Effects of atmospheric nutrient inputs and climate change on the trophic status of Crystal Lake, Wisconsin


Introduction

Atmospheric deposition of nutrients may be an important non-point source of nutrients to lakes (Axler et al. 1994). Particulate and gaseous forms of nutrients are transported via wet and dry deposition to waterways, where they have potential impacts upon phytoplankton productivity and bloom dynamics (Parrish 1997), particularly in oligotrophic systems which are dominated hydrologically by rainfall. There is concern that changes in fossil fuel combustion and fertilizer use, the major emission sources of nitrogen and phosphorus, respectively, as well as climate change, could have serious impacts on the dynamics and trophic status of sensitive lake ecosystems.

To understand the potential impacts of atmospheric nutrient deposition on water quality, a one-dimensional hydrodynamic water quality model, DYRESM-WQ (Hamilton & Schladow 1997), coupled with a model of ice dynamics and atmospheric nutrient deposition, was used to assess potential changes in trophic status from altered atmospheric nutrient deposition and climate changes associated with a doubling of CO$_2$ (2CO$_2$). The model was applied to oligotrophic Crystal Lake in Wisconsin, USA, which receives most of its annual water and nutrient load through rainfall (Anderson & Cheng 1993).

Methods and study site

Crystal Lake is a small (area, 36.7 ha; mean depth, 0.4 m), oligotrophic seepage lake in Vilas County, Wisconsin. Runoff of surface water to the lake is negligible and groundwater inputs, which have been estimated from lake levels and from direct measurements (Kenoyer & Anderson 1989, Anderson & Cheng 1993, Hamilton et al. 2001), represent <5% of the annual volumetric contribution of rainfall. A 2-week (open-water season) or monthly (ice-covered season) vertical profiles of temperature, dissolved oxygen, nutrients (PO$_4$, TP, NO$_3$, NH$_4$, TN) and chlorophyll a were taken at a central lake station as part of the North Temperate Lakes Long Term Ecological Research program (Magnuson et al. 1997, Kratz et al. 1998).

Input data to DYRESM-WQ included vertical profiles of temperature, nutrients, dissolved oxygen and chlorophyll a, for model initialization and validation, hypsography and geometry of Crystal Lake, daily meteorology (taken from Minocqua Dam, 14 km south-west of the lake) and daily inflow and outflow volume and inflow composition. The model runs on a 1-h time step, with daily output of vertical profiles for each state variable. For a more comprehensive description of the model structure, processes and input data see Imberger & Patterson (1981) or Hamilton & Schladow (1997).

Atmospheric nutrient inputs were quantified as daily fluxes to the water or ice surface. Phosphorus inputs from terrestrial leaf and insect litter were quantified through a modeling approach developed for Mirror Lake, New Hampshire, in which surface flux is dependent on season, lake size and distance from shore (Cole et al. 1990), and nitrogen inputs from this source were determined from N/P ratios in leaf litter. Phosphorous and nitrogen mass fluxes in rainfall were determined from rainfall volume, phosphorus concentrations in rainfall taken to be 3 μg L$^{-1}$ (Lienks & Bormann 1995), and routinely measured concentrations of nitrogen species in rainfall at a National Atmospheric Deposition Program station 5 km from the lake. Further details of the effect on water column nutrients of lakewater freezing and ice and snow melting are given by Spillman (2000).

To simulate the response of Crystal Lake to climate change associated with a doubling of carbon dioxide, DYRESM-WQ was run with meteorological data from four different global climate change models (GCMs). The Crystal Lake meteorological dataset was multiplied by a factor derived from 2CO$_2$:1CO$_2$ ratios of the GCM monthly output. The four GCMs were: the Goddard Institute of Space Studies model (GISS; Hansen et al. 1988), Geophysical Fluid Dynamics Laboratory model...
(GFD; MANABE & STOUFFER 1980), the Oregon State University Model (OSU; SCHLESINGER & ZHAO 1988) and the Canadian Climate Center model (CCC; BOIR et al. 1992). All models are based on a 2CO₂ case but differ in the resultant warming.

Results and discussion

Modeled temperatures varied on average by 0.14°C from measured temperatures, based on an extensive dataset for comparison (n = 4851), and in the absence of calibration of physical parameters in the model. The model simulations also reproduced the general timing and thickness of ice and snow cover using only fixed parameter values relating to ice formation and ablation (Fig. 1). Chlorophyll a output from the model was calibrated to reproduce measured data (Figs. 2a, 2b) over a 3-year period, as were the nutrients (PO₄, NO₃, NH₄, TP and TN) and dissolved oxygen. The deep chlorophyll maximum in Crystal Lake was only reproduced through adjusting light saturation requirements of the phytoplankton to relatively low levels, although there was slight tendency for the model to under-predict the magnitude and duration of the deep chlorophyll maximum that persisted from spring to fall. Differences between measurements and model results also reflect the smoothing of the measured chlorophyll a isopycnals as sampling frequency of measured data (2-weekly or monthly) was low in comparison to simulation output (daily).

