2022 (outlined points: Barnum, Otter, Rat, Upper Saranac, Willis, Whey), with an additional two lakes reported during August 2022 (green points: Copperas, Fern). This problem is expected to expand substantially as climate warming continues. Algal blooms have officially become a problem in Adirondack lakes.



When cyanobacteria start to dominate the plankton in an algal bloom, their capacity to produce toxic compounds leads to designation as a harmful algal bloom (HAB). There are several different classes of cyanobacterial toxins, exposure to which can produce acute and/or chronic symptoms ranging from rashes to cognitive impairment to liver failure. Thus, entering the lake or using it as a drinking water source—as is commonplace at lakeside Adirondack homes and camps—are strongly discouraged during and after HABs. Some toxins can also accumulate in the tissues of fish or other aquatic animals; in extreme cases, the resulting consumption risks can last long after the HAB itself. Collectively, these dimensions of diminished water quality and ecosystem impairment are a major threat to the use and economic value of U.S. lakes. During the period 2017-2019, over 300 emergency room visits in the U.S. were linked to HAB exposures, and hotspots of Lou Gehrig's Disease have been ascribed to long-term HAB exposure in residents around New England lakes.

Cyanobacterial HABs are generally associated with two factors: warm water and abundant nutrients. Nutrient enrichment is typically attributed to either external loading of phosphorus from watersheds or internal loading from anoxic lake sediments. However, cyanobacterial blooms are reported from lakes ranging from eutrophic through mesotrophic to oligotrophic, and decades of research on preventing HABs has led to few generalizations about what controls their onset, duration, and intensity. Most Adirondack lakes are cold and oligotrophic, which may reduce the risk of HABs even in response to warming and nutrient enrichment. However, rising temperatures and stronger stratification may shift them toward more favorable conditions for cyanobacteria.

Given the widely-reported upward swing in HABs across New York lakes, it is important to take stock of the current prevalence of HABs in the Adirondacks, and to establish a baseline for future interpretation of why some lakes develop HABs while others do not. More generally, given the protected status of the Adirondack Park, these lakes can serve as a baseline for understanding how climate change is affecting the prevalence, severity, and frequency of HABs.

4.2. Measuring HABs

SCALE will adopt a multipronged approach to assessing HABs across Adirondack lakes. Remote sensing and sediment-based methods will enable us to address historical patterns, *in situ* sensors will be used to characterize algal biomass during field surveys, and toxin analysis of water and fish will provide a snapshot of potential contamination in the most vulnerable ecosystems.

Remote sensing will be used to characterize both historical and contemporary algal blooms in numerous lakes. For instance, the first (June 2015) and second (March 2017) launches of Sentinel-2 satellites provide an overpass of the Adirondacks every 5 days, and these data have been widely used to categorize both general algal biomass and the presence of potentially-toxic cyanobacteria at high spatial resolution (10x10m pixels). There are longer remote sensing datasets with lower spatial resolution and less frequent overpasses (e.g. Landsat) that can also be used to assess trends in algal biomass dynamics in the larger Adirondack lakes. These methods are well accepted for detecting plankton blooms, while the detection and quantification of HABs is a newer application with methods still under development. In fact, SCALE's combination of field surveys and remote sensing of oligotrophic lakes will help to advance that field of research.

Cores collected for carbon accounting will also be analyzed for pigments made by cyanobacteria that can persist for decades in the sediment. Using these compounds as a proxy for HABs will extend our understanding of historical evidence of potential HABs prior to the advent of high-resolution remote sensing. There are many such pigments used by paleolimnologists, including echinenone, myxoxanthophyl, and zeaxanthin. Some of the cyanobacterial toxins, such as microcystins, are stable in sediments for millennia, so we will also use enzyme linked immunosorbent assays (ELISAs) as a low-cost, rapid assay for the historical presence of toxic cyanobacteria.

In situ measurement of algal pigments using sophisticated sensors has become the primary means of characterizing algal biomass and monitoring for blooms over the last decade. Chlorophyll *a*, the major pigment used in photosynthesis by all types of algae and cyanobacteria, can be robustly characterized using optical sensors. Phycocyanin is an additional pigment made by most freshwater cyanobacteria, and there are several brands of optical sensors that quantify its abundance *in situ*. Field teams will characterize both chlorophyll *a* and phycocyanin at the surface of every study lake, and measure depth profiles at the deepest point in a subset of lakes. Confirmation of these *in situ* data will be derived from filtering water, extracting pigments, and quantifying them by fluorometry in the lab. Both types of pigment data will be used to 'ground truth' the remote sensing of algal blooms and HABs.

