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Lake Nutrients, Eutrophication, and Climate Change

33

John Jones and Michael T. Brett

Contents

Keywords
Eutrophication • Lakes • Nutrients • Nitrogen • Phosphorus • Trophic state • Carbon • Cyanobacteria

Definition

Research suggests the problems of nutrient over-enrichment (eutrophication) and climatic warming are coalescing in lakes globally. This oftentimes leads to cyanobacteria dominance of lake algal communities, which is problematic because cyanobacteria can produce toxins, degrade beneficial and aesthetic properties of lake water, and impede fisheries production. Cyanobacteria are prevalent when lakes have high nutrients (especially phosphorus) and high water temperatures. Currently, industrialized animal production is a locally important source of

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excess nutrients. Various means have been employed to alleviate the negative consequences of eutrophication and cyanobacteria blooms, with controls on external nutrient inputs being the most effective. More aggressive nutrient control programs will be called for in the future just to hold pace with the steadily declining water quality in many lakes.

Lake Nutrients and Eutrophication

Nutrient enrichment of lakes from human activity is known as cultural eutrophication; this worldwide problem is typically manifested as a dramatic increase in the density of algal cells suspended in water (Smith and Schindler 2009). In extreme cases algae detract from human uses of water and reduce the natural diversity of aquatic communities. Eutrophication is costly to society. Concern about changes in lake water quality intensified in the 1960s following the widespread use of phosphorus in household detergents, sharp increases in the application of nitrogen fertilizer to boost crop production, and localized waste disposal from "industrialized" animal production (Schindler and Vallentyne 2008). The human eye can easily detect the green hue of lakes that have been enriched with algae. Consequently even the general public can visually assess the status of individual lakes and detect changes over time. The green color becomes apparent as lakes switch from moderate to increased fertility at about 10 parts per billion of the photosynthetic pigment, chlorophyll.

Over the past four decades, fundamental research has characterized the eutrophication processes and informed lake restoration programs (Cooke et al. 2005). Initially phosphorus was identified as the most important nutrient-limiting algal biomass of lake waters. This conclusion was based on the nitrogen-phosphorus (N:P) ratios found in algal cells relative to concentrations in natural waters and the results of numerous nutrient addition experiments, conducted in enclosures and whole lakes, showing phosphorus amendments stimulated algal growth. The geochemistry of phosphorus also suggests it should be more limiting; it has no gas phase and readily binds with iron, aluminum, and carbonates and subsequently becomes buried in the sediments. Phosphorus limitation is also linked with high atmospheric nitrogen deposition and agricultural runoff; both sources can supply nitrogen in excess thereby enhancing phosphorus limitation. Research has shown carbon, an element that accounts for about half the mass of algal cells, is readily available from inorganic sources such as bicarbonates dissolved in lake water, and carbon dioxide from the atmosphere and organic matter decomposition. Carbon can limit algal growth rates in the short term but does not limit biomass in the long term.

Phytoplankton nitrogen deficiency has also been identified using N:P ratios in lake water and algal growth responses to nutrient addition bioassays. N-limitation is more common than previously thought and is detected routinely. It is often found in productive lakes, lakes in regions were atmospheric nitrogen deposition is low and lakes in arid or tropical/subtropical regions. Initially the gas phase of nitrogen was considered to be an available nutrient pool that could be used by N-fixing cyanobacteria to alleviate nitrogen shortfalls and maintain lakes in a state of P-deficiency. In productive lakes, N-fixers are common, but numerous studies show nutrient limitation in moderately productive lakes is often balanced, resulting in temporal shifts between nitrogen and phosphorus limitation. The factors contributing to nitrogen limitation include high inputs of phosphorus from anthropogenic sources of domestic and animal wastes (characterized by low N:P ratios), geologic sources of P, temporal differences in the competitive abilities of phytoplankton to use plant nutrients, and sediment release of phosphorus to lake water concurrent with losses of nitrogen via denitrification (anoxic release of N_2 back to the atmosphere). There is no simple explanation for why N-fixers do not consistently satisfy nitrogen deficiencies, and the importance of nitrogen limitation remains a key research question.

