Throwing Fuel on the Fire: Synergistic Effects of Excessive Nitrogen Inputs and Global Warming on Harmful Algal Blooms

HANS W. PAERL*
Institute of Marine Sciences, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

J. THAD SCOTT
Department of Crop, Soil and Environmental Science, University of Arkansas, Fayetteville, Arkansas

A worldwide proliferation of harmful (toxic, food-web altering, hypoxia-generating) algal blooms (HABs) has been linked to human nutrient (phosphorus (P) and nitrogen (N)) overenrichment. In addressing this pressing environmental and human health issue, reducing P inputs has received the most attention, in part because this nutrient was first identified as driving eutrophication (1), and because P is simpler and less expensive to remove from pollution sources (e.g., wastewater, industrial effluents). Furthermore, P reductions have been prescribed to control a particularly noxious group of HABs, the N_2 fixing cyanobacteria, which can obtain N_2 from the atmosphere, thereby minimizing ecosystem-level nitrogen (N) limitation (1). However, less than 50%, of primary production demands are typically met by N_2 fixation, even when P supplies are sufficient. Furthermore, denitrification, the microbially mediated reduction of nitrate to N_2 gas, often offsets fixed N input (Table 1). The net balance of these N transformations in eutrophic waters can result in sustained ecosystem N limitation (2). Also, eutrophying freshwater, estuarine, and marine systems are increasingly plagued with non-N_2 fixing Cyanobacterial HABs (Cyanohabaeae) and eukaryotic bloom-forming groups (dinoflagellates, chrysophytes, pynomesiophytes), indicating that these systems may be increasingly influenced by accelerating N loads.

Nutrient loading dynamics have changed substantially over the past several decades. While P reductions have been actively pursued, human population growth has been paralleled by accelerating N inputs, often at rates much higher than those of P. Sources of N inputs include fossil fuel combustion, agricultural fertilizers, stormwater discharge, groundwater pollution, and urban, agricultural, and industrial wastes (3). Biologically available reactive nitrogen (N_r), includes reduced (ammonium, organic N compounds) and oxidized (nitrate, nitrite) forms; inputs of all have increased dramatically. On the global scale, human activities now create approximately 2-fold more N_r than natural ecosystems, while in the U.S., anthropogenically generated N_r is about 5-fold larger than natural processes (3). A large proportion of N_r loading, generally exceeding 50%, is from diffuse, nonpoint sources (agricultural and urban runoff, atmospheric deposition, groundwater), which complicates remediation of this vast and rapidly growing supply of N pollution.

Excessive N loading has been recognized as promoting marine (estuarine and coastal) eutrophication and HAB expansion. However, the “N problem” is not isolated to these waters. Increasingly N, plays either a primary or secondary (i.e., colimiting) role as a limiting nutrient in freshwater ecosystems. For example, oligotrophic, alpine, tropical, and subtropical, and other lakes having small watersheds relative to the lake surface/volume, and lakes experiencing various stages of eutrophication, tend to be N-limited (4). Additionally, numerous reservoirs, rivers, and fjords worldwide exhibit N limitation and N and P

* Corresponding author e-mail: hpaerl@email.unc.edu.

**TABLE 1. Ecosystem-Scale Dinitrogen Gas Flux from Several Eutrophic Lakes Indicating a Net Loss (Negative Net N_2 Flux) of Reactive Nitrogen to the Atmosphere (All Rates Reported in g N m^{-2} yr^{-1})**

<table>
<thead>
<tr>
<th>lake</th>
<th>nitrogen fixation</th>
<th>denitrification</th>
<th>net N_2 flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake 227 (ELA*), Canada</td>
<td>0.5</td>
<td>5 – 7</td>
<td>−6.5 to −4.5</td>
</tr>
<tr>
<td>Lake Mendota, Wisconsin</td>
<td>1.0</td>
<td>1.2</td>
<td>−0.2</td>
</tr>
<tr>
<td>Lake Okeechobee, Florida</td>
<td>0.8 – 3.5</td>
<td>0.3 – 3.0</td>
<td>−2.2 to 0.5</td>
</tr>
<tr>
<td>Lake Erken, Sweden</td>
<td>0.5</td>
<td>1.2</td>
<td>−0.7</td>
</tr>
</tbody>
</table>

* Refs 1 and 2, and citations therein. * Experimental Lakes Area.
colimitation, either simultaneously or in seasonally shifting patterns. Under these circumstances, N inputs can determine the spatial and temporal extent of summer nuisance blooms. Lastly, N inputs, including those from increasing levels of atmospheric deposition, impact nutrient stoichiometry, with cascading effects on nutrient limitation, productivity, and ecosystem nutrient cycling characteristics. Therefore, N inputs play a critical role in determining biogeochemical response, trophic state, and water quality conditions of affected freshwater ecosystems.

Lake Okeechobee, the largest lake in the Southeastern U.S., has experienced at least 4 decades of increased P loading coincident with high loads of N, and it periodically experiences large CyanHAB blooms. Reactive P is highly available in this lake, and changes in N availability can control the magnitudes and persistence of algal blooms. In the 1980s and 1990s, blooms were predominantly caused by the N2-fixing CyanHAB *Anaabaena*. However, the most recent widespread bloom, which covered almost the entire lake surface in summer 2006, was caused by *Microcystis*, a non-N2-fixing CyanHAB that depends on dissolved inorganic N (DIN: ammonium, nitrate, nitrite) and possibly organic N for its growth. *Microcystis* is the most common toxin producer in Florida lakes, and it has the ability to store excess P from lake sediments before rising through the water column and increasing its biomass proportionally to N availability. Because Lake Okeechobee’s sediments contain massive quantities of reactive P, successful control of *Microcystis* blooms will require reductions in both P and N inputs.