If HABs are sustained for an extended period, they may produce enough toxins to contaminate drinking water or food fishes. This is unlikely at present in Adirondack lakes, but has not been directly assessed. We will analyze water and fish samples collected during August-September (the period of peak stratification and surface temperatures) for the presence of microcystins using ELISAs. If microcystins are detected, they will be identified and quantified using high-pressure liquid chromatography and mass spectrometry (HPLC-MS).

Interpretation of how lake conditions contribute to formation of HABs will rely upon comparisons of temperature, nutrients (nitrogen, phosphorus, DOC), nitrogen stable isotopes, and land cover data among study lakes that do and do not show evidence of cyanobacteria blooms. Collection of these supporting data was outlined earlier.

4.3. Sampling strategy

Our SCALE efforts will complement and extend other efforts to identify, quantify, and forecast HABs in New York State and across the United States. These include efforts such as the Cyanobacteria Assessment Network (CyAN), which is a multi-federal agency effort to use remote sensing to develop a HABs early warming indicator system. Within New York State, the Citizens Statewide Lake Assessment Program (CSLAP) uses input from citizens to characterize water quality conditions on a large number of NYS lakes, and citizen engagement in SCALE could be useful to provide frequent characterization of potential HABs through samples or pictures, especially in relatively impacted and frequently visited lakes.

Our assessment of the incidence and risk of HABs will rely upon comparing results across nested subsets of Adirondack lakes. Remote sensing will be applied to as many lakes as possible, likely exceeding the number of lakes where field sampling can be accomplished. Every lake visited for SCALE (i.e. low-intensity class) will be sampled using optical sensors for phytoplankton pigments and samples for laboratory determination of major classes of HAB toxins (e.g., microcystins) in water. Sediment cores will be analyzed for cyanobacterial pigments and toxins at regular time intervals for every lake that is cored for carbon accounting. Microcystins accumulated in fish will be analyzed from every lake sampled for fish tissues.

Analyses of remotely sensed imagery will be conducted by a specialized lab following standard methods and complementing CyAN efforts. Adirondack lakes are unusually challenging environments for remote sensing because they are mostly shallow, small, surrounded by mature trees, and strongly stained with DOC, all of which require the highest-possible resolution and spectral width possible. Methods for reliably detecting and quantifying cyanobacterial pigments (i.e., phycocyanin) from hyperspectral images are still under development, and will continue to evolve even during the SCALE project period. Thus, we anticipate that experimentation will be needed, and ground-truthing using field data and laboratory assays will be essential for drawing robust inferences.

In situ analysis of phytoplankton (chlorophyll a) and cyanobacterial (phycocyanin) pigments will rely upon the *bbe* FluoroProbe system. The FluoroProbe sensors simultaneously profile a wide range of different pigments, and translate the results into the relative biomass of many different classes of algae and cyanobacteria. This unit will be used for both rapid characterization of surface phytoplankton, and creating a vertical profile from the surface to bottom of a lake. However, optical sensors sometimes suffer from complex background chemistry in lakes, especially due to DOC. To validate and quantitatively calibrate results from the Fluoroprobe, phytoplankton will be collected on glass-fiber filters, extracted in an organic solvent, and analyzed using standard methods in the lab.

Processing of sediment cores requires specialized facilities, and samples must be kept cold and analyzed within a few weeks of collection to avoid degradation of plankton pigments. Extracted pigments will be analyzed by HPLC. Microcystins are more stable, and sediments that have been dried for carbon analysis will be subjected to ELISA assays. If microcystins are detected, samples will be sent to a specialized lab for further analysis and quantification.

Fish muscle will be dried, ground, subsampled, extracted, and analyzed by ELISA for microcystins. Any positive detections will be further analyzed and quantified by HPLC-MS in a specialized lab.

To develop a predictive understanding of HAB risk in Adirondack lakes, we will use statistical modeling. Nutrient concentrations, nitrogen isotope ratios, water temperatures, watershed land use, and lake characteristics (surface area, depth, volume, macrophyte presence, fish presence) will be tested as predictors of the presence and intensity of algal blooms. A second phase of modeling will explore the predictors that differentiate lakes with cyanobacterial blooms from those with algal blooms that do not feature cyanobacteria. Such predictive models could then be applied to lakes that were not sampled for SCALE, thereby creating the possibility of classifying all Adirondack lakes into HAB vulnerability groups to direct future monitoring efforts by citizens (CSLAP, lake associations), DEC staff, and researchers.

