Representativeness of Adirondack Long Term Monitoring Lakes and Recovery from Acidification

T. Sullivan[1], C. Driscoll[2], B. Cosby[3], J. Zhai[2], I. Fernandez[4], A. Herlihy[5], K. Snyder[1], R. Stemberger[6], T. McDonnell[1], D. Moore[1], J. Sutherland[7], C. Boylen[8], S. Nierzwicki-Bauer[8]

ABSTRACT:

Seventy Adirondack lake watersheds, extrapolated to the regional population, were studied to assess changes in acid-base chemistry and biology in response to changes in acidic deposition. The effort involved field sampling to develop a statistically representative soils database, model projections using the MAGIC and PnET-BGC models to classify lakes according to their sensitivity to changes in atmospheric sulfur (S) and nitrogen (N) deposition, and evaluation of the extent to which Adirondack Long-Term Monitoring (ALTM) lakes are representative of the regional population.

Concentrations of exchangeable soil base cations, base saturation (BS), and soil pH were low. More than 75% of the target lakes received drainage from watersheds having average soil B horizon BS less than 10.3% and pH (H2O) less than 4.5. Monitoring data indicate that lake water chemical recovery is ongoing in many lakes as acidic deposition levels decline. However, our modeling results suggested that, for many Adirondack lakes, chemical recovery might fail to continue in the future. We simulated that many low-ANC lakes would actually reacidify under emissions control regulations in place at the time of development of this modeling effort. This response was due to projected continued declines in mineral soil % BS within the lake watersheds. Continued chemical recovery of lake water was suggested, however, under more stringent emissions controls.

We developed empirical relationships between lakewater acid neutralizing capacity (ANC) and the species richness of zooplankton and fish, based on available data. These relationships were then applied to PnET-BGC model hindcast and forecast projections to generate estimates of the extent to which changes in species richness might accompany projected chemical changes. The median inferred loss of zooplankton species from 1850 to 1990 was 2, with some lakes inferred to have lost up to 6 species.

Ignoring other factors that might influence habitat quality, we estimated that the median Environmental Monitoring and Assessment Program (EMAP) study lake had lakewater acid-base chemistry consistent with the presence of five fish species in 1850, prior to the onset of regional acidic deposition. Twenty percent of the lake population was estimated to have pre-industrial lake water ANC consistent with supporting fewer than 4.1 fish species. By 1990, these median and 20th percentile values for estimated fish species richness had been reduced to 4.6 and 2.0 species, respectively. The 20% of the lakes that were most acid-sensitive were simulated to change ANC in the future to an extent consistent with a further loss of fish species by 2100 under the Base Case emissions scenario (reflecting regulations in place as of 2003), and small gains in fish species under the Moderate and Aggressive Additional Emissions Control scenarios.

Both MAGIC and PnET-BGC estimated that the modeled ALTM lakes were largely among the lakes in the population that had acidified most between 1850 and 1990. Both models estimated that virtually all of the modeled ALTM lakes were in the top 50% of acid sensitivity compared with the 1,829 Adirondack lakes in the EPA EMAP statistical frame. The results of this research will allow fuller utilization of data from on-going chemical and biological monitoring and process-level studies.

BACKGROUND:

Ecosystem damage from air pollution in the Adirondack Mountains, New York has been substantial. In particular, many surface waters have experienced decreases in pH and ANC and concentrations of inorganic Al have increased, with consequent adverse impacts on fish, zooplankton, and other aquatic biota. In recent years, S deposition has declined, and is projected to continue to decline, in response to enactment of the Clean Air Act Amendments of 1990 and other legislation. Long-term monitoring programs have been collecting data for more than two decades, and continue to collect chemical and biological data, some of which show evidence of resource recovery. However, there previously was not a mechanism available to extrapolate results of these monitoring studies to the regional population of Adirondack lakes, and this has seriously curtailed the ultimate utility of these important data. Resource managers and policymakers need to know the extent to which current and projected future emissions reductions will lead to ecosystem recovery, both chemical and biological. Such recovery is being quantified at these monitoring site locations, but previously could not be directly extrapolated to the region.

Prior to this study, there was not a regional soils database for the Adirondack Mountains that was well-suited for providing the basis for model projections of resource recovery. This previous information gap was important because the degree to which regional Adirondack soils conditions exert controls on lakewater chemistry is not well understood, but may be substantial. Regional knowledge will provide a stronger basis for setting emissions reduction goals, for evaluating incremental improvements, and for conducting cost/benefit analyses.

