Regional Assessment of the Response of the Acid−Base Status of Lake Watersheds in the Adirondack Region of New York to Changes in Atmospheric Deposition Using PnET-BGC

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Understanding the response of soil and surface waters to changes in atmospheric deposition is critical for guiding future legislation on air pollution. The Adirondack region of New York experiences among the most severe ecological impacts from acidic deposition. The region is characterized by considerable variability in atmospheric deposition, surficial and bedrock geology, hydrologic flow paths, and vegetation resulting in variability in effects of acidic deposition. In this study, an integrated biogeochemical model (PnET-BGC) was applied to 37 forest lake watersheds to assess the response of soil and surface waters of the Adirondacks to changes in atmospheric deposition at a regional scale. Model-simulated surface water chemistry was validated against data from two synoptic surveys conducted in 1984 and 2001. Results indicate that the model is able to capture the observed changes in surface water chemistry during this period. The model was further used to forecast the response of soil and surface waters to three future emission control scenarios. Results indicate that under the Clean Air Act, surface water SO_4^{2-} concentrations will continue to decrease at a median rate of −0.38 μeq/L-yr, and surface water ANC is predicted to increase at a median rate of 0.11 μeq/L-yr. More aggressive emission reductions will accelerate the rate of recovery. Under an aggressive control scenario, which represents an additional 75% reduction in SO_2 emissions beyond the implementation of the Clean Air Act, surface water SO_4^{2-} concentrations are predicted to decrease at a median rate of −0.88 μeq/L-yr, and surface water ANC is predicted to increase at a median rate of 0.43 μeq/L-yr. Model predictions of several biologically relevant chemical indicators are also reported.

Introduction

Emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) from combustion of fossil fuels are transported long distances, potentially affecting forest and aquatic ecosystems over large geographic areas (*1*). Deposition of strong acids (e.g., HNO_3, H_2SO_4) impacts forest health through both direct effects of precipitation and pr-2380(precipitation)-238(i(e.9]333(tong)-20LeAda(relev4m55(9c867e.9](of)]TJ-2.7869 -141 0 0 8-2 Tml2 Tm.55(biol2ic

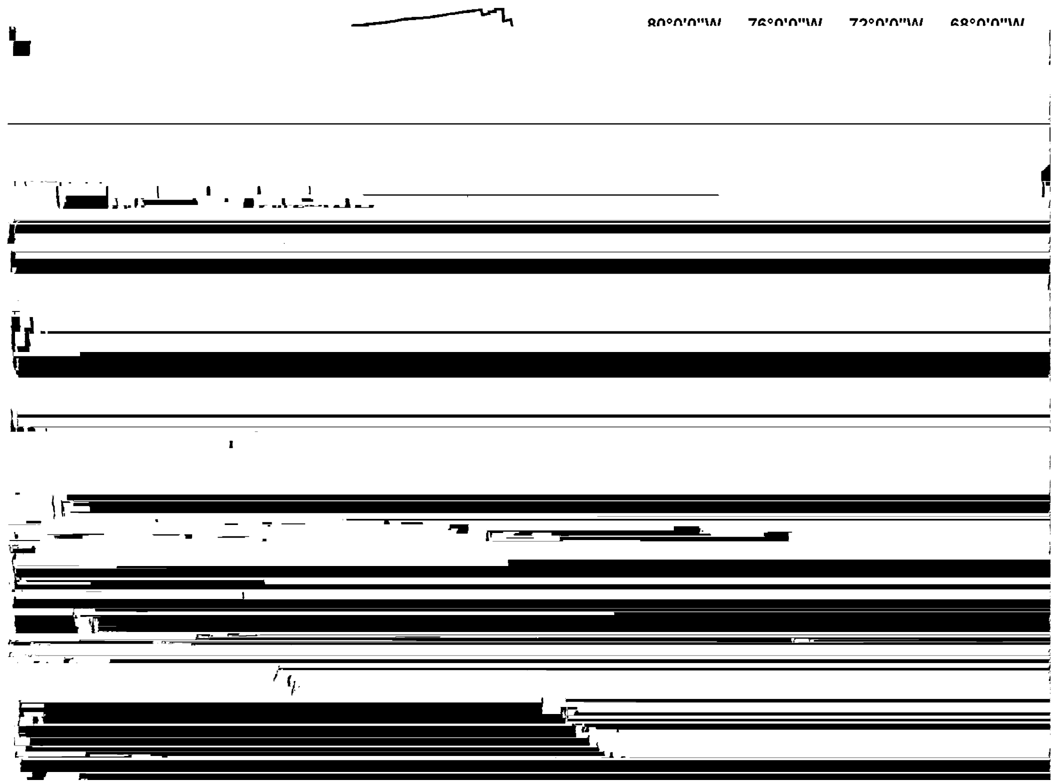

FIGURE 1. Locations of the Direct/Delayed Response Program lake watersheds in the Adirondack region of New York.

