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A global problem: trends in nutrient loadings of lakes with climate change and increasing human developments

By Clelia Luisa Marti

Lake ecosystems are resources providing many valuable services. Some (like food, drinking water, energy production, flood damage reduction, navigation, recreation and tourism) are directly valued by the human population while others (such as aquatic wildlife habitat, biodiversity hotspots, conservation of endangered species) have positive environmental impacts that benefit us indirectly[1]. The ecosystem benefits provided by lakes are variable, depending on their underlying ecology and on their location, because lakes are intimately connected with their surrounding landscape and human communities[2].

Lake ecosystems around the world are being exposed to environmental changes having origins both anthropogenic (inputs of excess nutrients, harmful algal blooms, overexploitation of water and food resources, emerging organic pollutants, etc.) and climatic (global warming, changes in precipitation patterns and amounts). Changes occur in the physics, biology and chemistry of lakes, as well as in interactions between their internal compartments and their connectivity with the surrounding landscape. These changes are predicted to intensify in the future, threatening the functioning of the ecosystems and the services they provide on both local and global scales, and causing unprecedented world-wide concerns[2, 3]. Some anticipated impacts are likely to be similar across different lake ecosystems, while others may be system-specific[4].

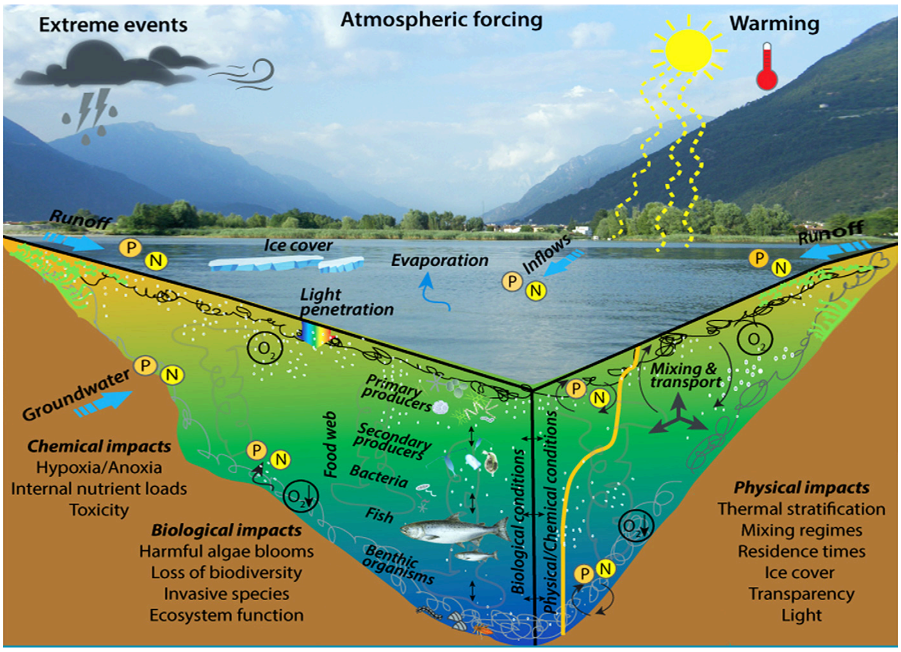

Figure 1 | Schematic showing the major impacts of global warming and increased nutrient loading on lakes.

Intensive research efforts over past decades have provided alarming evidence worldwide of resource depletion (particularly water and food), increasing water temperatures, reduction in polar ice cover, depletion of oxygen in deep waters, fragmentation and destruction of habitats and ecosystems, loss of biodiversity and accelerating pollution, among others[1, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13]. Furthermore, long-term monitoring datasets together with increasing in situ real-time high resolution monitoring data and numerical modelling (i.e., ranging from land-use and climate models to hydrodynamics, biogeochemical and physiological models) have played a key role in quantifying this degradation and increasing our knowledge and understanding of the possible impacts on lake ecosystems[14]. Continued efforts are therefore required to focus on how long-term and emerging threats (including micropollutants and microplastics) will interact and how lake ecosystems will respond. Prediction of these effects will be critical to resource management, to public understanding of changes that have already begun, and to establishing lake restoration and adaptive management strategies for protecting and sustaining lake ecosystems. Increased nutrient loading and climate change are the most widespread stressors having strong impacts on the lake ecosystem environment[13, 15, 16] (Figure 1). A description of the main impacts and trends is summarized below. Increased nutrient loadings as a result of agricultural, urban and industrial development of catchments and lake shoreline areas is, as in the past, a key cause of this 'cultural eutrophication'[16].

