Lake Management in a Browning World: **Beyond the Holy Grail of Nutrients**

Craig E. Williamson

Water clarity is a primary determinant of water quality in lakes across the continent. The economic, recreational, and aesthetic value of lakes, and, in particular, their value as drinking water resources, is directly related to their clarity. Even in the clearest of lakes, water resource managers and the public shout slogans like "Keep Tahoe Blue!" The good news is that scientists have found the holy grail of lake management – excess nutrients, most often from human activity, are a primary contributor to algae blooms and green lakes. But why then, has there been so little change in the relationship between nutrients and algae in lakes across much of the continent in spite of the many success stories of controlling nutrients and decreasing algae blooms in individual lakes? The largest study to date of changes in water quality in over 2,900 lakes in the northeastern and Midwestern USA has shown that in spite of this awareness of the importance of nutrients and extensive management efforts, there has been little change in nutrients or algae in lakes since 1990; rather, we have seen an "unexpected stasis in a changing world" (Oliver et al. 2017).

At the same time that an unexpected stasis has been observed in nutrients and algae, many lakes across northeastern USA, northern Europe, and beyond, have seen up to a doubling or more in their dissolved organic matter (DOM) (Monteith et al. 2007), a phenomenon often referred to as "browning." Thus we need to think beyond the holy grail of nutrients, and consider how DOM and browning influence lake ecosystems (Figure 1). DOM is a major regulator of the clarity of inland waters around the world, often more important than chlorophyll. Our most pristine, oligotrophic, blue lakes are threatened not only by nutrients turning them green with algae, but also by DOM that can turn them into dystrophic brown lakes. When both chlorophyll and DOM are high, lakes can become mixotrophic, with a brownish-green color (Figure 1).

This special issue of *LakeLine* includes articles that examine the multiple effects of lake browning on many aspects of lakes ranging from the thermal structure and dissolved oxygen in water to zooplankton, fish, and human health and wellbeing. This lead article provides an overview and answers to key questions about the causes and consequences of browning and their implications that will enable more effective lake management in a browning world.

What is DOM and why is it increasing and turning lakes browner?

