The impact of climate change on Lake Peipsi

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Lake Peipsi is situated between Estonia (European Union) and Russia and is the largest transboundary lake in Europe. Its surface area is 3,555 km^2 and includes three basins. The mean depth is 7.1 m and is typically non-stratified. The largest basin is in the north (Lake Peipsi *sensu stricto*, *s.s*), while the southern basins, Lake Lämmijärv and Lake Pihkva, are considerably smaller and shallower. These southern basins are thus more sensitive to eutrophication and climate warming. Nutrient loading decreased considerably in the late 1980s and early 1990s, but the lake is still eutrophic, and water quality in all three basins has further deteriorated, as evidenced by cyanobacterial blooms and fish kills in summer (Nõges et al., 2020; Tammeorg et al, 2022).

Climate warming will lead to more years of low water levels

In Estonia, air temperature has risen by an average of 0.4 °C per decade since the 1960s, and this trend is also reflected by water temperature in Lake Peipsi (Nõges et al., 2010). According to the worst-case scenario for climate change from the Intergovernmental Panel on Climate Change (IPCC), water temperatures in Europe's lakes will rise by 2-7 °C by 2100, and durations of ice and snow cover will decrease sharply (Nõges et al., 2009). Winter and spring temperatures, in particular, will increase, shortening ice cover by 1 to 2 months by 2070-2100. A dramatic increase in water temperature occurred in 1987–1989 (Nõges & Nõges, 2011), and winter 2019/2020 was the first time that no winter ice cover persisted on Lake Peipsi.

Climate forecasts for 2071-2100 predict a shift in spring high water up to three months earlier than in 1961–1990 (i.e., January). Precipitation and evaporation also depend on air and water temperatures and influence lake water levels, which are pronounced in the relatively shallow Lake Peipsi. The impact of water level changes on shallow lake ecosystems is strong. Water level changes in Peipsi are 1.4 m in annual amplitude, causing up to 57% change in water volume and 26% change in depth (Kliimamuutuse…, 2012). In the hot summer of 2021, water temperatures in Lake Peipsi were among the highest observed in the last 24 years, and water level was significantly lower than average. Natural water level cycles in Lake Peipsi are strongly linked to North Atlantic Oscillation (NAO) index fluctuations. Mild winters (high NAO) lead to higher water levels and high phosphorus inflows from the watershed, which is a large threat for ecosystem health in Lake Peipsi (Nõges &Nõges, 2011).

Climate alterations in shallow lakes at higher latitudes, where the length of the growing season is driven by ice regimes and phenology, are expected to cause increases in phytoplankton abundance and sediment resuspension, decreases in submerged macrophyte biomass and zooplankton size, and enhancement of pelagic primary production at the expense of benthic production (Jeppesen et al. 2014).

Global warming supports the competitiveness of cyanobacteria

Lake Peipsi is well mixed due to wind and waves and does not stratify during summer, in contrast to deep lakes, where nutrients released from sediments can be "locked" under a thermocline (the water level where sharpest temperature, density, and oxygen concentration gradients occur). With low water levels, waves in Lake Peipsi will resuspend bottom sediments, repeatedly releasing accumulated nutrients over time, resulting in proliferation of algae and large plants (Nõges et al., 2008).

Nitrogen inflows from catchment areas and atmospheric deposition into lakes have decreased in some lakes, leading to nitrogen deficiencies (Weyhenmeyer et al., 2007). In these cases, as in Lake Peipsi, the proliferation of atmospheric nitrogen-binding, potentially toxic blue-green algae (cyanobacteria) has been a problem each summer. Temperature dependence is the main factor determining the proportion of atmospheric N_2 fixing species in the phytoplankton community in Lake Peipsi (Nõges et al. 2008), and water temperatures are increasing. Non-N_2-fixing cyanobacterial taxa, such as *Microcystis*, are also common in Lake Peipsi and capable of producing harmful toxins (Panksep et al. 2020).

