PNAS COMMENTARY

A continental view of climate effects on lakes

Stephen R. Carpenter[a,1]

Lakes and their watersheds play vital roles in the climate system through connections among inland waters, land, and the atmosphere. The watershed, which drains into a lake, influences the lake's water balance, nutrient levels, and thermal properties. These factors in turn affect how lakes respond to climate changes and thereby affect the water cycle and climate. For instance, precipitation patterns on watersheds affect nutrient runoff which determines algal biomass in lakes (Fig. 1). Growth and decay of the algae affect lakes' oxygen balance, carbon sequestration, and emissions of CH_4 and N_2O, gases with greater atmospheric warming potential than CO_2 (1). Lakes are among the largest sources of these potent greenhouse gases (2, 3) and emissions from eutrophied lakes are projected to increase in coming decades (4). Thus, precipitation and watershed characteristics act through lakes to either amplify or moderate climate changes, depending on land use and management practices. Understanding these complex dynamics is crucial for predicting and managing feedbacks between climate change and inland waters. In PNAS,

Author affiliations: [a]Center for Limnology, University of Wisconsin, Madison, WI 53706

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[1]Email: steve.carpenter@wisc.edu.

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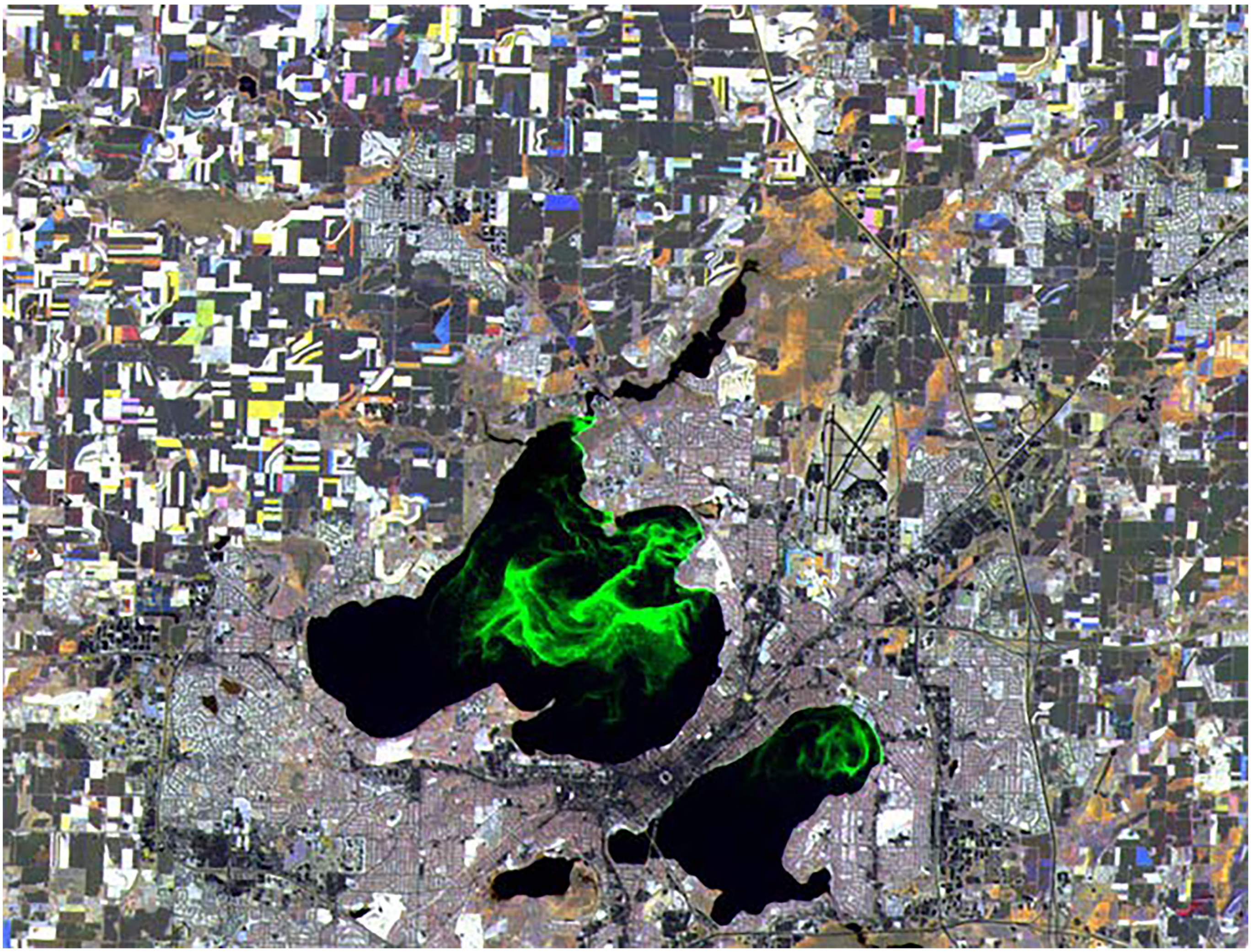

Fig. 1. Multitemporal Landsat 7 image composite from 1999 showing blooms of algae in Lakes Mendota and Monona, Madison, WI. Image Credit: Jonathan Chipman (Space Science and Engineering Center, University of Wisconsin-Madison) and Samuel Batzli (Space Science and Engineering Center, University of Wisconsin-Madison) (https://www.ssec.wisc.edu/airportexhibit/slideshow/index.html?slide=8). Provided courtesy of Space Science and Engineering Center, University of Wisconsin-Madison.