Studies in a variety of lake types subsequently showed that lake total phosphorus concentrations (TP) are a function of external inputs from watersheds, lake hydraulic residence time, and the tendency of the phosphorus to settle from the water column (Brett and Benjamin 2008). Release of phosphorus from lake sediments (internal loading) during anoxic periods can also be a critical component of the phosphorus cycle. Nitrogen models are more complex because they must account for the flux of the gas phase in and out of lakes as N-fixation and denitrification, respectively. Regardless, inflow concentration is a critical factor in determining lake water concentrations for both nutrients. Collectively, models show increased inputs from anthropogenic sources such as municipal sewage, agricultural crops and manures, and non-point sources from developed watersheds, such as lawn fertilization, promote eutrophication. As a consequence, there is very large variation in the nutrient content of lakes due to the intensity of anthropogenic activities (e.g., agriculture and urban areas) within their watersheds. Usually deep lakes with low human activity and intact vegetation in the watershed are less eutrophic than shallow lakes with large, disturbed watersheds.

Plant nutrients are considered “causal variables” because the undesired consequences of eutrophication can be attributed to their concentrations in lake water. The response of lakes to nutrient inputs is often demonstrated with cross-system comparisons showing patterns across a broad range of lake types. The underlying assumption is that the response in an individual lake can be predicted by the overall pattern shown for many lakes. The patterns between causal and response variables are strong enough to stand out among other sources of variation. The empirical relationship between total phosphorus (TP) and algal chlorophyll (Chl, a surrogate for algal biomass, Fig. 33.1a) shows the pattern of increased algal biomass with lake water nutrients and provides a framework for predicting the outcome of nutrient controls (Nürnberg 1996). There is large variation in the Chl:TP ratio in individual samples; low ratios can be attributed to processes that secondarily reduce cell density; including light limitation from mineral turbidity and seasonal deep mixing, limitation by other nutrients, and rapid flushing such that algal cells cannot take complete advantage of available nutrients. Also, intense algal grazing by filter feeders (zooplankton or mussels) can outpace algal production and result in low