In spite of extensive research since the 1960's, cultural eutrophication remains a major concern worldwide[15] and has emerged as an increasingly important issue in the context of protection of water resources for future generations[17]. Cultural eutrophication may lead to many drastic lake ecosystem changes[15, 16]:

- Decrease in water transparency.
- Increased incidence of oxygen depletion (anoxic events < 0.5 mg/L or hypoxia < 2 mg/L).
- Overgrowth of phytoplankton.
- Accumulation of organic matter and a large recyclable sediment phosphorus (P) pool.
- Loss of biodiversity and rapid homogenization of biotic assemblages.

Figure 2 | HAB in Burlington Bay, Lake Champlain (Vermont, USA).

It has been known for many decades that eutrophication fuels excessive plant and algal growth, including harmful algal blooms (HABs). These blooms may produce noxious toxins and high water turbidity, cause fish kills due to hypoxia/anoxia, food-web alterations and impair important ecosystem services such as water supplies for human consumption, agriculture, irrigation, aquaculture, and fisheries, as well as recreational and aesthetic values (Figure 2). There is a vast literature on this topic[13, 14, 15, 16].

Historically, cultural eutrophication has been associated with an oversupply of P[16]. However, nitrogen (N) loading from anthropogenic sources has increased at alarming rates and has been shown to be directly implicated in water quality degradation and eutrophication[16, 18]. More than 40% of lakes are eutrophic and affected by algal blooms. Between 1900 and 1950 surpluses of P and N in agricultural soils increased by nearly eight-fold and two-fold, respectively, and by around four-fold for both nutrients between 1950 and 2000. Despite enhanced efficiency of nutrient recovery, surpluses are projected to increase further to 2050[19]. Between 2010 and 2050, the number of inhabitants connected to a sewage system will have increased by 2 to 4 billion people and nutrient discharge to surface water will have increased by 10% to 70% despite a 10% to 40% increase in nutrient removal in future wastewater treatment facilities[20]. A portion of these additional nutrients inevitably enters the aquatic ecosystems and such increases are and will be stressing aquatic resources in the future.

Reduction of P load inputs to aquatic ecosystems has generally been advocated as a key eutrophication mitigation step based on the assumption that P universally limits HABs[15, 16]. Phosphorus accumulates in both the water column and sediments, as there are no gaseous forms facilitating P escape from aquatic ecosystems, other than phosphine (phosphane) and diphosphane, which are occasionally generated in "marsh gas" from stagnant waters. Phosphorus mainly leaves aquatic systems by flushing or ending up in the sediments leading to a legacy of P supply supporting persistent internal loadings (which are regularly activated by resuspension of bottom sediments, as well as effective P regeneration from the sediments). These "legacy nutrients" provide a positive feedback loop supporting HABs, so even if P inputs are reduced, reversing the harmful effects of eutrophication can take a substantial period of time, especially in large lake ecosystems with long water residence times. Reduction of P has decreased HABs in many lakes but has been unsuccessful in others[16, 21]. Nitrogen can leave an aquatic ecosystem as a gas (e.g., N_2, N_2O, NO, NH_3), but some N also ends up in solution leaving a legacy in water bodies. Annual rates of denitrification often exceed rates of N_2 fixation especially in bloom-prone eutrophic systems. Therefore, chronic limitation of N is maintained, and external N inputs play a critical role in supporting eutrophication and sustaining HABs. Recent studies have shown that combined P and N enrichment rather than N or P alone often stimulates HABs more, indicating that the dynamics of both nutrients are important for their control. As a result, external loads of both P and N need to be constrained in order to impose more nutrient-limited conditions, so as to mitigate the HABs problem in light of global agricultural, urban and industrial expansion, and climate change[16, 18].