APPROACH:

- Acquire long-term monitoring data for 32 acid-sensitive lakes
- Statistically select a subsample of Adirondack lake watersheds from EPA's EMAP for regional characterization
- Compile watershed data on atmospheric deposition, vegetation, soils types, land use, and disturbance
- Conduct a survey of soils chemistry within 70 long-term monitoring and EMAP watersheds, stratified by lakewater ANC, soils type, and forest cover type
- Apply the MAGIC and PnET-BGC models to the 70 study watersheds, and simulate past and future responses of lakewater chemistry to changing levels of S and N deposition
- Classify watersheds according to responsiveness to future decreases in S and N deposition
- Develop and apply biological response algorithms for zooplankton and fish
- Compare and contrast model output from MAGIC and PnET-BGC

MAJOR OBJECTIVES:

- Develop approaches for extrapolating spatially-limited knowledge regarding chemical and biological recovery of acid-sensitive lakes and their watersheds to the regional population of Adirondack lakes and watersheds
- Develop a statistically-representative soils database for the Adirondack region
- Classify watersheds according to their responsiveness to ongoing and future changes in S and/or N deposition
- Generate model projections of past acidification of Adirondack lakes, and future change in response to varying levels of emissions control

[1] E&S Environmental Chemistry, Inc.
[2] Syracuse University
[3] University of Virginia
[4] University of Maine
[5] Oregon State University
[6] Dartmouth College
[7] NYS Department of Environmental Conservation
[8] Rensselaer Polytechnic Institute

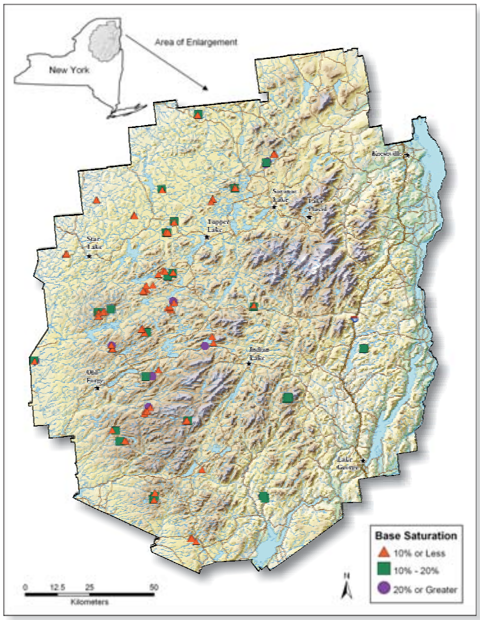


Figure 1. Map of the Adirondack Park indicating the location of the soil sampling sites selected to represent the region, coded by measured soil base saturation.

RESULTS:

SOIL CONDITIONS

Soil characteristics were determined at 199 locations within 70 watersheds. Results of soil analyses were extrapolated to the population of 1,320 watersheds containing lakes larger than 1 ha that had ANC less than 200 μeq/L. More than 75% of the lake population received drainage from watersheds having average B horizon exchangeable Ca concentrations less than 0.52 cmolc/kg, base saturation less than 10.3%, and pH (H_2O) less than 4.5. Soils having base saturation less than 10% were widely distributed throughout the western half of the Adirondack region (Figure 1). These data provide a baseline against which to compare future changes in regional soil chemistry, and also provided input data for the aquatic effects models.

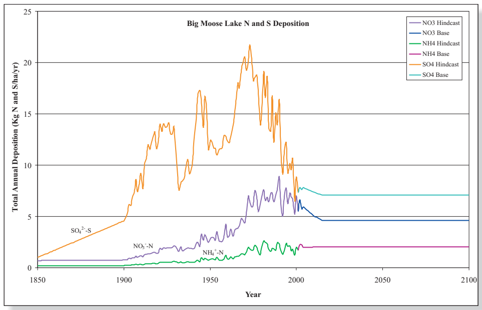


Figure 2. Estimated total annual atmospheric deposition of S and N from pre-industrial times to 2100 at the location of a representative watershed in the southwestern Adirondacks (Big Moose Lake). Future emissions were estimated by U.S. EPA, assuming existing and expected emissions control legislation in 2003.