4.4 Resources needed

Assessing HABs requires specialized field equipment, laboratories, and computation facilities. Sediment cores, water samples, and fish muscle will already be collected for other components of SCALE. Only the deployment of the Fluoroprobe will require additional effort by the field team. The additional staff time required is modest, but FluoroProbes are expensive (~$40,000 each). To make the most of the field efforts, every field team should be equipped with a FluoroProbe. DEC has already embraced the FluoroProbe platform, and we will inquire about opportunities to borrow or share equipment.

In the laboratory, analyses of filtered phytoplankton samples for chlorophyll *a* is routine for limnologists, and will not require additional equipment. However, HPLC-based analysis of cyanobacterial pigments is more specialized. Analysis of microcystins by ELISA is straightforward using commercially-available kits, and could be performed at any consortium lab. If SCALE samples are shown to contain microcystins based on ELISA, then quantification of concentrations requires both specialized lab facilities and expertise, such as those at Rensselaer Polytechnic Institute or SUNY ESF.

Finally, processing, analysis, and synthesis of data from remote sensing requires specialized expertise and powerful computers. A consortium member with the required expertise would already have the hardware or software required, so the primary costs for remote sensing are staff time. The same applies to developing predictive statistical models of HABs, and classifying Adirondack lakes by vulnerability to HABs.

Hierarchy of research questions

All four research themes described above are high priority topics identified by workshop participants. However, questions 1 (regarding temperature, oxygen, and nutrients) and 2 (focusing on the biota) represent the core components of SCALE. The sampling needed to address these questions provides essential measurements for measuring climate change impacts on Adirondack lakes, and also provides critical contextual knowledge for themes 3 (carbon accounting) and 4 (HABs). In other words, surveying the lake conditions and biotic responses is critically important in its own right, but will also provide essential data and major cost-saving in supporting assessment of how carbon dynamics and algal blooms are changing now and into the future. There will likely be opportunities for the SCALE consortium to partner with agencies whose specific mission pertains to questions 3 and 4, and who might be able to provide additional staffing, analytical support, or supplemental funding.

Nested design of lake surveys by intensity of effort

The broad range of questions and methods embraced in SCALE necessitates prioritization of efforts across lakes. For very labor-intensive methods, it is only feasible to analyze a small number of lakes, whereas remote sensing allows examination of all Adirondack lakes that exceed the grain of the imagery. To balance the depth of assessment against the extent of the survey, we will study four sets of lakes that are hierarchically nested. Particularly time-intensive, equipment-intensive, or costly analyses will be performed only on 25 high-intensity lakes. The next tier of metrics will be analyzed from an additional 30 medium-intensity lakes (55 lakes in total), and the least intensive methods will be applied to an additional 245 lakes (300 in total). These numbers of lakes represent loose goals across three years of field work, and are subject to revision.

There are two critical features of this sampling plan. First, the intensity classes of lakes are fully nested, such that every method is applied in parallel to the high-intensity lakes, and then fewer analyses are conducted for each successive intensity class. This pattern is summarized across analytical tasks in the table below. Second, every intensity class contains a representative set of lakes across many key variables. For instance, high-intensity lakes will include a wide range of lake sizes, depths, mixing types, DOC concentrations, fish diversity, pH, hydrology, watershed geology, and human disturbance. As the number of study lakes increases with reduced intensity of work, each of these factors will become even better represented. The pilot work presently underway includes mining of the existing data from all Adirondack lakes to support the selection of specific lakes for each intensity class.

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		Survey intensity class			
Theme	**Metric**	**High (25 lakes)**	**Medium (55 lakes)**	**Low (300 lakes)**	**Remote (all lakes)**
Baseline conditions	Sonde profile (temp, oxygen, etc.)				
	Water chemistry (nutrients, pH, etc)				
	Submerged oxygen/temp loggers (1 year)				
	Submerged oxygen/temp loggers (3 years)				
	Temp, ice, chlorophyll, DOC (remote sensing)				
Biotic responses	Phytoplankton, zooplankton, macrophytes				
	Fishes & benthicinvertebrates				
	eDNA				
	Stable isotopes (C, N, H) (current & historic)				
	Mercury in fish (current & historic)				
Carbon budgets	Carbon burial rates from sediment cores				
	CO_2, N_2O, and CH_4 concentrations				
	Lake metabolism (GPP, ER, NEP)				
	Seasonality in CO2, N2O, and CH4 concentrations				
Harmful algal blooms	Phytoplankton biomass and blooms (remote sensing)				
	Historic HABs (cyanopigments in sediment cores)				
	Phytoplankton pigments and cyanotoxins				
	Cyanotoxins in fish				