Nitrates and water temperature are the main environmental variables influencing cyanobacterial community composition and the abundance of toxic genotypes. Historically, algae blooms in Peipsi appeared in late summer, but blue-green algal blooms have more recently been observed in June, or even May. Combined with eutrophication, climate warming shifts phytoplankton communities towards bloom-forming and potentially toxic cyanobacteria (Kosten et al., 2012; Panksep, 2022). If water temperatures in Peipsi *s.s.* exceed, even for a short time, 24 °C, or if mean water temperatures for July, August, or May-September exceed 20.7 °C, 19.3 °C, or 16.5 °C, respectively, then blue-green algae blooms can be expected in Lake Peipsi *s.l.* given current total phosphorus (TP) concentrations (Nõges, 2020). A simplified model considering the effects of only water temperature and TP concentration on the proportion of cyanobacteria in the phytoplankton community (CY%) showed that TP concentration must be decreased 3 mg/m^3 to maintain the current ecological state of the lake and compensate for the 0.3 °C increase in ten-year average summer water temperatures (Nõges & Nõges 2013). When cyanobacteria reach a stable state in shallow eutrophic lakes, climate warming will only enhance their competitiveness and dominance (Nõges, 2020).

Algae blooms may cause fish kills

Low water levels coinciding with elevated water temperatures have repeatedly caused cyanobacterial blooms, which contribute to summer fish kills in Peipsi (Kangur et al., 2005; Kangur et al., 2016). A large biomass of algae produces oxygen during the day via photosynthesis, but cyanobacteria can respire at night to maintain cellular function, and cyanobacterial biomass is constantly 'turning over', with dead cells being decomposed by heterotrophic bacteria, which also consume oxygen. Large fluctuations in oxygen in warm water are difficult conditions for which fish must adapt. In addition, high photosynthesis increases pH, which can result in ammonium, a decomposition product, being transformed into toxic ammonia (Nõges & Nõges, 2011).

The situation for fish is aggravated by cyanobacterial toxins. There are five known cyanobacterial genera in Peipsi that are capable of producing toxins. The most notable species are *Dolichospermum* spp. (*D. crassum*, *D. lemmermannii*), *Aphanizomenon flos-aquae*, *Gloeotrichia* *echinulata*, *Microcystis* (*M. viridis, M. wesenbergii*), and *Planktothrix agardhii* (Panksep, 2022). *Microcystis* cannot fix atmospheric N_2, is pervasive in eutrophic freshwater systems globally, and is dominant among potentially toxic algae in Peipsi (Laugaste et al., 2013; Panksep et al., 2020). *Microcystis* can remain viable under dark and cold winter conditions in lake sediments (Brunberg and Blomqvist, 2002), assimilate P from sediments, and then use this internal storage to help support rapid growth when water temperatures increase and nitrogen (N) is available (Šejnohová and Maršálek, 2012). In late summer, cyanobacteria dominance and *Microcystis* spp. biomass in Peipsi s.s. is supported by internal nutrient loading from sediments. Despite decreased TP loading since 1995, internal nutrient loading from sediments still exceeds external TP loads (Nõges, 2020; Tammeorg et al., 2020). Similar trends have also been shown for other northern, temperate, shallow, eutrophic lakes (Istvánovics et al., 2004; Steinman et al., 2009; Nürnberg & LaZerte, 2016).

Another potentially toxic cyanobacteria, *Gloeotrichia echinulata*, inhabits the moderately eutrophic Peipsi *s.s*., and the presence of this species increases at water temperatures higher than 22 °C and low water levels, but independent of nutrient concentrations (Laugaste et al., 2013). Microcystins were found in all 69 monthly samples collected from Peipsi (2010-2012), but toxin concentrations in integrated water samples were generally less than 1 µg/L (Panksep et al., 2020). In a previous study (Tanner et al., 2005), microcystin concentrations up to 2183 µg/L were measured in nearshore areas, where algae can accumulate due to wind influence. Therefore, even low concentrations of microcystins in open waters may represent a risk for recreational lake users (Panksep et al., 2020).