TABLE 1. Summary of the Characteristics of the Direct/Delayed Response Program Lake Watersheds in the Adirondack Region of New York (*10*)

variables	median	range
latitude (deg)	43.8	43.1−44.7
longitude (deg)	74.6	73.8−75.1
elevation (m)	565.7	418.5−791.0
watershed (ha)	206.7	36.3−1782.2
lake area (ha)	14.8	3.9−398.9
percent shallow deposit (%)	46.7	0−100
wetland percentage (%)	2.1	0−12.8
hardwood (%)	76.0	3.2−100
coniferous (%)	9.4	0−57.7
mixed forest (%)	21.1	0−96.1
wet S deposition (kg of S/ha-yr)	9.1	7.6−10.1

ing a detailed sensitivity analysis of parameter values is available in Gbondo-Tugbawa et al. (*12*).

. The 37 lake watersheds in the Adirondacks included in this study are among the 145 watersheds in the northeastern United States that were statistically selected by the Direct/Delayed Response Program (DDRP) initiated by U.S. EPA in 1984 to represent the acid-sensitive watersheds in the region (>4 ha in lake area; *9*, *10*; Figure 1). The watersheds selected receive a wide range of acidic deposition and exhibit considerable variability in elevation, watershed area, lake area, vegetation composition, and sensitivity to acidic deposition (Table 1). Among the 37 lakes, 28 lakes have ANC values less than 50 μeq/L. Vegetation of the region is dominated by northern hardwoods with red spruce and balsam fir at higher elevation and conifers adjacent to the lakes. Wetlands are a common landscape feature in the region, and many watersheds have extensive wetland coverage. Many forests in the Adirondacks have undergone severe disturbances including fire, logging, and hurricane impacts (*6*, *17*, *18*). These lake watersheds also show considerable variability in historical land disturbance. Nine of these 37 watersheds were largely burned during 1903−1908.

. D o t o Cl t. Regional regression models of wet S, N, base cation and Cl^- deposition, and dry S and N deposition as a function of latitude and longitude are available for the northeastern United States and were used to derive deposition inputs based on location of each site (*19*). The model was developed based on data from 26 wet and 13 dry deposition monitoring sites across the northeastern United States (*19*). PnET-BGC estimates dry deposition based on user inputs of dry to wet deposition ratios. Therefore, dry deposition estimated from the regression model was converted into dry to wet deposition ratios. Dry to wet deposition ratios for base cations and Cl^- were derived from the DDRP study, in which dry deposition was estimated based on the relationship between annual wet deposition and the ambient air concentration (*9*).

Using relationships between current emissions and deposition (*20*) plus estimates of past emissions (*21*), we reconstructed historical patterns of atmospheric wet deposition of S, N, and base cations at the Huntington Forest (HF) in the Adirondacks (*22*). In previous model applications, a constant dry to wet deposition ratio was assumed for each ion (*12*). However, based on data from several dry deposition monitoring sites in the Northeast, a relationship was found between air SO_2 concentrations and dry to wet S deposition ratios, suggesting decreases in dry to wet S deposition ratios in response to decreasing air SO_2 concentrations (*23*). This relationship along with the relationship between air SO_2 concentrations and SO_2 emissions were used to derive the historical changes in dry to wet S deposition ratios at the HF (*23*). The reconstructed temporal pattern was applied to all the sites as scalars. A throughfall study in a central Adirondack watershed suggested that S deposition under coniferous were 2.5 times greater than deciduous forests (*24*). Therefore the enhanced collection of dry S deposition under coniferous and mixed forests were accounted for by applying an enhancement factor (2.5 and 1.75 for coniferous and mixed forests, respectively) to the dry-to-wet ratios estimated from the regression models. Dry deposition for each watershed was estimated as a weighted percentage of the area of deciduous, coniferous, and mixed forests.

Climate inputs were derived from regression models developed by Ito et al. (*25*) for the Adirondacks (i.e., precipitation, temperature) and solar radiation was derived from models developed by Aber and Freuder (*26*) for the northeastern United States.

L D t b c H to y. Past land disturbances have considerable impact on N cycling within forest ecosystems (*27*, *28*). Site-specific land disturbance history was generally derived from maps from the Adirondack Park Agency (APA) and the descriptions of McMartin (*18*) and Sullivan et al. (*17*). For sites that experienced logging prior to 1890, 20% biomass mortality was assumed. Logging after 1920 was considered to be slight. Therefore for sites that experienced logging after 1920, we assumed 20% cutting at a 20-yr rotation. A severe hurricane in 1950 impacted many forests and was followed by salvage logging (*18*). An APA map was used to derive hurricane-affected areas for each watershed for use in model simulations. We assumed that 40% of the downed biomass was removed by salvage in the affected areas.