Data management

SCALE will provide a large volume of data, with data types varying substantially in many attributes such as frequency, complexity, methods used, and accuracy. Much of the data will be collected through the survey effort itself, but additional data from public sources such as remote sensing and CSLAP programs will be used. Ensuring high data fidelity is essential to the long-term utility of SCALE and therefore data management will be an essential component of SCALE efforts in all phases of the project.

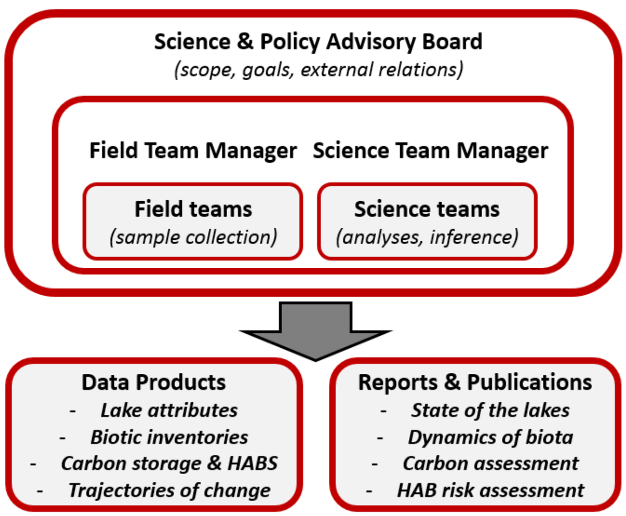
SCALE leaders and all project participants will conform to established best practices for protecting against lost data, data quality assurance and control, creating and tagging appropriate meta-data, dataset versioning, and data set publication. Given the complexity of data management in SCALE, a dedicated database manager will be supported if funding is sufficient to do so. Quality assurance protocols will be implemented before data are collected to ensure data are collected in ways that maximize their accuracy and fidelity. Quality control procedures will be implemented post-collection to correct data for factors such as calibration and drift. All raw data will be retained, and data versioning will be used through multiple levels of increased flagging and correction. Final data sets will be appropriately tagged with metadata and published in online public repositories to maximize transparency and use of the data.

SCALE Consortium Approach

A consortium approach is a central tenet of the SCALE vision and was embraced by all attendees of the planning workshop. Developing a consortium is important for four reasons. First and foremost, SCALE seeks to apply numerous cutting-edge scientific methods to the challenges faced by Adirondack lakes under climate change. No single institution or organization has the facilities and expertise to fill all of these knowledge gaps. Rather, each partner in the consortium will focus on doing what they do best, thereby drawing upon talent, skills, and facilities across a wide range of New York institutions. Second, the insights from each method depend upon results from other methods, therefore a collaborative and inclusive approach to the project is required to obtain syenrgistic inferences. A siloed approach is very likely to lead to redundancy in measurements and inefficient (or absent) communication among groups working on different topics. Third, the expansive field campaign envisioned for SCALE requires centralized execution of lake sampling in order to be efficient. While every science team in the consortium can devise their own sampling protocols, visiting a large number of disparate lakes must be done in a concerted manner that results in a single consolidated sample archive and database of results. Finally, raising funds to support such a large effort will require buy-in from a wide range of stakeholders and participants. Members of the SCALE planning workshop already have a strong track record of advocating for SCALE within the New York State legislature as a consortium. It is reasonable for New York State to expect that many organizations throughout the State will benefit from public investment in executing the survey. For all of these reasons, the design of the SCALE initiative outlined herein is premised on engaging and supporting a consortium of research partners.

SCALE Project Structure

The success of SCALE will depend upon creating an appropriate organizational structure that provides oversight for a diverse team of scientists while enabling them to innovate and respond to evolving monitoring, research, and policy needs. To that end, we recommend the organizational structure illustrated here, with the goal of achieving high-quality outputs (data products, reports, and publications) and ensuring responsiveness to policy needs. The core data sets and innovative interpretations produced by SCALE will help New York State to understand, adapt, and reduce climate change impacts on Adirondack lakes.