Anyone who has walked on a sidewalk after a fresh leaf-fall followed

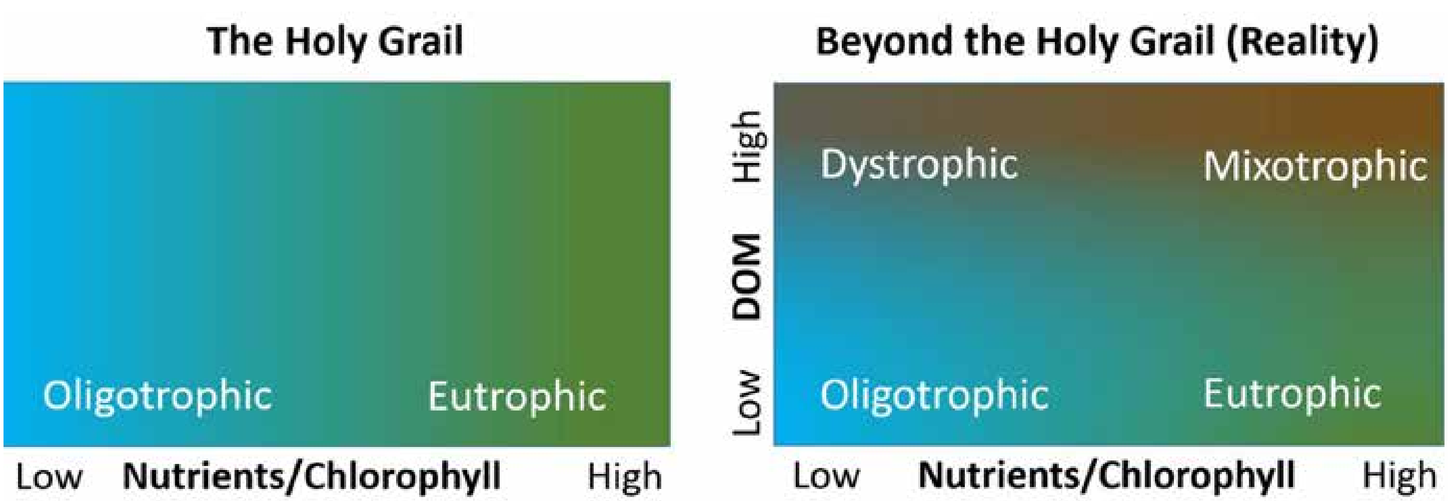

Figure 1. Conceptual diagrams showing the holy grail of nutrients and chlorophyll from the conventional, single-dimensional perspective (left), and a more complete paradigm that includes dissolved organic matter (DOM) and browning (right). Lakes do not vary only along a single gradient of nutrients and chlorophyll from oligotrophic blue lakes to eutrophic green lakes. DOM is a major regulator of water transparency, and in many regions around the world it is leading to more dystrophic (brown) lakes, or mixotrophic lakes in which both chlorophyll and DOM reduce water clarity.

by an autumn rain has seen DOM staining the sidewalks (Figure 2). The DOM that is turning lakes brown is largely derived from terrestrial sources, has a dark yellow-brown to black color, and is thus often referred to as colored, or chromophoric DOM, CDOM. The extent of the color of this DOM is a function of the plants from which it is derived, with some plants producing more highly colored DOM than others (Figure 2). This DOM is in turn processed by microbial degradation in the soils and receiving waters (biodegradation) and by the short wavelength visible and ultraviolet (UV) radiation in sunlight (photodegradation), which alter both its color and its quality.

Figure 2. Dissolved organic matter in lakes, reservoirs, and other inland and coastal waters is derived primarily from terrestrial plants, as can be seen from freshly fallen leaves leaching DOM on a sidewalk (left). Different types of trees and other plants leach different types of DOM, which vary in their color, and thus potential contribution to changes in inland water quality. Soil microbes and photodegradation by sunlight can further alter the composition and thus color and quality of the DOM, with important consequences for aquatic ecosystems.

There are multiple causes of the observed increases in DOM and browning in lakes and other inland waters. The two primary causes tell contrasting good news and bad news stories. The good news story is that acid deposition has decreased substantially since the 1990 Clean Air Act legislation was passed to limit industrial emissions of sulfur and nitrogen-based compounds that were acidifying the soils (Figure 3). Less acidic soils have increased the mobilization of DOM to downstream waters. The bad news story is that climate change is leading to strong increases in precipitation, and extreme precipitation events in particular (Figure 3). These increases in precipitation saturate the soils with water, creating anoxic conditions that increase DOM production. Heavy precipitation also increases the flow of water from terrestrial ecosystems, washing increasing quantities of DOM into inland waters (Strock et al. 2016). Climate change is causing an acceleration of the hydrologic cycle that is expected to continue to increase browning of inland waters far into the future. The associated increases in extreme events will also cause more severe droughts, which will offset browning, and depending on the hydrology of the lake basin, may even increase water clarity in lakes (Williamson et al. 2016).