Volumetric mean water column temperature, chlorophyll a and dissolved oxygen were determined for each day over a 3-year simulation period following ice thaw (day 122) in 1989. The mean and range of the volumetric means were determined for the 3 years under current climate and atmospheric nutrient deposition conditions (Base), without any (0D) and with a 4-fold (4D) increase in deposition, and for the four 2CO₂ cases (GISS, GFD, OSU and CCC). The summary statistics presented in Table 1 illustrate the marked increases in mean and maximum volumetrically averaged temperature for all of the 2CO₂ cases. Further, duration and thickness of ice and snow cover, averaged over the four 2CO₂ cases, declined substantially (Table 1) compared with the Base case simulation. There was an associated small reduction in dissolved oxygen concentration for each of the four 2CO₂ cases, which corresponds approximately to the reduction in oxygen concentration at saturation with the elevated temperature. The present study represents one of the first attempts to extend quantitative modeling of aquatic ecosystems beyond solely physical predictions (cf. DE STASSO et al. 1996). There are still many unknowns in the present approach, however, as effects of changes in ground water, surface-water runoff and sediment heat exchange are not altered under the 2CO₂ cases.

![Graph](image_url)

Fig. 1. Comparison of measured ice and snow cover (Field), including points denoting ‘ice-on’ and ‘ice-off’, against the base case simulation values (Base) and the mean values taken for the four GCM simulations (2CO₂).
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**Fig. 2.** Water column chlorophyll a distributions based on (a) measurements, (b) base case model simulations and (c) model simulations with atmospheric nutrient deposition increased 4-fold.

Chlorophyll a concentrations were increased by 32% for the 4D case (Table 1). This case is considered representative of a moderately
riched atmosphere (e.g. through fossil fuel use or fertilizer volatilization (Spillman 2000)).

Water column chlorophyll a distributions for this case (Fig. 2c) indicated greatest relative increase near the water surface, with potential to alter the current deep chlorophyll maximum through greater self-shading in surface waters.

<table>
<thead>
<tr>
<th>Case</th>
<th>T (mean)</th>
<th>T (range)</th>
<th>Chl a (mean)</th>
<th>Chl a (range)</th>
<th>DO (mean)</th>
<th>DO (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>10.0</td>
<td>1.7–22.0</td>
<td>1.9</td>
<td>0.4–4.1</td>
<td>11.2</td>
<td>9.2–12.8</td>
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<tr>
<td>OD</td>
<td>10.1</td>
<td>1.5–22.7</td>
<td>1.7</td>
<td>0.4–3.6</td>
<td>11.2</td>
<td>9.1–12.9</td>
</tr>
<tr>
<td>GFD</td>
<td>9.9</td>
<td>1.4–21.9</td>
<td>2.5</td>
<td>0.4–6.3</td>
<td>11.2</td>
<td>9.4–12.9</td>
</tr>
<tr>
<td>OSU</td>
<td>13.5</td>
<td>2.4–26.2</td>
<td>1.8</td>
<td>0.6–3.6</td>
<td>10.6</td>
<td>8.9–12.7</td>
</tr>
<tr>
<td>CCC</td>
<td>12.3</td>
<td>1.6–26.7</td>
<td>1.9</td>
<td>0.4–3.6</td>
<td>11.0</td>
<td>8.7–13.6</td>
</tr>
<tr>
<td>GFD</td>
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<td>1.2–25.5</td>
<td>1.9</td>
<td>0.4–4.7</td>
<td>11.0</td>
<td>8.9–12.9</td>
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<tr>
<td>OD</td>
<td>13.2</td>
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Table 1. Mean and range over a 3-year model simulation period of volumetrically averaged water column temperature (T in °C), chlorophyll a (Chl a in μg L⁻¹) and dissolved oxygen (DO in mg L⁻¹). The cases pertain to current conditions (Base), no atmospheric deposition (0D), atmospheric deposition increased 4-fold (4D), and four global warming cases (GISS, GFD, OSU and CCC) pertaining to 2°C.
Nitrate concentrations in rainfall to Crystal Lake range from 500 to 2200 μg L⁻¹, which equates to an annual load of 175–773.3 kg year⁻¹. The corresponding annual load for ammonium and phosphorus is 7–351 kg year⁻¹ and ~1 kg year⁻¹, respectively. Variations in the concentration of nitrogen species, in particular, occur with season, precipitation characteristics and washout processes, as well as meteorological conditions such as storm intensity and duration. The dominance of nitrogen over phosphorus in loadings from rainfall suggests that in lakes dominated hydrologically by rainfall, phytoplankton production is more likely to be limited by phosphorus than nitrogen, and this may be further enhanced by the current trend of increasing NO, emissions from fossil fuel use (Paerl 1997). Periods of drought, however, may need to be examined carefully.

Acknowledgements

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