Science & Policy Advisory Board: This group of scientists and policy experts will play an essential advisory role. Key points of input will include: setting the scope of the project based on the sources and stipulations of funding; prioritizing specific goals that will maximize project impact given the available budget; facilitating coordination between with the Field Team Manager and Science Team Manager; selecting scientists from consortium institutions to lead each Science Team in consultation with the Science Team Manager; and transmitting stakeholder input to the management team throughout the project. To avoid conflicts of interest, Science Team leaders will not be eligible to serve on the Advisory Board, and Advisory Board members will be prohibited from becoming Science Team leaders.

Field Team Manager: This position will coordinate all facets of field work, including regular communication between the Advisory Board and Field Teams. The Field Team Manager will hire, train, and coordinate multiple teams of field technicians; ensure proper implementation of sampling protocols; manage sample inventory and storage processes; and ensure adherence to safety standards. Also, close coordination with the Science Team Manager will ensure that sampling efforts serve science needs in an efficient manner.

Science Team Manager: This position will coordinate all facets of the scientific analysis of samples and data, including regular communication between the Advisory Board and the Science Teams. The Science Team Manager will arrange annual meetings of all Science Teams; assist with solving challenges that arise; ensure QC of data produced by each Science Team; compile verified data across all Science Teams; and produce coordinated reports and data publications that integrate across all Science Teams.

Field Teams: A set of Field Teams will sample Adirondack lakes each year. Each team will comprise two technicians, and they will rotate among lakes with regular trips back to a home base to deposit samples and data. The number of field teams will be dictated by the budget and final number of selected lakes that will be surveyed. The Field Team Manager may also serve as a member of a Field Team.

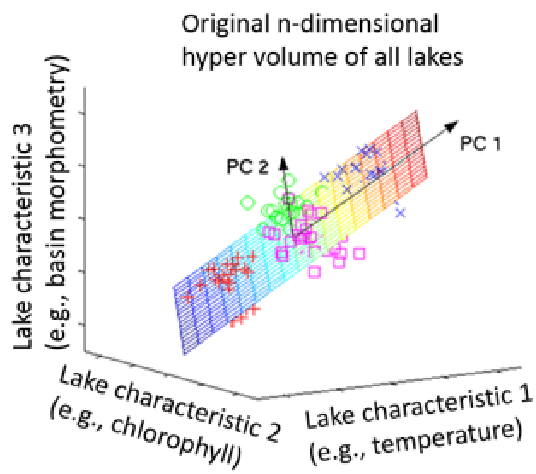
Science Teams: Scientists from consortium institutions will lead research on each major dimension of SCALE (see themes listed above), reflecting their expertise in the required methods, access to existing facilities for producing high-quality data, and ability to integrate and oversee trainees and collaborators as appropriate. The leader of each Science Team will be responsible for developing field sampling protocols in consultation with the Field Team Manager and Science Team Manager; developing analysis protocols that meet or exceed accepted QC standards; ensuring timely analysis of samples; conveying verified datasets to the Science Team Manager; developing inferences in accordance with the specific goals of SCALE; contributing to reporting and publication of findings; and presenting at annual SCALE project meetings.

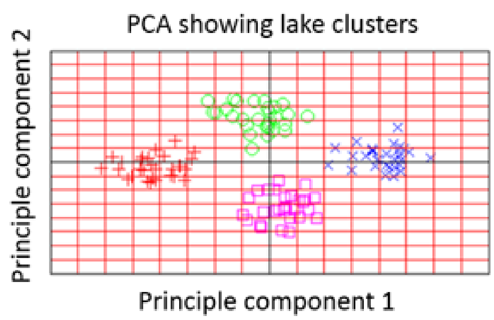
SCALE Project Process

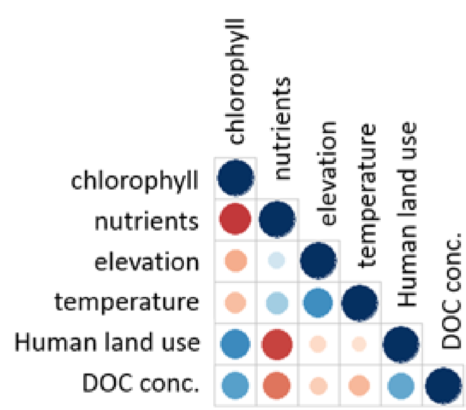
SCALE can be envisioned in four phases over a six-year period (2023-2029). The first phase is the planning stage, which is currently underway. The 2021 workshop and this report are key initial steps in planning, but additional follow-up steps are outlined below. The second phase is sample collection, which includes both field sampling and remote sensing. The third phase is the sample analysis and data compilation phase. The fourth and final phase is data analysis and reporting, where results will be used to generate transformative and actionable scientific insights. As a complement to SCALE, ongoing monitoring (e.g., NYSERDA’s ALTM program) can be modified over time to align with SCALE priorities and to respond to insights from SCALE’s findings.