Soranno et al. (5) used Landsat images, limnological data, climate records, and watershed characteristics spanning 34 y to assess effects of climate on median summer chlorophyll concentrations (CHL) for thousands of lakes distributed widely across the conterminous United States. The paper demonstrates a new approach for analyzing climate and watershed effects on lake water quality at the continental scale.

> **In PNAS, Soranno et al. (5) used Landsat images, limnological data, climate records, and watershed characteristics spanning 34 y to assess effects of climate on median summer chlorophyll concentrations (CHL) for thousands of lakes distributed widely across the conterminous United States.**

The methodology of the continental approach is explained by the paper's first two multipanel figures, the methods section, and open-access R scripts. For each lake authors determine out-of-sample predictability, nonlinearity, presence of discontinuities or breakpoints, and causal linkages from climate to CHL using time-series models and nonparametric reconstruction of attractor manifolds (6, 7). Time series are then clustered by groups with similar interannual patterns, and according to presence of breakpoints, anomalies, or monotonic trends.

Trends in CHL were related to trends in precipitation or temperature in about a third of the lakes. In other cases CHL trends were related to human disturbance and watershed characteristics, or causes of change were not discernible. About half of the lakes' time series were too unpredictable to model but it is possible that patterns will come into focus as data series become longer. If the scope is narrowed to certain types of watersheds or lakes, or specific climate events, then patterns may sharpen. In the case of drought, for example, some of the same authors found that lake CHL responses are related to lake type, surface connectivity, historical conditions, soil erodibility in the watershed, and minimum air temperature (8). For a single lake (Fig. 1) precipitation and the frequency of extreme storms have increased over the past 80 y, thereby increasing phosphorus loads and eutrophication of the lake (9, 10).

For the past century ecosystem scientists have used long-term observations, cross-ecosystem comparisons, whole-ecosystem experiments, landscape studies of cross-scale dynamics, and quantitative models to disentangle drivers of ecosystem processes (11). Whole-lake experiments identified the drivers and interactions that determine lake CHL and other indicators of ecosystem state (12–16). Some sites initiated for ecosystem experiments evolved to became long-term observatories (17) that identified effects of climate change on streams and lakes (18). In certain watersheds quantitative models based on long-term data have compared effects of climate and landscape processes on lake hydrology and water quality (19, 20). At broader spatial scales spanning many ecosystems, the concepts and methods of landscape ecology have revealed factors that control nature's benefits for people including water quality (21). Data-intensive place-based studies add precision and detail to the findings of Soranno et al. (5) while their expansive approach weaves a continental synthesis from local data.

The Landsat images used in this study were taken 16 d apart (5). That time step is longer than the life cycles of many organisms that affect CHL values measured by the satellite. Such rapid dynamics could be missed if the sampling time step is too long but may not matter if the intent is to study climate effects on aggregate ecosystem properties. Analyses of long-term dependence of 14 y of concurrent daily data for Lake Mendota (Fig. 1) found that relaxation times were longer for algal biomass (8.77 d) than phosphorus load (1.37 d) or precipitation (1.07 d) because of the stabilizing effects of phosphorus recycling within the lake (22). Thus, CHL may provide a more persistent signature of cumulative impacts of extreme storms and thereby make climate effects easier to detect. Climate impacts on lakes could be underestimated if analyses miss the consequences of brief extreme events.

Soranno et al. (5) aggregated long-term studies from many lake districts in a central database (LAGOS). In this sense, the work represents data shared among many scientists from individual research projects and the U.S. Long-Term Ecological Research network (https://lternet.edu/). High-quality long-term datasets now exist for many different ecosystem types in the United States and many countries (https://www.ilter.network/). Satellite images are increasingly available at extensive spatial scales. Where meaningful indicators of ecosystem state can be derived from satellite images and linked to ground-based ecosystem data for many consecutive years then it is likely that the framework (5) can be applied.

Inland waters, including groundwaters, headwater springs, wetlands, lakes, rivers, and reservoirs offer life-giving benefits to people and communities. They are sources of fresh water, essential for drinking, agriculture, transportation, and industry. Inland waters also play crucial roles in maintaining ecosystem processes and supporting a wide array of plant and animal life. They offer recreational opportunities such as fishing and the protein it provides (23), boating, and swimming which contribute to the physical and mental health of people. They can also enhance local economies through tourism and leisure activities. Lakes and wetlands assist in flood control and water management, providing buffers against extreme weather events. They can be managed to store carbon and decrease emissions of greenhouse gases. Overall, these bodies of water are indispensable resources that enhance both the environment and quality of life. Soranno et al. (5) have taken a huge step toward an integrated understanding of climate change effects on lakes. Future research could expand their approach to include economic, public health, and sociological benefits of inland waters.

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