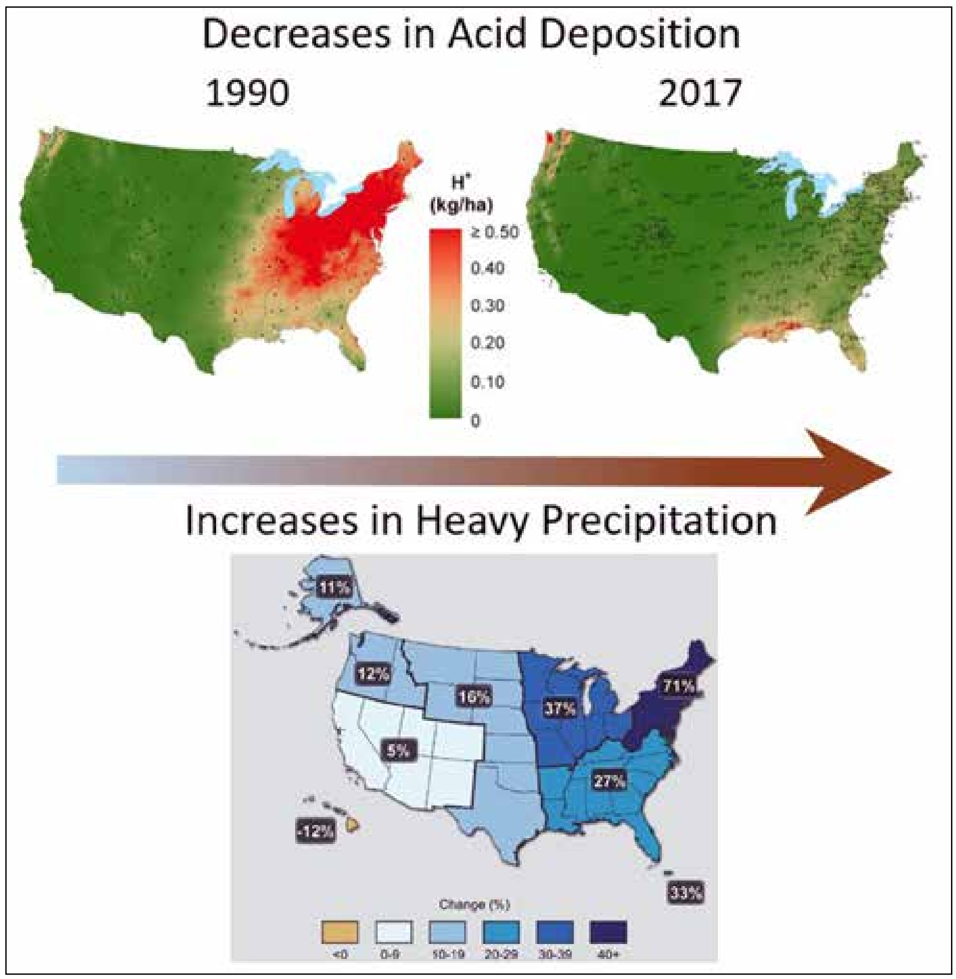

Figure 3. Two major causes of lake browning (horizontal middle arrow) include decreases in acid deposition related to the 1990 Clean Air Act Amendments (top), and increases in precipitation, particularly heavy precipitation events (top 1% of events) which have shown stronger increases in the north and east than in the western USA over the period from 1958 to 2012 (bottom). Sources (top): http://nadp.slh.wisc.edu/maplib/pdf/2017/h_dep_2017.pdf; (bottom): https://nca2014.globalchange.gov/report/our-changing-climate/heavy-downpours-increasing.

How does browning influence light, temperature, and oxygen in lake ecosystems?

The primary mechanism through which DOM alters lake ecosystems is through absorption of sunlight, which reduces light for photosynthesis, the primary source of energy that supports aquatic food webs. Thus, both photosynthetically active radiation (PAR) and UV do not penetrate as deep in brown lakes as they do in blue lakes (Figure 4). DOM strongly and selectively absorbs the shorter wavelength UV radiation (Figure 4), with important implications for the multiple effects of UV radiation on aquatic ecosystem services ranging from disinfection of parasites and pathogens, to photodegradation and nutrient cycling, to zooplankton vertical migration and invasion of warm-water fish into cool, clear-water lakes (Williamson et al. 2016). The absorption of sunlight in the surface waters of brown-water lakes also has multiple effects on the vertical habitat gradients in the water column. These effects include stronger thermal gradients (steeper thermoclines), and greater depletion of dissolved oxygen in deeper waters (Figure 4). The depth to which one percent (1%) of PAR penetrates approximates the compensation depth (see the intersection of the solid PAR line with the vertical axis in Figure 4). Below the compensation depth there is net consumption of oxygen and thus the threat of hypoxia and even "dead zones" in the cooler deeper waters that are anoxic, totally depleted of dissolved oxygen (Figure 4). Thus, the light-absorbing DOM in brown lakes creates vertical habitat gradients in light, temperature, and oxygen that are very similar to those observed in green lakes that have high concentrations of light-absorbing phytoplankton.

Why should water resource managers care that lakes are browning?

In addition to making lakes darker and aesthetically less desirable for some, browning has many effects on a wide variety of critical ecosystem services provided by lakes from drinking water to public health to fisheries. When drinking water is chlorinated, DOM combines with chlorine to produce carcinogenic disinfection byproducts such as trihalomethanes. The UV radiation in sunlight is also the most potent natural mechanism to disinfect the surface waters of lakes. By strongly and selectively absorbing UV radiation, DOM can reduce the effectiveness of solar disinfection of parasites and pathogens of humans and wildlife, leading to increases in parasitism and infectious diseases. Aquatic vectors of disease such as mosquitoes are also killed in their early larval stages by exposure to high levels of solar UV radiation. Increases in DOM associated with browning may thus provide a refuge from damaging UV that increases the breeding success of mosquitoes (Figure 5).