Phase one: Mining historic data and piloting key methods (~1 year)

This document outlines overarching research priorities and includes recommendations for specific types of SCALE measurements. Before a survey can be launched, however, it is essential that we identify the number and specific identity of lakes that represent the entire range of lake conditions in the Adirondacks. The number of lakes needed to answer each research question varies widely, in part reflecting the realities of field and laboratory logistics. Optimizing site selection is essential for maximizing the strength of inferences about climate impacts on unstudied lakes, as well as minimizing project costs in terms of time and funding required. For example, many attributes regulate the concentration of dissolved oxygen, such as plankton productivity (e.g., chlorophyll, nutrients), water clarity, temperature, depth, and time since the seasonal onset of thermal stratification. Adirondack lakes encompass a spectrum in each of these characteristics, so it is not a trivial task to select a small subset of lakes where findings will be representative. A complicating feature is that many of these lake characteristics are related to (or covary with) one another. For example, surface temperature and time since onset of thermal stratification are sure to be correlated, as are productivity and water clarity. Therefore, it may not be feasible to identify a suite of lakes that spans every combination of these characteristics.







A thorough statistical analysis of existing data from Adirondack lakes is essential to (1) identify the lake attributes that are most likely to govern the response variables of interest and (2) identifying clusters of similar lakes from which to sample. For example, dimension-reduction approaches such as principal components analysis (PCA) may reveal that lakes that are shallow, low elevation, warm, and have high nutrient levels represent a distinct cluster of covarying attributes, such that few lakes have one of these characteristics (e.g., high nutrients) but not the others. In this way, complex multivariate lake data (upper figure) can be reduced to a small number of dimensions (middle figure) that reveals how lakes cluster across all variables. New machine learning techniques can also be used to group lakes by similarity. Once these clusters are identified, a stratified sampling approach can be used to select particular lakes (and alternates). This systematic approach will ensure that selecting even a modest number of high-intensity lakes will nonetheless capture the major axes of variation among Adirondack lakes, thereby representing the broader population of lakes without bias. Informed by the statistical distribution of each key lake characteristic across lakes, every level of sampling intensity can appropriately represent the overall variation among lake ecosystems.

Moreover, examining the correlations among key regulating variables (bottom figure) will help to identify unique lakes that differ from the general clustering of lake types, so that we can include these special ecosystems in SCALE field sampling.

Identifying lake clusters and specific lakes to sample requires a thorough examination of past historic data. Fortunately, there have been initial efforts to compile some of the available data, but a great deal of additional data wrangling is required before robust lake selections can be made. We anticipate that a year of full-time effort from someone skilled in bioinformatics will be required. The key outputs of that work would be identifying key lake characteristics with sufficient historical data, analyzing the statistical patterns of each characteristic, application of dimension-reduction methods to identify clusters of lakes for stratified random sampling, and selecting representative lakes (and alternate selections) that will ensure that the suite of lakes sampled is representative.

A second priority for phase one is piloting field and laboratory methods for key analyses where off-the-shelf methods have not been proven for Adirondack lakes. For example, interpretation algorithms for remotely sensed imagery have not been calibrated or validated for Adirondack lakes, which have higher and more variable DOC than most temperate lakes. Remote sensing also will be complicated by shoreline and bottom interference in the numerous small lakes, requiring careful quality control and potentially development of new algorithms tailored to these limitations. Similarly, eDNA inferences rest on the completeness of a reference database of relevant species for which genetic barcode data are already established. Compiling and validating that database is laborious, and requires test samples from lakes as well as bioinformatics work. Stable isotope food web analysis, carbon budgeting, and cyanobacterial proxies are additional topics where pilot work would enable us to optimize field and lab protocols prior to the launch of large-scale field sampling.