MODEL PROJECTIONS

Model simulations were conducted using the MAGIC and PnET-BGC models. Results for the 44 statistically-selected lakes and their watersheds were extrapolated to the population of 1,817 Adirondack lakes less than 1 ha in area depicted on 1:100,000-scale topographic maps, and also to the subpopulation of 1,320 of those lakes that had ANC less than 200 μeq/L at the time of EMAP sampling. Model simulations were extended into the future assuming S and N emissions controls expected to be enacted under existing air pollution control regulations in 2003. Under the Base Case emissions control scenario (Figure 2), SO2 emissions were projected to decrease over a 15-year period by 10.9% from 2001 values. NOx emissions were projected to decrease by 30.6% and NH3 emissions to increase by 4.8% over the same period. Both models showed close agreement between simulated and measured water chemistry. Model simulations suggested large decreases in lakewater ANC and pH from pre-industrial times to the period of maximum acidification (approximately 1980 to 1990). Limited chemical recovery is currently occurring (Table 1). The median Adirondack lake, from among the population of 1,320 lakes having current ANC ≤200 μeq/L, was simulated by MAGIC to have decreased in ANC by 38 μeq/L between 1850 and 1990. Twenty-five percent of those lakes were simulated to have acidified since pre-industrial times by more than 56 μeq/L. Under the scenario of existing emissions control legislation, more than 75% of these 1,320 lakes will increase in ANC between 1990 and 2050, with a median future increase of 6 μeq/L. However, not all lakes were simulated to recover some of the lost ANC in the future. Model simulations suggested future reacidification of some lakes under S and N emissions control regulations that were in place in 2003. In particular, the simulations suggested future increases in the number and percentage of lakes that are low in ANC (Table 2). Model simulations for many of the lakes that are lowest in ANC suggested that the on-going chemical recovery will come to an end around 2020 and will be followed by a lengthy period of gradual reacidification for some lakes (Figure 3). Such reacidification was not simulated for the study lakes currently highest in ANC. Both models suggested that the number of acidic lakes would approximately hold constant from 2000 to 2100. The models projected that the numbers of lakes having ANC less than 20 μeq/L and less than 50 μeq/L would both increase in the future (Table 2) under the Base Case scenario. These simulation results may be attributable to decreasing soil base saturation in many of the more acid-sensitive modeled watersheds.

Table 1. Simulated water chemistry percentile values for the population* of potentially acid-sensitive Adirondack lakes, based on the MAGIC model, for the period from 1850 to 2100, assuming S and N emissions control regulations as of 2003.

Variable	Year	Percentile				
		10	25	50	75	90
ANC	1850	28	72	95	174	253
	1900	29	69	97	180	259
	1980	4	25	64	133	189
	1990	4	31	63	118	180
	2000	6	35	67	117	183
	2050	0	35	67	129	200
	2100	-7	32	61	132	200
pH	1850	5.9	6.5	6.8	7.1	7.3
	1900	5.8	6.5	6.8	7.1	7.3
	1980	4.8	5.5	6.5	6.9	7.2
	1990	4.8	5.5	6.5	6.9	7.2
	2000	4.9	5.8	6.5	7.0	7.2
	2050	5.0	5.8	6.5	7.0	7.2
	2100	5.0	5.7	6.5	7.0	7.2
SO_4	1850	5	7	9	15	23
	1900	17	20	23	32	38
	1980	86	95	107	123	138
	1990	71	81	93	108	129
	2000	49	55	71	81	94
	2050	36	40	50	57	62
	2100	36	40	49	57	59
SBC	1850	45	88	111	199	293
	1900	65	109	134	232	320
	1980	101	145	172	260	342
	1990	85	131	151	239	320
	2000	68	114	133	215	295
	2050	46	95	117	195	286
	2100	41	89	115	191	286

* Percentages are based on the population of 1,320 Adirondack lakes having ANC less than 200 μeq/L. This population constitutes a subset (based on having ANC ≤ 200 μeq/L) of the larger population of 1,817 Adirondack lakes greater than 1 ha depicted on 1:100,000-scale topographic maps

Table 2. Estimated number of Adirondack lakes below ANC criteria values for the population of 1,320 Adirondack lakes larger than 1 ha that have ANC less than 200 μeq/L, based on MAGIC model simulations for 44 statistically selected lakes.

	MAGIC			PnET-BGC		
	ANC 0	ANC ≤20	ANC ≤50	ANC ≤0	ANC ≤20	ANC ≤50
1850	0	93	191	0	0	202
1900	93	109	216	0	17	218
1980	204	279	519	201	289	563
1990	204	263	581	217	289	533
2000	175	217	399	200	289	517
2050*	175	229	437	188	289	639
2100*	175	243	437	200	305	639

* Simulations for future years (2050 and 2100) are based on a scenario of emissions controls that had been enacted under existing regulations in 2003.