Increases in DOM during either long-term browning, or during extreme precipitation events that result in DOM-rich river plumes such as observed in Western Lake Erie (Figure 6) may also favor the development of cyanobacteria and harmful algal blooms. These blooms have been on the rise nationwide as illustrated by an animation from the Environmental Working Group at https://www.ewg.org/key-issues/water/toxicalgae. There are several mechanisms through which DOM can favor cyanobacteria blooms. First, cyanobacteria are better at regulating their buoyancy than other algae, and they can thus remain in the more well-lit surface waters when DOM darkens the water. Second, the increased absorption of sunlight in surface waters can lead to shallower, warmer surface waters that favor cyanobacteria due to their higher temperature optima compared to other types of algae. Third, DOM can increase nutrient availability through transport

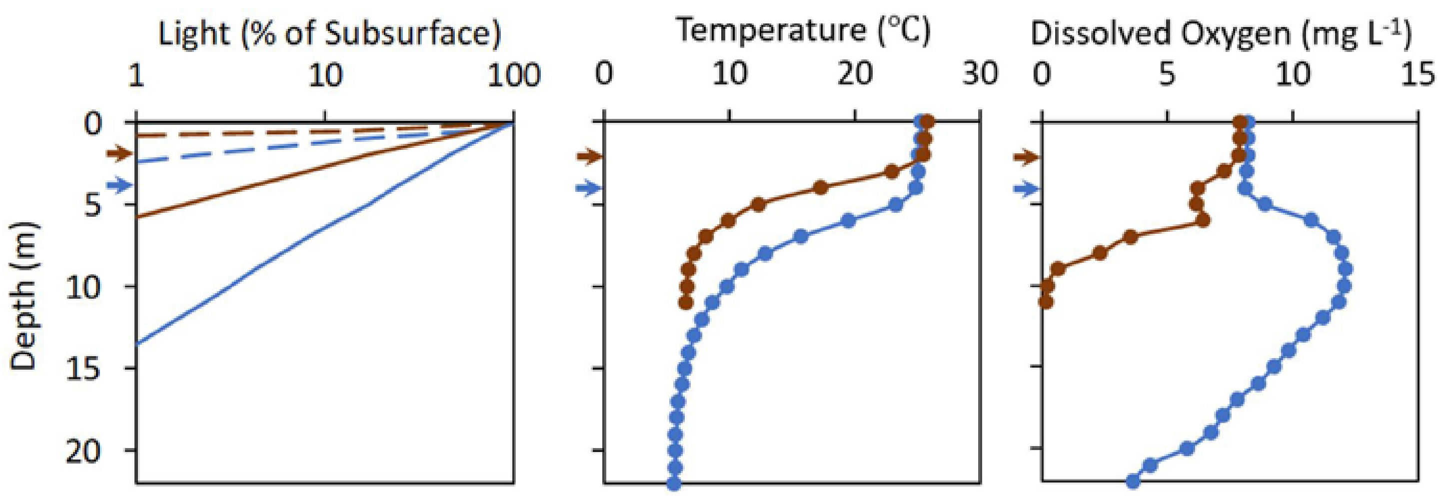

Figure 4. Vertical profiles in a dystrophic brown and an oligotrophic blue lake in northeastern Pennsylvania showing attenuation of light, including photosynthetically active radiation (PAR, solid line), and ultraviolet radiation (320 nm UV, dashed line), temperature, and dissolved oxygen in the water column (averages for 2016-2019). Arrows indicate the average depth of the mixed layer. Note the more rapid attenuation of light, steeper thermocline, and total depletion of dissolved oxygen in the deep waters of the dystrophic brown lake, all characteristic of what is found in eutrophic green lakes as well. The midwater peak in dissolved oxygen in the oligotrophic blue lake is due to a combination of the higher solubility of oxygen in colder water, and a deep-water peak in oxygen-producing phytoplankton that have plenty of light for net photosynthesis at depths shallower than the compensation depth (1% PAR depth).

