# The Causes & Food Web Consequences of Lake Browning: How are They Linked?

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If one were to take snapshots of lakes and their watersheds in places such as throughout the northeastern U.S. or Northern Europe over the past few decades, it would be easy to tell that many things have changed. Looking underwater, one of the most dramatic would be a color change. Many lakes are substantially darker today than they were in recent past decades.

Many lakes are undergoing what is referred to as "browning." Browning is often described as a measure of increases in dissolved organic carbon (DOC) content. DOC is what gives many lakes a brown, "tea-like" hue to them, and browning is, first and foremost, a measure of water color change. Color often closely correlates with DOC content, but color is also sensitive to DOC quality. In turn, DOC quality refers to characteristics such as the sensitivity to photochemical or biological degradation (Jane and Rose 2018).

## Quantifying lake color and DOC

Lake color can be measured in several different ways. Traditionally, water color was measured in Platinum Cobalt units (and still is measured this way regularly, for example in the US EPA National Lakes Assessment program). Another, more contemporary method, is measuring water color by spectrophotometry. Using this method, lake color is typically characterized by absorbance at 440 nm. Other optical indices, such as the change in absorbance per wavelength (called "spectral slope") can provide additional information on DOC quality such as information on the source and past light exposure of the organic matter (Williamson et al. 2014).

Meanwhile, DOC content is typically measured using a total organic carbon analyzer after filtration to remove particulates. Often, color and DOC content closely correlate, but there are some reasons why they do not always correlate. For example, iron absorbs light and can contribute to dissolved absorbance without contributing to DOC content, thereby affecting the DOC:color ratio.

## What causes lake browning?

It has convincingly been demonstrated that browning occurs as inland water bodies recover from previous decades of acidification. While other drivers are also plausible, lakes in regions that are historically downwind of large sources of atmospheric pollution (e.g., coal power plants) such as in the northeastern U.S. and Northern Europe were sensitive to acidification and many waterbodies in these regions are undergoing contemporary browning (Monteith et al. 2007) widespread increases in concentrations of dissolved organic carbon. Since the 1990s, policies such as the Clean Air Act Amendments in the U.S. have led to cleaner air, soil, and water.

Contemporary increases in pH and decreases in ionic strength closely correlate with observed trends in both color and DOC content in regions such as the Poconos in Pennsylvania and the Adirondacks in New York, U.S. In these regions, acidification was pervasive in part due to poorly buffered soils. These regions are now recovering. In the Adirondacks, for example, DOC has increased by about 0.5 mg per liter per decade over the period 1994-2012 (Figure 1; Leach et al. 2019). However, other anthropogenic changes may also contribute to browning in some regions. For example, climate-change induced increases in precipitation may facilitate increases in DOC loading from the terrestrial landscape, and recovery of forests in some regions may stimulate browning (Kritzberg 2017). In the longer-term, climate-changed induced increases in growing-season length may increase the amount of vegetation and thus carbon available for export to aquatic ecosystems. Thus, it is plausible that browning may continue for decades to come even after lakes fully recover from acidification, but perhaps at slower rates than have been observed.

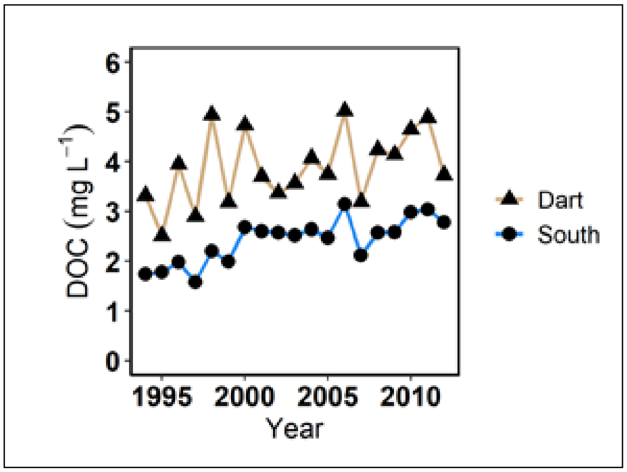


*Figure 1. Mean annual summer (July, August, September) dissolved organic carbon (DOC) concentration for two lakes in the Adirondacks region. South Lake is denoted by a blue line and circles while Dart Lake is denoted by a tan line and triangles. South and Dart DOC increased at rates of 0.62 and 0.69 mg per liter per decade, respectively.*

Concomitant with acidification-associated browning, many aquatic ecosystems are undergoing many other changes in water chemistry. For example, in the Adirondacks lakes have increased in pH and acid neutralizing capacity, and decreased in nitrogen, sulfate, calcium, and aluminum concentrations in recent decades. Most, if not all, of these water chemistry changes are driven by a decline in acid deposition, indicating that, at least chemically speaking, the lakes are recovering and browning is but one of many changes occurring. Some characteristics, such as declines in lake water clarity (as measured by Secchi disk depth) are directly attributable to lake browning.