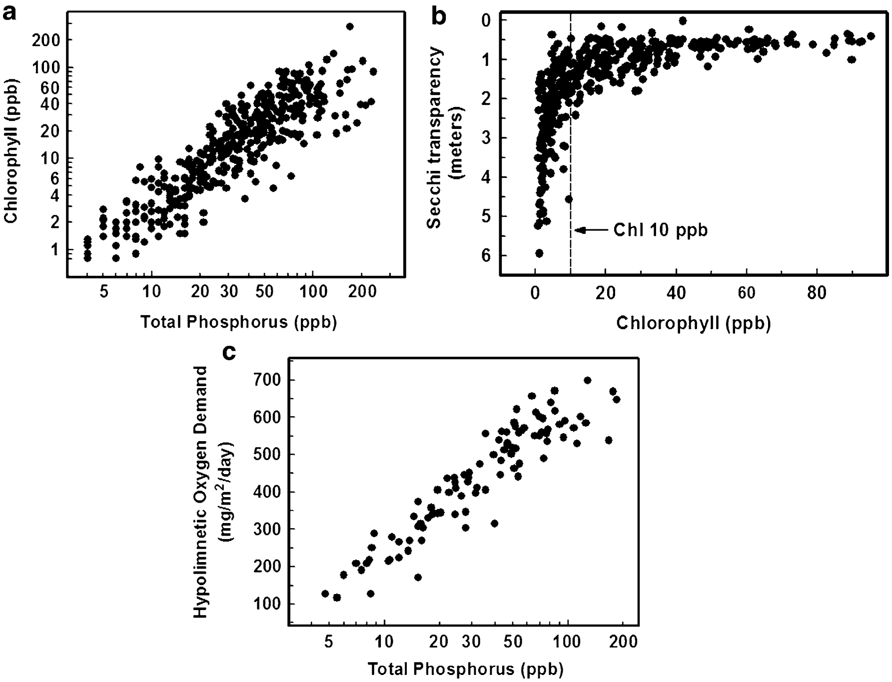

Fig. 33.1 Panel (**a**) – algal biomass measured as chlorophyll pigment (parts per billion, ppb) from Missouri reservoirs sampled in summer 2005 plotted against the total phosphorus concentration (ppb) in the same sample (axes were transformed using log base 10). Panel (**b**) – secchi transparency as a measure of water clarity (meters) in Missouri reservoirs sampled in summer 2005 plotted against the corresponding chlorophyll value (from Panel a) showing the hyperbolic relationship between the two variables. Panel (**c**) – a hypothetical representation of the established relationship between deep-water oxygen consumption in lakes (hypolimnetic oxygen demand, mg/m^2/day) and total phosphorus concentrations. The equation for oxygen demand and total phosphorus is from Nürnberg (1996), and data are from Missouri reservoirs in summer 2005

cell densities (Cooke et al. 2005). High Chl:TP ratios (near the top of the distribution, Fig. 33.1a) represent periods when algal growth is not strongly constrained by physical factors or intense grazing. In these samples algal density reaches the potential set by nutrients, and maximum Chl:TP ratios are about four times the long-term average. Maximum algal densities are rare but suggest nuisance conditions occasionally occur in otherwise aesthetically pleasing, relatively clear-water lakes (Jones et al. 2011). In contrast, these same concentrations are a common feature of nutrient-rich lakes. For example, Chl values of 10 ppb, where algae are visually noticeable, are uncommon when TP is <10 ppb but have sharply increasing frequencies among lakes with 20 ppb TP and are the norm in lakes with >50 ppb TP (Fig. 33.2a). Nuisance conditions are associated with Chl >30 ppb; but these conditions are rare in lakes with <20 ppb TP (Fig. 33.2b).

Cyanobacteria often dominate bloom events. At dense concentrations these photosynthetic bacteria with algal characteristics (also called blue-green algae)

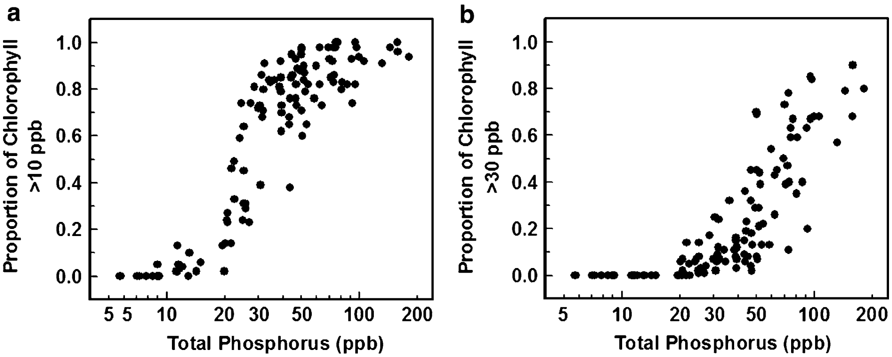

Fig. 33.2 The proportion of chlorophyll values that exceed 10 and 30 ppb (panels (**a**) and (**b**), respectively) plotted against the long-term average total phosphorus concentration in intensively sampled Missouri reservoirs

are buoyant and can form conspicuous surface scums that accumulate in wind rows and along shorelines (Schindler and Vallentyne 2008). They shade aquatic plant beds and contribute to oxygen depletion and subsequent fish kills. In general, they greatly detract from the aesthetic value of lakes and reduce energy flow to higher trophic levels because they are a poor food resource for zooplankton. Many cyanobacteria are also capable of producing a wide variety of highly potent, natural toxins with diverse toxic mechanisms (liver, neurological, digestive, and dermal, Chorus 2001). Many of these chemicals are more toxic than insecticides or herbicides and have steep dose–response curves so the margin between no observable effect and toxicity is small and the onset of toxicity can occur rapidly. Typically, these toxins are dilute, but they are concentrated when cells accumulate during blooms and have been implicated in the poisoning wild and domestic animals worldwide. Cyanotoxins that caused mortalities of farm animals were first reported more than 125 years ago but are increasingly reported because of proliferation associated with eutrophication, greater awareness, and improved detection methods. Increasingly, field surveillance is used to detect algal toxins in recreational waters resulting in swimming beach warnings and closures. Current research is addressing the genetic and environmental factors that favor cyanotoxin production.