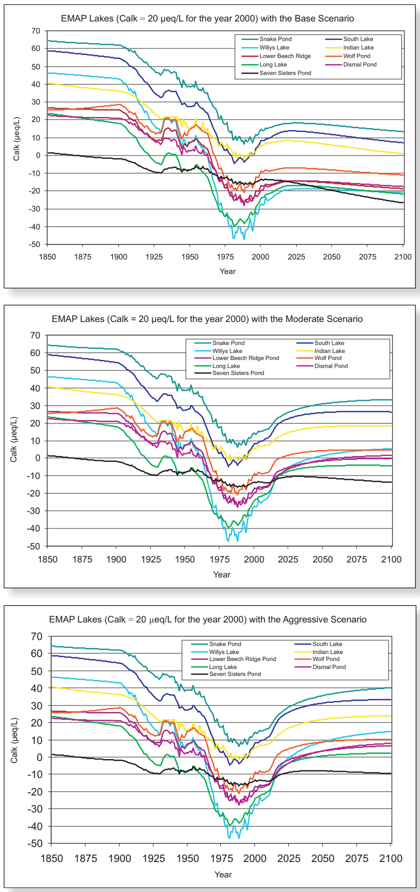


Figure 3. MAGIC simulations of calculated ANC (calk) for the probability lakes that had ANC ≤20 μeq/L in 2000 under three scenarios of emissions controls. The Base Case scenario results are on the top, Moderate Additional Controls scenario in the middle, and Aggressive Additional Controls scenario on the bottom. These are the lakes expected to have the greatest biological impacts from acidification and chemical recovery.

REPRESENTATIVENESS OF ALTM LAKES

ALTM lakes included in this study are not representative of the population of Adirondack lakes larger than 1 ha with respect to current water chemistry or the degree to which they have changed, or in the future will change, in response to acidic deposition (Figure 4). Rather, the ALTM study lakes are reasonably well distributed across the population cumulative frequency distribution (cfd) for current ANC only for the portion of the population distribution below ANC ~125 μeq/L (the approximately 55% of the lakes in the EMAP statistical frame having lowest current ANC). Similarly, of the 32 ALTM study lakes, only one falls within the lower half of the population distribution of acid-sensitivity based on simulated historical acidification, and only three lakes fall within the lower half of the population distribution for ANC recovery from 1990 to 2050.

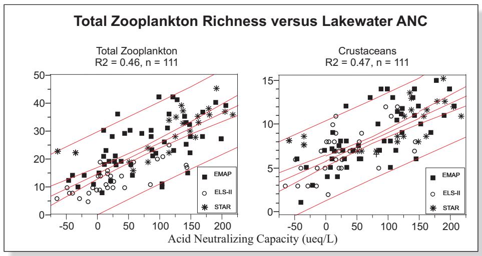
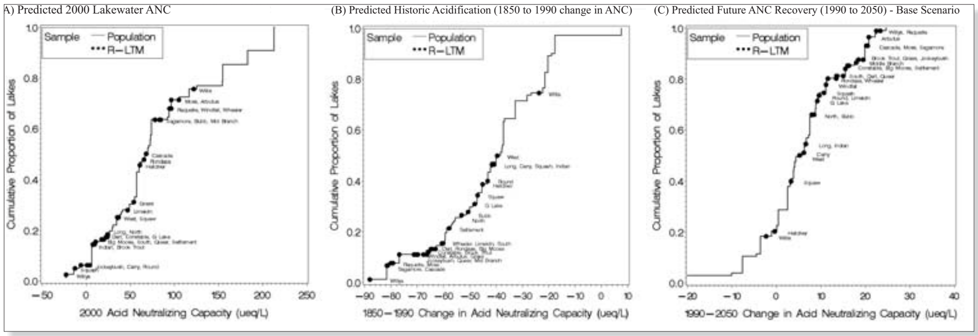


Figure 5. Relationships between lakewater ANC and zooplankton species richness.