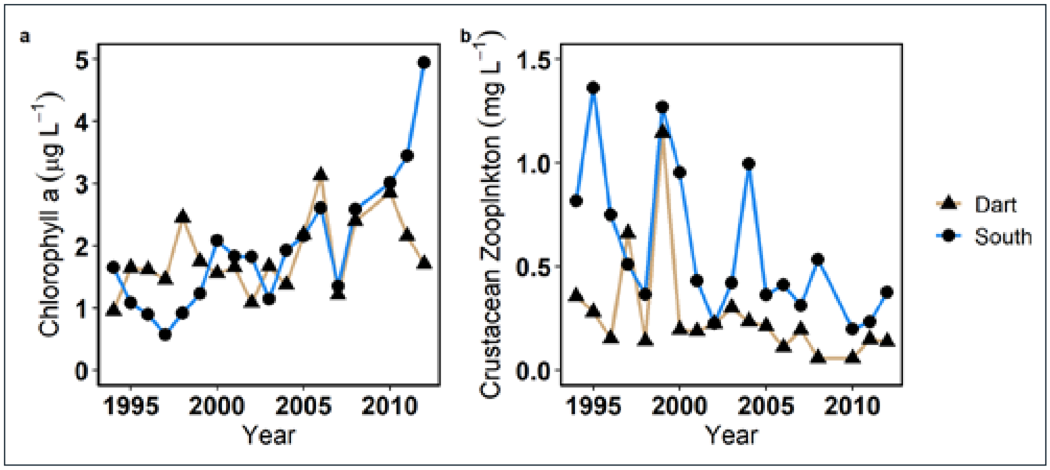


*Figure 2. Mean annual summer (July, August, September) chlorophyll-a concentration (a) and crustacean zooplankton biomass (b) for two lakes in the Adirondacks. South Lake is denoted by a blue line and circles while Dart Lake is denoted by a tan line and triangles. South and Dart chlorophyll-a increased at rates of 1.56 and 0.48 μg per liter per decade, respectively. Zooplankton biomass declined at rates of -0.38 and -0.20 mg per liter per decade, respectively.*

## Implications of browning for aquatic food webs

What are the implications of browning for lakes and the organisms that inhabit them? Short-term and cross-sectional surveys have been conducted to understand browning, but long-term changes may not be well-predicted from spatial surveys if the drivers of long-term change are not also important drivers of spatial variability. For example, spatial surveys show that limiting nutrient concentrations (e.g., nitrogen and phosphorus) are closely correlated with DOC content, but they are not through time. Unfortunately, there are few datasets to examine the long-term impacts of browning and other associated water chemistry changes on aquatic food webs.

One of the few such datasets that has monitored lake browning, phytoplankton, zooplankton, and many other water chemistry characteristics was collected 1994-2012 in the Adirondacks (Leach et al. 2018). In those lakes, chlorophyll concentrations were slowly increasing (Figure 2a) and there were no changes in phytoplankton biovolume. Meanwhile, zooplankton populations were in substantial decline (Figure 2b; median biomass decline >50 percent across 28 lakes). Similar zooplankton declines have also been observed in Pennsylvania, U.S. in lakes undergoing browning and acidification recovery (Williamson et al. 2016) multi-decadal studies that document the net ecological consequences of long-term browning are lacking. Here we show that browning over a 27-year period in two lakes of differing transparency resulted in fundamental changes in vertical habitat gradients and food web structure and that these responses were stronger in the more transparent lake. Surface water temperatures increased by 2-3 °C in both lakes in the absence of any changes in air temperature. Water transparency to ultraviolet (UV). Water chemistry changes other than lake browning regulated these food web changes. For example, calcium appears to be the primary regulator of zooplankton, as recovery from acidification has been associated with substantial declines in calcium and many lakes are now at levels below which many zooplankton taxa can survive. Additionally, aluminum is declining; in past decades high aluminum concentrations were toxic to fish, but fish recovery has been uneven, perhaps due to limited dispersal pathways.

Overall, many of the observed long-term food web changes that have occurred in Adirondack lakes are concomitant with browning, but likely not driven by browning itself. However, recovery from acidification, which stimulates lake browning as well as many other water chemistry changes observed, appears to be the single overarching driver of observed food web changes. The ultimate driver of browning – whether it be recovery from acidification, climate change, land use change, or something else – may ultimately regulate the overall magnitude and diversity of food web changes that are observed. In Adirondack lakes (e.g., Polliwog Pond, Figure 3), recovery from acidification is associated with a whole suite of water chemistry changes. In regions where climate or land-use change are responsible for browning lakes, it is likely that food web changes will be markedly different from those observed in Adirondack lakes. Only through further research and monitoring, including documenting long-term biological changes and concomitant water chemistry and quality changes, can we disentangle the complexities of browning to fully understand the linkages between the causes and food web consequences of lake browning.

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*Figure 3. Author Dr. Rose and his son canoeing on Polliwog Pond in the Adirondacks (New York, U.S.). Pollywog Pond, like many lakes in the Adirondack region, has undergone browning in recent decades. The lake's brown color is visible in the lower foreground.*


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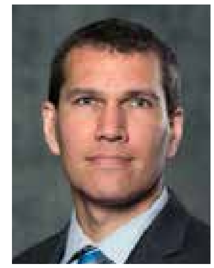

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