Significant progress has been made in developing and implementing management strategies to minimize the effects of cultural eutrophication since the 1960s. The reduction of external nutrient loading has proved to be one of the most effective measures for sustainable control of HABs. However internal loading of legacy nutrients from the sediments enriched by years of high nutrient inputs often causes a delayed response in water-quality improvements following reduced external nutrient loading. In-lake methods of HAB control (mechanical mixing, hydraulic or pneumatic pumping, floating covers, biological control, chemical control, sediment removal) represent a final fallback position, sometimes necessary to prevent the negative impacts of severe HABs but mostly failing to address the root cause of nutrient over-supply. These approaches are generally expensive and have been successful in small (< 50 ha) ecosystems, but not in large lakes[18].

Climate change has been identified as one of the most important issues facing humanity today and has already had an impact on the structure, function, and ecosystem services provided by lakes[1, 3]. A substantial body of research demonstrates the responses of lakes to climate change[6] including increases in surface water temperature[5], reduction in ice cover[8], altered stratification and mixing regimes[7], and increases in evaporation rates[22].

Deep lakes, which tend to be large in surface area, are more likely to lose ice cover in a warming climate than shallow lakes at similar latitudes[8]. Similarly, the average *surface water* temperatures of large, deep lakes have often been found to be rising at rates as high as 1.0 °C per decade and these rates are projected to increase in the future[5]. On the other hand, *deep water* temperatures have shown little change on average[23]. It is predicted that higher latitude lakes will tend to become more like lower latitude lakes[24]. The warming rates seem to vary widely among lakes[5], and even spatially across large lakes[25]. Interactions with other stressors can also lead to negative consequences[16, 26]. For example, changes in precipitation patterns and amounts, runoff, evaporation, and water usage have contributed to shifts in seasonal water levels in some lakes, whereas historically low or high water levels in others, leading to changes in water quantity and quality. Factors varying feedback from large lakes to the atmosphere have also been identified, such as increasing regional air temperatures[3].

Changes in the thermal structure of lakes affect their ecological function, including key processes like nutrient cycling and depletion of deep-water dissolved oxygen[7, 9, 10]. During the stable stratified period, increases in the strength or duration of thermal stratification isolate the cool, deeper waters by reducing vertical mixing, with profound implications for nutrient and oxygen availability, food-web structure and habitat[11]. These deeper waters are the sources of important thermally dependent biogeochemical processes, such as P release from anoxic sediments and methane production[27] and they offer critical habitats for many temperature-sensitive aquatic organisms. There is increasing concern about the loss of cold-water fish species, such as salmonids[28].

Besides the extent of the stratified season, the maximal depth of convective mixing in winter (the “winter mixing depth”) also plays a key role in oxygen renewal, nutrient upwelling and primary productivity in deep lakes. Deep lakes have considerable quantities of nutrients stored in the deep hypolimnion. These can increase productivity when penetrative convective events or strong winds allow mixing with the euphotic zone. For example, in Lake Constance (Bodensee) that borders Germany, Austria and Switzerland and Lake Garda in Italy, nutrient availability in their upper layers depends to a substantial degree on the winter mixing depth[10, 29, 30]. Given ongoing climate warming, the increase in both autumn stratification and winter temperatures will continue to reduce the winter mixing depth resulting in reduced nutrient availability in the spring, which is often the limiting factor for primary production. Recent studies have reported decreased upwelling of nutrient rich deep-water with potential impacts on primary productivity in deep lakes[29], so shallower winter mixing will lead to a reduction of algal growth (“climate warming-induced oligotrophication”). However, changes in nutrient availability may also cause shifts in phytoplankton communities, which in turn affect nutrient budgets[10]. The mixing depth affects oxygen replenishment during winter-spring turnover. In some Italian lakes (e.g., Magiore, Como, Garda) a decrease in deep-water oxygen content has been reported and in others (e.g., Lugano and Iseo) there is an increase in the extent of anoxic conditions as a result of climate change[9]. Such conditions may adversely impact the habitat of benthic organisms[31], enhance the internal P cycling[32] and limit fish habitats[12]. In particular critical conditions, such as those experienced by anoxic lakes, there is potential for the whole water column to be oxygen-depleted, resulting in death of all aerobic organisms as an effect of full lake turnover[9].