Phase two: Collecting field samples (~3 years)

The four research themes outlined earlier included descriptions of many aspects of sample collection. However, the specific scope and priorities for field sampling will be dictated by results from analysis of historical data, consultation with stakeholders, and the amount of funding available. The process of mining historic data sets will inform the specific lakes to be sampled, which will enable logistical planning for field sampling (e.g., field team size, visit duration). Field sampling should proceed only after a full suite of target lakes has been identified, and pilot work demonstrates the robustness of the sampling protocols for each type of data. It is also critical that the consortium engage with stakeholders (including Adirondack residents and educational institutions) to ensure that sampling plans address their priorities to the maximum degree possible. Finally, the amount of funding anticipated will determine the number of lakes visited, duration of field sampling, and breadth of Science Teams involved in SCALE. The priorities identified by workshop attendees would require extensive field sampling across a 3-year period, involving active field work for roughly 4 months per year.

Phase three: Sample analyses and data compilation (concurrent with Phase two)

Once samples are collected, many tasks are required to turn them into reliable and useful data points. First, many samples will need further processing. Samples for chemical measurements will need to be shipped to consortium partner laboratories for analyses, and then data (and associated metadata) will need to be returned to a central site for compilation.

Assuring high quality of final data products derived from the numerous sensors and analyses encompassed in this vision for SCALE starts with preparation and planning before Field Teams are deployed. Thoughtful sampling design, mature field protocols, well-calibrated sensors, and fully-functioning field equipment will be requisite. For sensor data, after field deployments are completed, all sensors should undergo quality checks and calibration, and the data should be revised accordingly. All laboratory analyses should use established standards and protocols. All data generated will need to be quality checked, and a robust quality assurance plan will be needed. A data management plan will be essential because high-frequency sensors, eDNA, and remote sensing generate huge datasets that are not be trivial to process or manage. A well-organized database architecture plan and central repository for all types of data will be needed, as well as clearly defined controlled vocabulary, metadata standards, and data versioning.

An automated quality control procedure should be implemented following established best practices based on thresholds and statistical attributes. For example, the US National Ecological Observatory Network (NEON) has a well-documented quality control checklist for sensor data consisting of six "plausibility tests". These tests include checks for data outliers, variance, step changes, and missing data, which are all common issues with sensor datasets. Checks for appropriate date and time, range, persistence, change in slope, internal consistency, and spatial consistency should also be undertaken, following established recommendations.

Following data compilation and quality checks, all data should be made publicly available. If possible, a manuscript describing the raw data and/or analysis package to assist future users to access and process the data should be created.

Phase four: Synthesizing data into insights, and engaging with stakeholders (2 years)

Once a database of results is complete, statistical analyses will be required to elucidate patterns, interpret relationships among variables, and resolve each of the research questions that motivate SCALE. This final phase is no less challenging than field and laboratory work, but it requires very different skill sets and engagement strategies. It will take several years to analyze the data and report results to fulfill the SCALE mission, and this effort must be planned into the overall project timeline and funding needs from the start.

A minimum of two years of effort from one postdoctoral researcher per Science Team will be required for synthesis, reporting, and stakeholder engagement to make good on the potential of SCALE. Key products of this process will include peer-reviewed publications, summary assessment reports, and presentations across the Adirondack region to ensure that communities and their leaders are aware of how climate change is affecting their waters. The consortium should also strive to produce predictive models—validated using real data—that can project future conditions and risks to the degree possible. The amount of time necessary to generate these products will vary depending on the complexity of the patterns in the data, and the causal mechanisms that underlie them.

In addition to analyzing data from direct measurements, it is a priority to use these data to calibrate and validate remote sensing algorithms and ecosystem models. This will enable the SCALE survey data to be used to make inferences for a much broader suite of Adirondack lakes and make forecasts of future ecological conditions under various climate (and/or other) scenarios. Some properties can be remotely sensed such as temperature, ice cover, water clarity, chlorophyll, and dissolved organic carbon. Thus, generating remote sensing algorithms to characterize spatial patterns in these characteristics from remotely sensed imagery should be a priority. A number of satellite products could be used, including both publicly available imagery (e.g., Landsat, Sentinel) and private-sector products (e.g., Planet Labs). Process-based hydrodynamic and ecological models can be calibrated and validated using field data. Hydrodynamic models can be used to characterize full-year lake temperature dynamics and forecast temperatures for decades to come. Ecosystem models can be coupled with hydrodynamics and validated against *in situ* measurements to predict future changes in characteristics such as dissolved oxygen, water clarity, or carbon emissions and burial. Subsequent scenario analyses can then explore the implications of various management decisions or tradeoffs. Applying these remote sensing and modeling tools would substantially leverage field-collected data to better understand the sensitivity of Adirondack waters to climate change even for lakes that have not yet been directly surveyed.

