

Effects of Climate Change on Lakes

W F Vincent, Laval University, Quebec City, QC, Canada

© 2009 Elsevier Inc. All rights reserved.

Introduction

Lake ecosystems are vital resources for aquatic wildlife and human needs, and any alteration of their environmental quality and water renewal rates has wide-ranging ecological and societal implications. The increasing accumulation of greenhouse gases in the atmosphere as a result of human activities has begun to affect the structure, functioning, and stability of lake ecosystems throughout the world, and much greater impacts are likely in the future. Current global circulation models predict an increase in air temperatures of several degrees by the end of the twenty-first century, combined with large changes in the regional distribution and intensity of rainfall. These changes will also be accompanied by massive disruption of the cryosphere, the ensemble of ice-containing environments on Earth. These shifts in climate forcing appear to have already begun, and the onset of changes in the physical, chemical, and biological attributes of lakes is affecting their ability to maintain the present-day communities of aquatic plants, animals, and microbes, and their capacity to provide ecosystem services such as safe drinking water and inland fisheries (Figure 1).

Lakes have always been subject to the impacts of climate change, and natural climate variations in the past have been one of the main reasons that lakes are ephemeral features of the landscape. Most of today's lakes are the result of climate amelioration and the retreat of the Pleistocene glaciers some 10 000 years ago, and so most present-day lakes are relatively young. A powerful approach toward understanding the potential impacts of future climate change on lakes is the application of paleolimnological methods in which lake sediment cores are dated and analyzed to infer climate impacts in the past. Most such analyses have been restricted to the time period of the last few 1000 years; however, detailed records of greater than 100 000 years are becoming available from studies of ancient lakes. Studies of present-day lakes of different ages (chronosequences) and across latitudinal gradients are also providing valuable insights into the consequences of climate change. Additional knowledge about climate impacts is coming from modeling and experiments, combined with multi-decade, regional analyses of lakes that are currently experiencing shifts in temperature and precipitation.

Some of the most striking examples of climate impacts to date are from limnological and paleolimnological studies in the polar regions. Global circulation models predict that the fastest and most pronounced warming will be at the highest latitudes because of a variety of feedback processes that amplify warming in these regions. These include the capacity of warm air to store more water vapor, itself a powerful greenhouse gas, and the reduced albedo (reflection of sunlight) as a result of the melting of snow and ice, leaving more solar energy to be available for heating. Some of the immediate impacts of climate change on high-latitude lakes include loss of perennial ice cover, increasing duration of open water conditions, increasing water temperatures, stronger water column stratification and shifts in water balance, in some cases leading to complete drainage or drying up of the waterbodies.

Changes in air temperature and precipitation have direct effects on the physical, chemical, and biological characteristics of lakes, and they also operate on lakes indirectly via modifications in the surrounding watershed, e.g., through shifts in hydrological flow pathways, landscape weathering, catchment erosion, soil properties, and vegetation. Of particular interest to limnologists (lake and river scientists) are the interactions between variables, the feedback effects that accelerate or dampen environmental change, and threshold effects by which lakes may abruptly shift from one environmental state to another.

Physical Effects of Climate Change

Basin Integrity

Changes in the precipitation regime that accompany climate change have the potential to cause shifts in the connectivity of lakes (with biological implications, e.g., for migratory fish species), as well as in erosion rates that could affect the inflow and outflow dynamics of lakes. The latter effects are particularly conspicuous in the tundra permafrost. Many thaw ponds (also called thermokarst ponds) on the Siberian and Alaska tundra are draining as a result of increased melting of the permafrost, while certain thaw ponds further south in discontinuous, subarctic permafrost have begun to expand as a result of the differential melting of such