Furthermore, climate change has altered the horizontal temperature structure in some lakes by warming offshore surface water more rapidly than shallower nearshore waters[25]. This change has implications for lake organisms, given that temperatures above a particular threshold are lethal to some species[12]. This is important for colder water species in a warming climate. The seasonal timing of population development for organisms within lakes is being affected by changes in the growing season length within lakes[12]. Climate change has led to phenological shifts within and among trophic levels, which might cause a mismatch between prey and predator with wide-ranging consequences in reproductive success, survival and growth, especially when the warming rate is seasonally heterogeneous, thereby ultimately affecting lake ecosystem structure and function[33].

Climate change is also expected to amplify the adverse impacts of eutrophication in the future and further degrade lake ecosystem health and the services provided by them[1, 13]. The combination of rising temperatures with higher nutrient loading is linked to HAB magnitudes, frequency, distribution and duration and can also enhance the toxicity of HABs[16]. Climate change has altered the duration, magnitude, and frequency of extreme events, including flooding, droughts, forest fires, and heatwaves[26], with significant environmental impacts on both terrestrial and aquatic ecosystems reducing ecological resilience. Excessive episodic rainfall events (Figure 3) followed by extensive summer droughts can promote large nutrient pulses followed by lengthy residence times, and enable the development and proliferation of HABs[16]. Climate change is fueling wildfires leading to nutrient loading due to increased sediment movement from catchments, especially when followed by extensive rainfall and flooding. This has been the case in California and recently in eastern and southern Australia[14, 34].

Figure 3 | High intensity storm over the catchment of Lake Argyle (Western Australia, Australia).

In addition to augmenting P inputs associated with the mobilization of sediments, deforestation also triggers N loadings, as seen in the shift in the Laurentian Great Lakes nitrogen cycle[35]. Thus changes in these climatic drivers will need to be integrated into the development of nutrient input reductions that will effectively maintain HABs potentials below specific nutrient loading thresholds for individual lake ecosystems[16].

Key uncertainties remain about how climate change will affect lake ecosystems: continued research efforts and long-term assessment will be required to fully understand and predict future changes and effects on humanity.

Lake Constance is an example of successful management of eutrophication. Total phosphorus (TP) concentrations have now decreased by an order of magnitude to levels (6-8 μg/L) typical of those prior to the massive eutrophication that occurred from the 1950s to the 1970s [36]. Until quite recently, phytoplankton and zooplankton populations responded as predicted and extirpated species reappeared. Conversely, species that increased with eutrophication declined [37], and blooms of cyanobacteria also decreased [36]. Overall productivity decreased, which probably contributed to reduced growth and standing stock biomass of whitefish, the most commercially important fish species in Lake Constance, threatening the sustainability of fishery resources in the lake [38]. Recently, massive changes affecting multiple tropic levels of the pelagic food chain have been observed in Lake Constance. Most remarkably, the invasive sticklebacks, a littoral fish present in Lake Constance since the 1950s, changed its habitat and is now the dominant fish species in the pelagic zone [39], the habitat of the originally dominant whitefish. Its growth, and also (possibly due to stickleback predation on eggs and larval fish) recruitment, declined [39]. The zooplankton community has changed due to the overall increased predation pressure in the pelagic zone. Moreover, despite TP concentrations below 10 μg/L, the abundance of the cyanobacterium *Planktothrix rubescens* recently increased. Although lake managers have successfully combated the eutrophication problem in Lake Constance, the extent to what food web structure modifications due to the massive stickleback invasion of the pelagic zone and/or climate warming are causing these changing environmental conditions is currently unclear; thus likely to alter the ecosystem services that this lake provides[3].

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Her main research is focused on improving the scientific understanding of transport and mixing processes in SWS and the interplay between these processes and the biogeochemistry of the environment using high-level process fieldwork and data analysis, numerical modelling and mathematical scaling.

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