The large amount of data generated by SCALE (including the derived data products and models described above) will fuel insights for many years beyond the proposed two-year synthesis phase. Thus, the consortium will likely wish to seek further funding for data synthesis, stakeholder engagement, and field and laboratory work if justified by the initial results.

Funding strategy

Ideally, sufficient funding will be available to collect and analyze data for all four research themes simultaneously, and covering the costs of all four phases. Indeed, the efficient use of resources for a complex project like SCALE requires investing in careful planning on the front end, and adequate personnel to perform statistical syntheses across metrics on the back end of extensive field and laboratory work. If sufficient funding is not available to cover the full set of priorities outlined herein, it might be better to reduce the breadth of SCALE consortium and research agenda than to underfund the planning, inference, and engagement steps.

We have planned SCALE in a modular way, in which some stakeholders may be sufficiently motivated to fund dedicated work on certain themes that leverages the core field and laboratory effort, and contributes to fulfilling the overall vision. Specifically, data collected for questions 1 (temperature, oxygen, and nutrient conditions) and 2 (lake biota) are essential for questions 3 (carbon budgets) and 4 (HABs). Therefore, if budgets are constrained, it would be an option to emphasize the first two themes for core work funded by state or federal authorities, and then seek supplemental funding for themes 3 and 4. For example, carbon accounting may be of special interest to the NYSDEC's Office of Climate, and HABs are a priority for the US Geological Survey and EPA. Such additional funding would be highly leveraged, thereby enhancing return on research investment for all parties.

In order to minimize the overall budget request, the preliminary analyses of historical data will seek to identify both (1) the minimum and (2) the ideal number of lakes to sample for each research question. These estimates can be used to balance the robustness of inferences against budgetary requirements. Beyond adjusting the number of lakes sampled, further budget reductions would require trimming the breadth of SCALE.

To complete field sampling for SCALE within three years, several field teams will be required each year. Indeed, centralizing the field sampling effort is essential for cost-efficiency; it would be very inefficient for each scientist to send out their own personnel to collect samples from the same set of lakes. Within a coordinated effort, the minimum field team size would be two technicians, due to both safety considerations and equipment requirements.

A wide range of field equipment will need to be purchased for SCALE, but we hope to keep lab equipment needs to a minimum by using existing laboratory facilities and technical expertise from across the consortium. Part of the planning process under Phase 1 is to survey the resources available from consortium partners, beginning with a survey of all workshop attendees after this draft report is approved.

Provisional budget estimate

Creating well-constrained budgets is not possible at this time, given the many unknowns involved, but the workshop and reporting process has helped us to resolve some rough estimates. The figures that follow should be considered provisional rather than binding.

We estimate that the work described herein will require seven Science Teams. Costs for each Science Team will average $250k per year for personnel (total ~$5.25M across three years of Phase 3). It should be noted that this is a loosely-estimated average, and the range may be variable due to contrasting costs associated with different types of research. Moreover, costs of each type of scientific work may vary between years. In addition, we estimate $1.25M of equipment costs and $1.5M of analysis fees across the period of SCALE.

We estimate field sampling will cost ~$500k per year for salaries and travel, totaling ~$1.5M during Phase 2. Project management costs during Phase 2/3 (two personnel plus Advisory Board) are estimated at $330k per year, totaling $1M. Synthesis and engagement personnel (seven postdoctoral researchers) and reporting costs are estimated at $2.5M for Phase 4.

This yields a total budget estimate of $13M across six years. This figure remains conjectural, but will become increasingly resolved as planning within Phase 1 proceeds. For comparison, the inflation-adjusted cost of the 1980s ALS, which was more limited in scope, exceeded $12M.

The cost figure above excludes the $500k already provided by New York State for Phase 1. The work currently underway includes the wrangling and synthesis of historical data to identify specific lakes for sampling, piloting of field protocols, development of field and laboratory methods for eDNA and stable isotope analyses, refinement and calibration of remote sensing algorithms to document rates of change in lake temperature, ice cover, and water color across decades, and all associated field work and project management costs. These preparatory efforts will ensure that Phase 2 can launch smoothly, yielding rigorous data and appropriate archival samples from the beginning.