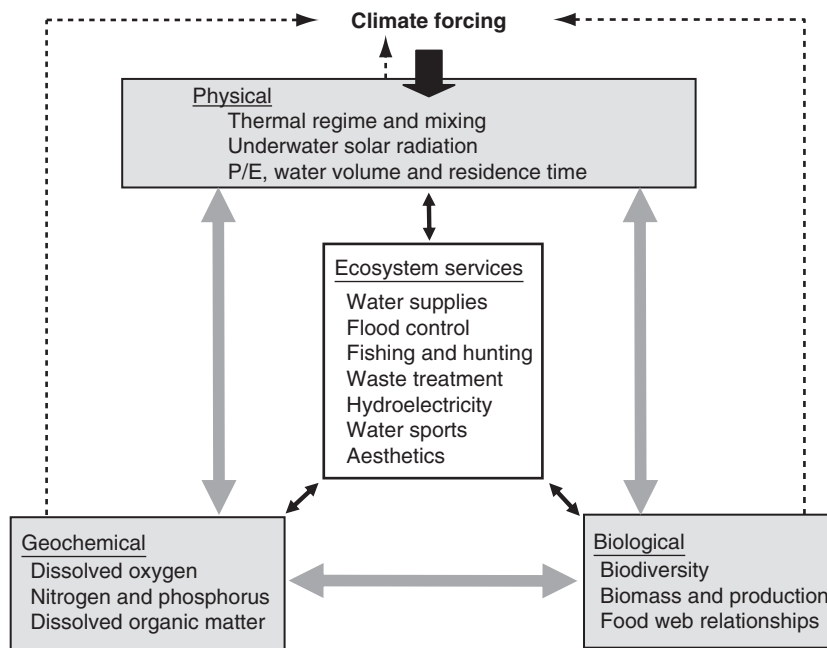


Figure 1 Changes in climate forcing affect the physical environment of lake ecosystems and thereby alter their chemical and biological properties. These changes affect the capacity of lakes to provide ecosystem services. P/E, precipitation to evaporation ratio. Dotted lines indicate positive feedback effects, e.g., via decreased ice cover or the release of greenhouse gases from lakes into the atmosphere.

soils. Ice-dammed lakes, e.g., those behind thick ice shelves (epishelf lakes), ice-jams on rivers, glacial dams, and behind coastal sea ice barriers (stamukhi lakes) are prone to complete loss because of climate-dependent ice fracturing and collapse.

Water Balance

Shifts in precipitation relative to evaporation (the P/E ratio) cause changes in the water budget and hydraulic residence time of lakes, as well as in their depth and areal extent. Ponds and wetlands are especially vulnerable to changes in P/E because of their shallow depths and large surface to volume ratio. For example, some rock basin ponds in the Canadian High Arctic have been drying up as a result of climate warming in the region, perhaps for the first time in millennia. Even large, shallow lakes can undergo major climate-driven fluctuations and loss. Lake Chad in north-western Africa is less than 7-m deep and has responded greatly to changes in climate over the last few decades. From the 1960s onward it experienced a precipitous decline in rainfall, and this has led to a major contraction in lake area, from 25 000 km² in the early 1960s to 1350 km² in the 1990s. This climate effect has been compounded by the increasing need to irrigate farmland during these drought conditions, and human water use appears to account for about half of the decrease in lake surface area.

Glaciers in many parts of the world are undergoing accelerated retreat, and glacial fed lakes and reservoirs are therefore particularly vulnerable to changes in their inflow regime. For example, the Chinese Academy of Sciences estimates that by 2050, up to 64% of China's glaciers may have disappeared, with serious consequences for the estimated 300 million people who live in China's arid west and who depend upon this vital water supply. At Lake Biwa, Japan, the reduced flow from snowpack in the surrounding mountains is thought to be a mechanism reducing cold underflows that play an important role in recharging the bottom waters of the lake with oxygen.

At the other extreme, global change may affect the frequency of extreme storm events and flooding in some regions. There is evidence that warming of the sea surface is resulting in an increasing intensity and duration of storms, and certain coastal lakes may therefore be exposed to increased flooding and wave erosion of their shorelines, as well as increased hydraulic flushing and storm-induced mixing.

Ice Cover

Many lakes in the north temperate zone are covered by ice and snow through much of the year. Climate warming is already showing an effect on such lakes by causing earlier dates of ice break-up, and later dates of freeze-up. The 2007 Intergovernmental Panel

on Climate Change report noted that for all available lake and river ice data over the last 150 years, the break-up date had become (mean \pm 2SD) 6.5 ± 1.2 days earlier per century, while the freeze-up date had occurred 5.8 ± 1.6 days later per century. At polar latitudes, the earlier occurrence of rain instead of snow is likely to hasten the ice melting process, which is also affected by changes in the wind field. Loss of snow and ice cover results in a major shift in the underwater irradiance regime, with increased solar energy for radiative heating of the water column, increased availability of photosynthetically available radiation (PAR) for primary production, and increased exposure to ultraviolet radiation (UVR). The latter will accelerate photobiological and photochemical processes, with a variety of positive and negative effects on ecosystem structure and productivity. Modeling analyses show that loss of ice cover can have orders of magnitude larger effects on underwater UVR exposure than does moderate ozone depletion in the stratosphere. The prolonged loss of ice cover also allows a longer period of wind-induced mixing of the surface waters of lakes, and may change the transport pathways and fate of inflows that during ice conditions are retained immediately beneath the ice.