A) Predicted 2000 Lakewater ANC

(B) Predicted Historic Acidification (1850 to 1990 change in ANC)

(C) Predicted Future ANC Recovery (1990 to 2050) - Base Scenario

Figure 4. Cumulative frequency distributions (cfd) of the population of 1,320 Adirondack lakes larger than 1 ha depicted on 1:100,000-scale topographic maps that had lakewater ANC less than 200 μeq/L at the time of EMAP sampling. Superimposed on each cfd is the location within the population distribution of each ALTM study lake. Projections are given for MAGIC model simulations of A) lakewater ANC in the year 2000, B) historic acidification from 1850 to 1990, and C) chemical recovery from 1990 to 2050 under the Base Case emissions scenario.

LINKAGES TO BIOLOGICAL RESPONSES

Among the most responsive species to changes in lakewater acid-base chemistry are the zooplankton, especially crustaceans. Data from 97 Adirondack lakes, collected in conjunction with three U.S. EPA research programs (EMAP, Eastern Lakes Survey Phase 2, and STAR) were used to establish relationships between lakewater ANC and metrics of zooplankton richness (Figure 5). These empirical relationships were used with PnET - BGC simulations to estimate past and future changes in zooplankton communities in response to changes in lakewater ANC.

Zooplankton species richness in the modeled EMAP lakes ranged from 15 in highly acidic lakes to 35 at high ANC, with a median of 22 species. Ignoring other aspects of habitat quality, other than lake acid base chemistry, acidification contributed to an estimated median loss of 1.9 species from 1850 to 1990, with some lakes having lost as many as 6 species. Emissions reductions scenarios suggested future changes by 2100 ranging from 1.6 additional species lost under the Base Case, to 1.6 and 2.0 species gained under the two additional controls scenarios (Figure 6).

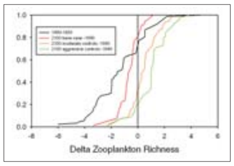


Figure 6. Cumulative distribution functions of changes in estimated total zooplankton species richness for Adirondack lakes, based on PnET-BGC simulations and the relationship shown in Figure 5. Changes are depicted for the past and into the future under 3 emissions control scenarios. Positive values indicate increase in species richness; negative values indicate decrease.

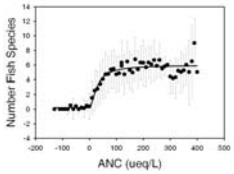


Figure 7. Fish species richness of Adirondack lakes as a function of ANC. The values shown represent the mean (filled circles) and standard deviation (bars) of 10 μeq/L ANC classes. Also shown as a solid line is the application of the logistic model. Data from Adirondack Lakes Survey.

CONCLUSIONS:

In response to existing and expected S and N emissions control regulations as of the end of 2003:

- Some lakes have been increasing in ANC and many of those having higher ANC are expected to continue increasing in ANC. Some of those having lower ANC are expected to stop recovering chemically and reacidify in the future.
- Both models estimated that virtually all of the modeled ALTM lakes were in the top 50% of acid sensitivity compared with the 1,829 Adirondack lakes in the EMAP statistical frame.
- The number of lakes having ANC less than 20 peaked in about 1980 or 1990. Model projections suggest a future increase under the Base Case scenario. Newer emissions controls enacted by the Clean Air Interstate Rule (CAIR) will reduce the likelihood of that happening.
- Estimated increases in future (to 2100) taxonomic richness of zooplankton and fish were modest, even under the Aggressive Additional Emissions Controls scenario. Lakes are generally expected to recover no more than two species of zooplankton and two species of fish in response to even aggressive emissions controls.

Over the range of ANC values of the modeled EMAP lakes, estimates of fish species richness ranged from 0 species in highly acidic lakes to 5.7 species at high ANC (Figure 7). Ignoring aspects of habitat quality other than acidity, the median estimated number of fish species lost from 1850 to 1990 was 0.4 species, with some lakes having lost as many as 4.4 species. Estimated future fish species gains were modest. The most responsive 20% of the lake population showed an additional loss under the Base Case, and small gains by 2100 under the additional emissions control scenarios (Figure 8).

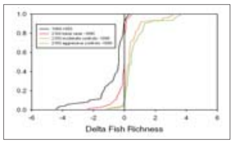


Figure 8. Cumulative distribution functions of changes in estimated fish species richness between 1850 and 1990; between 1990 and 2100 for the Base Case scenario; between 1990 and 2100 for the Moderate scenario; and between 1990 and 2100 for the Aggressive scenario for the EMAP population of Adirondack lakes based on PnET-BC simulations of ANC and the empirical relationship between fish species richness and ANC shown in Figure 7.

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Research Partners:

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