So l t. Soil parameters of soil mass, cation exchange capacity (CEC), and cation exchange coefficients were derived from the 1984 DDRP survey data (*9*, *10*). Soil pH-dependent SO_4^{2-} adsorption parameters were derived from experimental data from Woods Lake (Driscoll, C. T., unpublished) as described in Gbondo-Tugbawa et al. (*29*).

t t o y. PnET models (PnET-CN and PnET-BGC) use generalized inputs of four different vegetation types including northern hardwoods, spruce−fir, red maple−red oak mixture, and pine. For model calculations, vegetation species identified in DDRP were reclassified into these types and parameters for the dominant type at each watershed were used in model calculations.

W tl t t o. To account for the retention of SO_4^{2-} and N90(capacity)-290((CEC 224.079 Tm[(and)-398(N90(v8tTm[((v8tLDRP90(2 1 0o)-221ECT33(calculaTD,307 69.53 224.079witu 1 Tf(for)318(
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ALTM lakes. In contrast, larger variability was found in the survey data (Figure 3b).

Model-predicted ranges of changes in ANC were comparable to changes observed both in the DDRP lake surveys and the ALTM lakes (Figure 3c). Predicted rates of change in ANC are also relatively uniform compared to the survey data. Both the ALTM data and the survey data indicate approximately 35% of the lakes exhibit continuing acidification (i.e., ANC decreases). Model predictions generally agree well with these observations.

. Model hindcast of pre-anthropogenic (~1850) conditions indicate acidic deposition has greatly altered soil and surface waters in the region. Simulated and –

deposition. Model calculations, however, predict increase in
NO

< 20%. While most of lakes have pH >6 (80%) and Ali concentrations < 2

(25) Ito, M.; Mitchell, M. J.; Driscoll C. T. Spatial patterns of precipitation quantity and chemistry and air temperature in the Adirondack Region of New York. *At o . E o .* **2002**, *36*, 1051−1062.

(26) Aber, J. D.; Freuder, R. Sensitivity of a forest production model to variation in solar radiation data sets for the Eastern U.S. *Cl t .* **2000**, *15*, 33−43.

(27) Aber, J. D.; Driscoll, C. T. Effects of land use, climate variation, and N deposition on N cycling and C storage in northern hardwood forests. *Glob l B o och . Cycl* **1** , *11*, 639−648.

(28) Goodale, C. L.; Aber, J. D.; McDowell, W. H. The long-term effects of disturbance on organic and inorganic nitrogen export in the White Moutains, New Hampshire. *Eco t* **2000**, *3*, 433−450.

(29) Gbondo-Tugbawa, S. S.; Driscoll, C. T.; Mitchell, M. J.; Aber, J. D.; Likens, G. E. A model to simulate the response of a northern hardwood forest ecosystem to changes in S deposition. *Ecol. A l.* **2002**, *12*, 8−23.

(30) Kelly, C. A.; Rudd, J. W. M.; Hesslein, R. H.; Schindler, D. W.; Dillon, P. J.; Driscoll, C. T.; Gherini, S. A.; Hecky, R. E. Prediction of biological acid neutralization in acid-sensitive lakes. *B o- och t* **1** , *3*, 129−140.

(31) Warby, R. A. F.; Johnson, C. E.; Driscoll, C. T. Chemical recovery of surface waters across the northeastern U. S. from reduced inputs of acidic deposition: 1984−2001. *E o . Sc . ch ol.* (submitted for publication).

(32) Likens, G. E.; Bormann, F. H. *B o och t Fo t Eco t* , 2nd ed.; Springer-Verlag: New York, 1995; 159 pp.

(33) Chen, L.; Driscoll, C. T. Modeling the response of soil and surface waters in the Adirondack and Catskill regions of New York to changes in atmospheric deposition and historical land disturbance. *At o . E o .* **200** , *38*, 4099−4109.

(34) Weathers, K. C.; Lovett, G. M.; Likens, G. E.; Lathrop, R. The effect of landscape features on deposition to Hunter Mountain, Catskill Mountains, New York. *Ecol. A l.* **2002**, *10*, 528−540.

(35) Lovett, G. M.; Thompson, A. W.; Bowser, J. Elevational patterns of sulfur deposition in the Catskill Mountains, N.Y. *At o . E o .* **1** , *33*, 617−624.

(36) Aber, J. D.; F-166(D.wu1o)-366(J.)-1b TD(1987)Tj/F14T3lceBio-