Structural shifts in fish assemblages took place since 1990s

The Peipsi ecosystem responds to climate change in a variety of ways. Decomposition of abundant organic matter in shallow, warm water leads to siltation of fish spawning grounds and promotes the rapid expansion of reedbeds. Seasonal spawning patterns of organisms also may change; for example, the spawning season of bream (*Abramis brama*) in Estonian water bodies has shifted to about 10 days earlier, but spawning temperature has not changed. In contrast, no shift in the spawning time of roach (*Rutilus rutilus*) has been observed. The resulting difference between spawning times of roach and bream decreased from 22 to 13 days, and the difference in average water temperatures at the onset of spawning changed by about 3 °C (Nõges & Järvet, 2005). Increasing temperature and frequency and intensity of heat waves due to climate change primarily affect cold-water fish in Peipsi, such as Peipsi whitefish (*Coregonus lavaretus maraenoides*), vendace (*Coregonus albula*), burbot (*Lota lota*), and lake (dwarf) smelt (*Osmerus eperlanus* morfa *spirinchus*). These species require relatively clean, oxygen-rich water, and their decreased abundance is due mainly to changes in spawning conditions as a result of climate warming. If water temperature is above 20 °C for extended periods, the number of smelt decreases, and smelt populations have fluctuated strongly in recent years (Tammiksaar & Kangur, 2020). Structural shifts in fish assemblages in Peipsi are marked by domination of Eurasian perch (*Perca fluviatilis*), bream, and pike-perch (*Sander lucioperca*), which all prefer warmer, turbid water. During the last three decades, impacts of climate change on fish composition are greater than the impacts of excessive nutrient load and overfishing. Despite lower proportions of cool-water fish (declined about tenfold since the 1930s), none of these fish species have disappeared from the lake (Tammiksaar & Kangur, 2020).

Water transparency in the lake is decreasing

Dissolved organic matter (DOM), causing a yellowish-brown water colour, enters the lake from the catchment, changes light conditions for photosynthesis, and reduces water transparency, thereby affecting phytoplankton community structure. DOM is also an energy source for the less efficient bacterial food web. DOM concentration in Peipsi depends on large seasonal changes in riverine transport and water levels. The amount of DOM in water is characterized by chemical oxygen demand (COD_{Cr}) and biochemical oxygen demand (BOD_5) measurements. Data from Estonian environmental monitoring since 1992 (Peipsi järve…, 2022) show yearly increases in COD_{Cr} of 0.14-0.19 mg/L and BOD_5 increases 0.03 mg/L. Higher DOM concentrations are also associated with higher CO_2 release into the atmosphere, thus exacerbating the greenhouse effect and climate warming (Nõges & Nõges, 2011). Due to algal blooms and increasing organic matter content, water transparency has decreased on average 12 cm per 10 years in Lake Peipsi *s.s*, 21 cm in Lake Pihkva, and 29 cm in Lake Lämmijärv, since 1992.

The reeds expand

Recent expansion of the common reed (*Phragmites australis*) via colonization of new areas in Peipsi has been the most remarkable consequence of nutrient enrichment, and this expansion will likely continue as a result of climate change (Palmik, 2017). According to cross-border macrophyte monitoring data, the giant reed, *Phragmites altissimus* (Benth.) Mabille, has appeared in abundance on the Russian side of Peipsi in recent years. Its further invasion is likely due to climate warming, increasing nutrient concentrations, and siltation of littoral areas due to organic matter decomposition.

To mitigate the effects of climate changes, eutrophication must be slowed down

Generally, lake ecosystems are resilient, which helps them withstand adverse effects and recover during more favourable periods. However, when certain limits of environmental stressors are exceeded, the system may experience an alternative state of equilibrium. In Peipsi, large changes in water temperature caused shifts between low and high CY% states (P. Nõges 2020). Shifts to another stable state can be triggered by small, incremental changes when critical thresholds in complex ecosystems are exceeded (Scheffer & Carpenter, 2003). In most cases, the new stable state is worse than ecological conditions before the state change. Returning to the previous state may occur only at significantly better conditions than those that drove the initial equilibrium shift.

Climate change is a global phenomenon with effects over large areas, making it difficult to protect Lake Peipsi from these effects. Effects from climate change are broadly associated with human impacts, which are reflected in the rapid eutrophication of lakes due to high nutrient loading. Remediation will require appropriate changes in agriculture and forestry. More stringent management is needed to further limit nutrient loads to the lake, especially treatment of wastewaters in rural areas and improved retention efficiency of agricultural fertilizers.

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