Temperature and Stratification

Warmer air temperatures result in warmer surface waters via conduction, although this may be dampened in part by increased evaporation rates. For north temperate lakes, the increased duration of ice-free conditions will allow increased warming of the surface waters by sensible heat transfer (conduction) and by radiative transfer (penetration of solar radiation into the water column). These effects in turn cause changes in the density structure of lakes, with a layer of warmer, lighter water at the surface that prevents the transport of heat via turbulent mixing to deeper parts of the lake. This retention of heat in the upper waters acts as a positive feedback mechanism, and with increasing heating the thermal stratification becomes stronger and more resistant to wind-induced mixing. By trapping more heat in the surface-mixed layer, less is available for heating the lower column, and deep waters can become cooler as a result of climate warming. An example of the strong effects of climate change on water temperature is the current trend in Lake Superior, Canada–USA. The summer surface water temperatures of this lake increased by 2.5°C over the period 1979–2006, well in excess of the air temperature increase over the same period. This has been primarily attributed to earlier ice break-up and the earlier onset of stratification and

warming each year. This differential effect is not apparent in tropical lakes that lack winter ice cover, and such waters appear to be more closely tracking the regional trend in air temperatures.

At high latitudes, increased warming may lead to a complete change in the stratification and mixing regime. Deep polar lakes are usually cold monomictic; that is, they remain stratified under the ice through most of the year, and then mix at temperatures less than 3.98°C (the temperature of the maximum density of water) throughout their summer period of open water conditions. However, if the water temperatures warm above 3.98°C in summer, the lake will become stratified, and therefore dimictic, with periods of mixing before and after this summer period. This shift from cold monomixis to dimixis is a critical threshold that allows the retention of heat in the surface waters and it may lead to a higher biological productivity. Paleolimnological analyses have suggested that such transitions occurred in certain Finnish lakes over the last 200 years, and that the resultant increased productivity caused biological shifts toward a cladoceran zooplankton community.

Chemical Effects of Climate Change

In-Lake Effects

The hydraulic residence time of a lake (the time required to completely replace all water in a lake by its river, groundwater and rainfall inputs) affects the chemical composition of lake waters by controlling the time available for biogeochemical and photochemical processes to operate, the extent of accumulation and loss of dissolved and particulate materials, and the duration of biogeochemical interactions with the lake sediments and littoral zone. In lakes that experience anoxic bottom water conditions and nutrient release from the sediments, a prolonged residence time caused by reduced precipitation and inflows can result in increased phosphorus accumulation (internal phosphorus loading) and eutrophication. Conversely, in regions that experience increased precipitation and water flow, the increased flushing of nutrients and phytoplankton may result in reduced algal production. This latter effect may be offset by increased catchment erosion and transport of nutrient-rich soils into the lake if storm events become more frequent and severe.

The stronger and more prolonged stratification of lake waters is also likely to lead to more pronounced gradients in chemical variables down through the water column. In enriched lakes, this may trigger the shift from oxygenated to anoxic conditions in the bottom waters, and crossing this threshold is typically

accompanied by major upshifts in the concentrations of algal nutrients, including available phosphorus, and in various toxic compounds, notably hydrogen sulfide (H₂S). Anoxia can also lead to increased nitrogen losses from the ecosystem by denitrification, the bacterial process that converts nitrate to nitrogen gas.

Catchment Effects

Climate affects many landscape properties, including vegetation and soils, which in turn exert a strong influence on water quality and quantity in the receiving lake basin. Increased temperatures and precipitation may lead to increased rock weathering, thereby affecting solute composition and concentrations in the runoff. Long-term studies at Toolik Lake Alaska have detected a doubling of alkalinity over time, and this may be the result of climate-dependent increases in active layer depth in the permafrost that have exposed new soil material to weathering. Changes in precipitation may affect the magnitude of overland versus subterranean flow, thereby changing the nature and quantity of nutrient, major ion, and dissolved organic carbon (DOC) inputs from different soil horizons to lakes. DOC loading is particularly responsive to climate change, through the leaching and erosion of soils (compounded by permafrost melting in the Polar Regions), changes in microbial transformation rates of particulate and dissolved organics, and through changes in catchment vegetation. The effects of the latter are apparent from high-latitude paleolimnological studies, which indicate an increase in DOC concentrations associated with colonization of the catchments by woody shrubs and trees during periods of climate warming. The increased transport of the colored fraction of this DOC (colored dissolved organic matter, CDOM) can have both positive and negative effects on aquatic photosynthesis, by shading cells against damaging UVR and by absorbing PAR that would otherwise be available for photosynthesis.