Lake Okeechobee is not an isolated case of nutrient pollution coinciding with CyanHAB blooms. Lake Taihu, China’s third largest lake, is, like Okeechobee, a large, shallow subtropical lake that has, over the past 3 decades, changed from pristine, bloom-free conditions to a non-N2-fixing CyanoHAB that depends on dissolved inorganic N (DIN: ammonium, nitrate, nitrite) and possibly organic N for its growth. *Microcystis* is the most common toxin producer in Florida lakes, and it has the ability to store excess P from lake sediments before rising through the water column and increasing its biomass proportionally to N availability. Because Lake Okeechobee’s sediments contain massive quantities of reactive P, successful control of *Microcystis* blooms will require reductions in both P and N inputs.

How have CyanHABs re-emerged, despite concerted efforts to control P? Large lakes like Okeechobee, Taihu, Kasumigaura, Japan, deeper systems like Lake Erie, and even very deep systems like Lake Tahoe, U.S. tend to be colonized by N and P (4) largely because previously loaded P and N are effectively retained and recycled. While some N is “lost” via denitrification, this process does not appear to keep up with anthropogenic N inputs. N and P colimitation appears particularly common in eutrophic systems (4), which are most highly susceptible to HAB outbreaks. Because these lakes are now so overenriched with both N and P, the efficacy of N removal through denitrification is diminished. Thus, N input reductions are an essential step in getting these lakes below the bloom threshold.

Global climate change (particularly warming) is a complicating and increasingly problematic factor that must be considered when formulating N (and P) reduction strategies aimed at arresting HABs. Many aquatic ecosystems impacted by HABs are also experiencing increased water temperatures reflecting atmospheric warming. Warming has led to a suite of environmental changes that benefit HAB potentials. These include (1) longer seasons of elevated temperatures and ice-free conditions, (2) increased vertical stratification intensity (due to stronger surface heating), (3) salinization (increased evaporation rates and droughts), and (4) intensification of storm magnitudes and drought frequency and duration. Phytoplankton generally optimize growth as temperatures increase, but this is particularly true for CyanoHAB species (5). Furthermore, CyanHABs as well as other HAB taxa, most notably dinoflagellates and other bloom-forming flagellates, prefer positioning themselves in the upper water column through buoyancy regulation and motility. Under stronger thermally stratified (i.e., nonmixed) conditions, they will have a distinct advantage over nonmotile and often more desirable (from a water quality perspective) taxa such as diatoms. More extreme storms will lead to enhanced runoff and nutrient delivery. If these events are followed by severe droughts, nutrients supplied to affected waters will be retained longer because water residence times will increase. This ensures increased availability of N and P discharged from watersheds and airsheds to support blooms.

The “perfect storm” scenario would be large rainfall events (tropical cyclones, periods of thunderstorms), followed by a protracted drought during the summer—fall period when temperatures and stratification would be maximal. In addition, long-term (multiannual, decadal) increases in air and water temperatures, combined with human hydrologic alterations (e.g., increased reservoir construction due to supply/demand imbalance) would lead to increases in vertical stratification and water residence time. This complicates management strategies aimed at nutrient input control because CyanHABs and other HABs would be favored under such a scenario. Therefore, projected climate change scenarios, especially temperature increases and their physical—chemical—biological effects, will likely promote HABs.

Management strategies must incorporate climate change in the development of predictive bloom thresholds based on the interactions of nutrient enrichment, altered thermal and hydrologic properties of aquatic ecosystems. We must re-examine our management toolbox to ensure that our Best Management Practices (BMPs) and strategies work in the future as they can be. Specifically, fertilizer applications should be at agronomic rates and timed to optimize uptake by crops, while minimizing losses to downstream waters. Application schemes should take spring maximum runoff, tropical cyclone, and summer thunderstorm seasons into consideration. Municipal wastewater treatment should be expanded to reduce N (and P) concentrations in treated discharges, particularly during low precipitation periods that permit maximum treatment efficiency. Parallel efforts should focus on minimizing agricultural and urban sediment loss, as this is a significant source of both N and P. Other efforts should focus on retention and treatment of urban and rural stormwater runoff, another major source of new N inputs. Impoundment of freshwater runoff in storage ponds and reservoirs should be carefully evaluated however, as such steps will increase residence time and hence opportunities for HAB formation. Optimal use and minimal losses of N compounds, coupled to appropriate hydrologic discharge conditions should be formulated, and this may vary among watersheds and climatic regions. Controls on atmospheric emissions of all forms of biologically available N should be incorporated into regional N reduction strategies. Lastly, reductions in greenhouse gas emissions must accompany the above strategies, since they are the only “manageable” step we can take to minimize global temperature increases. These are formidable but essential challenges for balancing optimal use of watershed/airshed resources with acceptable and safe use of downstream/downdrift water resources.

**Literature Cited**