Figure 5. Aedes aegypti*, the yellow fever mosquito, is one of several species that are expanding their range northward from subtropical environments with climate change. Browning of inland waters where mosquitoes breed provides a refuge from damaging solar UV radiation that may contribute to the expansion of these vectors of infectious diseases that include zika, dengue, chikungunya, and other viruses.* Photo from Center for Disease Control (https://www.cdc.gov/zika/vector/range.html).

Figure 6. Dark brown plume of dissolved organic matter (red arrow) entering Western Lake Erie where toxic cyanobacteria blooms have been an ongoing problem. In 2014 high levels of microcystin closed down the water supply to over 400,000 people in the Toledo, Ohio, area. Integrating DOM into our understanding of toxic algae blooms is essential for more effective management of such blooms. NASA MODIS image May 16, 2016.

from terrestrial ecosystems followed by bio- or photodegradation and release of the nutrients. The selective binding of nutrients by DOM may also alter nutrient ratios and potentially stimulate toxin production. In spite of these many ways that DOM may enhance harmful cyanobacteria blooms, there has been inadequate integration of DOM into the models used by management agencies to predict and control these blooms.

The effects of browning on fisheries depends largely on the initial transparency of the lake. Many fish species spawn in shallow waters where exposure to UV radiation can kill often highly transparent eggs and larvae (Figure 7). The UV damage potential is likely important only in lakes of high water clarity such as Crater Lake in Oregon, Lake Tahoe, and the Upper Laurentian Great Lakes (Superior, Huron, and Michigan), and the many other highly transparent lakes across the continent such as alpine lakes as well as in shallow lakes. In cool-water, highly transparent lakes, native fish and other aquatic biota may possess UV protective mechanisms that enable them to survive under high UV exposures. At the same time, embayments with high DOM concentrations can provide refugia for less UV-tolerant invasive warm-water fish to spawn successfully, as has been demonstrated in Lake Tahoe. In contrast to these very clear-water lakes, the growth and reproduction of fish tends to decrease with increasing DOM in browner lakes with higher DOM concentrations.

Browning-related reduction in the value of the ecosystem services provided by lakes have obvious economic consequences that include increased costs ranging from water purification for drinking to the effective management of fisheries. Lake-front property values also decline with decreases in water clarity. A study of property values for lake-front cottages in Ontario showed a 10 percent reduction in Secchi depth (a crude measure of transparency) decreases property values by 2.2 percent (Clapper and Caudill 2014). Similar results have been obtained in New Hampshire and Maine. While these and other studies have assumed that changes in water transparency are due primarily to eutrophication, browning is now also having a strong effect on water clarity across much of North America and needs to be folded into the current nutrient-algae paradigm for more effective lake management.

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Figure 7. Photographs of the transparent larvae of three species of fish from Lake Tahoe. The two warmwater invasive species bluegill (top) and largemouth bass (middle), have little photoprotective melanin, and are correspondingly highly susceptible to UV damage in the shallow, clear waters of Lake Tahoe where they need to spawn to get warm enough temperatures for reproduction. In contrast, the native Lahontan Redside (bottom) contains higher levels of melanin (black granules) and correspondingly can tolerate higher levels of UV exposure. Photo credits: Andrew J. Tucker.

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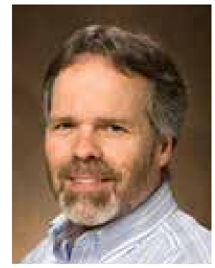

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UPCOMING IN *LAKELINE* – FALL 2020

NALMS at **40**

The fall issue will include some articles related to the evolution of NALMS and lake management over the last 40 years. We would like to include an array of personal stories from members of NALMS (both long-time and new) about what NALMS means to them. Articles on the evolution of lake management, and in particular some articles on how federal Section 314 funding was useful in the past, and the gaps it left behind when funding for that program was terminated. How did you adapt, or not adapt to that loss of funding on the state level? Case studies, data driven information, and/or anecdotal information is all useful. Also, it would be nice to have some short articles on how NALMS could and should grow and evolve for the next 40 years (what do we do well, what do we need to tweak or add).