Similarly, because algae are the energetic and biochemical foundation of aquatic ecosystems, there are empirical relationships that demonstrate the relationship between TP (or Chl) and the biomass of major food web compartments in lakes, including bacteria, zooplankton, and fish (Nürnberg 1996). The organic base of the food web is larger in nutrient-rich lakes so they support greater fish production. In extremely productive lakes, however, the most desirable sport fish species decline because of changes in the food base and oxygen deficiencies in deeper parts of lakes. Highly eutrophic lakes are characterized by rapidly reproducing omnivorous fish and small zooplankton that are ineffective cyanobacteria grazers. Cyanobacteria dominance is particularly problematic for upper trophic production because cyanobacteria generally lack long-chain omega-3 fatty acids. These fatty acids, which are prevalent in other phytoplankton such as diatoms and various flagellates, are important for zooplankton and fish growth and reproduction, and ultimately human health (Arts et al. 2001). As such, that climate and eutrophication caused cyanobacteria dominance can cause a biochemical bottleneck for higher trophic level production.

Many lake processes are also linked with algal biomass. Lake transparency decreases hyperbolically with Chl (Fig. 33.1b) with a steep response in lakes with <10 ppb Chl, whereas water transparencies above this Chl concentration are generally low. This pattern is a consequence of increasing cell densities scattering and attenuating light. In addition, mineral turbidity and dissolved humic matter can alter the relationship by further decreasing light penetration. Likewise with increasing algal biomass in surface waters, the oxygen content of bottom waters depletes faster and creates anoxia in a larger part of the water column, particularly during summer stratification (Fig. 33.1c). Total nitrogen is often highly correlated with TP in lakes and can be used to predict the biomass of food web compartments, transparency, and oxygen depletion almost as well as TP.

Eutrophication is typically addressed by controlling nutrient inputs (Cooke et al. 2005). The most often-cited example is the diversion of municipal wastewater from Lake Washington, which greatly reduced TP and algal biomass with resulting increases in transparency and deep-water oxygen (Edmondson 1972). There are numerous examples of lakes in North America and Europe responding similarly to nutrient load reductions, but often over a period of years or decades. Overall, controlling nutrients from point source wastewater discharges has been more successful than reducing nutrients from diffuse agricultural and urban/suburban sources (with vegetated buffers or stormwater retention ponds). The symptoms of eutrophication have been lessened mechanically by aerating lakes with perforated hoses or mixing devices to promote deep circulation and reduce the internal recycling of phosphorus from lake sediments. Alum ($AlSO_4$) has been applied to lakes where internal phosphorus return drives eutrophication. Phosphorus precipitates from the water column with aluminum hydroxide flocs. The alum layer in the sediments acts as a barrier for sediment phosphorus release and can be effective for 5 or more years.

Climate Change

Lakes are considered sentinels of climate change because they are responsive to temperatures and integrate changes in the catchment and atmosphere (Adrian et al. 2009). Lake water quality is expected to degrade in response to climatic warming (Moss et al. 2011). The increasing temperatures and more intense storms expected with climate change will also accelerate mineralization of nutrients from catchment soils and increase soil erosion. Collectively these factors will increase nutrient loading to lakes and promote eutrophication. Warmer temperatures will increase both the stability of thermal stratification and its duration in temperate lakes; lakes will stratify earlier in the year and destratify later in the fall, which extends the optimal growth period for cyanobacteria. Longer growing seasons and warm conditions will likely favor summer nitrogen limitation to the advantage of N-fixing cyanobacteria. Longer stratification will also favor anoxia in the bottom waters, which will enhance phosphorus recycling from bottom sediments and promote algal growth and increase the release of greenhouse gasses such as carbon dioxide, methane, and nitrous oxide (from denitrification). In a warming climate, cyanobacteria will likely increase in abundance and expand their geographic range. There are examples of cyanobacteria species which are now common in temperate, eutrophic lakes that were originally considered subtropical. Many of the lake management techniques currently used may become less effective as warming accelerates eutrophication. Research suggests nutrient controls must be intensified just to keep pace with climate change.

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