Biological Effects of Climate Change

The biological responses to the physical and chemical changes noted here involve multiple interactions, feedbacks and complex nonlinear responses that are not possible to fully predict on the basis of current knowledge. However, a great variety of direct and indirect effects can be identified as some of the likely impact pathways of ongoing climate change. These operate at multiple scales, from changes in whole ecosystem structure and dynamics, down to physiological and

molecular responses at the individual and cellular level that in turn feed back into overall ecosystem dynamics.

Ecosystem Integrity

At the broadest scale, climate change has the potential to radically alter the physical structure of lake ecosystems, and thereby cause the extinction or alteration of aquatic biota. The melting of the Siberian permafrost is one of the most striking examples, where 11% of thaw ponds in a large study area have recently drained and been lost, thereby eliminating the habitat for aquatic biological communities. The contraction of large shallow lakes also results in major habitat loss, and even deep lakes may lose important ecological features as a result of relatively small fluctuations in water level. For example, the coastal wetlands of the North American Great Lakes are important for migratory birds, and the majority of species of fish in the region depend on these littoral and supralittoral environments for reproduction. Small changes in lake levels as a result of shifting water balance make these environments especially vulnerable to climate change. Changes in the connectivity between aquatic habitats as a result of rising or falling water levels will also influence the species composition of aquatic biota, especially fish communities.

Vertical Habitat Structure

Changes in ice cover, stratification, and mixing, and thereby the vertical gradients in lake properties, will have far reaching effects on pelagic communities and production. The associated changes in light and nutrients will affect phytoplankton production, and therefore the availability of food to high trophic levels. For some high-latitude systems, decreased ice cover and stronger stratification may allow for increased irradiance supply and rates of primary production. For example, the strong climate warming at Signy Island in the maritime Antarctic has been accompanied by increased overwintering phytoplankton biomass. This was attributed to reductions in lake snow and ice cover and improved light conditions for summer growth, as well as increased nutrient inputs following deglaciation of the catchments. In contrast to this response, simulation analyses for the North American Great Lakes have shown negative effects of projected climate change. Earlier summer stratification results in a decreased period of mixing of nutrients from the sediments and from deeper waters into the euphotic zone, and therefore increased nutrient limitation of algal growth. These effects are compounded by

projected increases in cloud cover, which would reduce the availability of light for photosynthesis.

In Lake Tanganyika, the present trend of climate warming, decreased wind speeds, and increased water column stability appears to have resulted in decreased nutrient supply to the euphotic zone by mixing, resulting in a 20% decrease in phytoplankton production. The consequences of this effect are serious given that a large portion of animal protein available to the surrounding human populations is derived from the pelagic fishery, and this decrease in algal photosynthetic rates is estimated to have caused a 30% drop in fish yield.

A prolonged ice-free period in northern, temperate lakes, and therefore a decreased duration of winter ice cover, may prove to be advantageous for some fish species. In certain locations (e.g., small, enriched lakes in southern Canada and northern United States), prolonged winter stratification leads to complete oxygen depletion of the hypolimnion, resulting in the “winter kill” of fish stocks, and such effects may lessen as the period of ice cover contracts.

Photosynthetic Communities

Changes in light and nutrient availability that accompany climate change will also have a qualitative effect on species composition and diversity at the primary producer level, which in turn may impact on higher trophic levels. Paleolimnological studies have shown that the diatom composition of the periphyton and phytoplankton in ponds at many sites in the circumpolar Arctic has changed markedly over the last 150 years, consistent with a strong response to decreased ice cover and possibly increased nutrient supply. In ancient Lake Baikal, there is evidence that endemic, cold-dwelling diatom taxa that support the current food-web will be replaced by faster growing, nondiatom species, including picophytoplankton. Changes in lake level are likely to affect the species composition of aquatic macrophyte communities in the littoral zone of lakes, with implications for the birds, fish, and other biota that depend on these plants.

A major climate change concern at temperate latitudes is the prospect of a shift in phytoplankton species composition toward dominance by species of cyanobacteria that form noxious blooms. These organisms create many water quality problems in lakes and reservoirs, including the release of taste and odor compounds, the production of various toxins, and the overproduction of biomass that clogs water filters, disrupts zooplankton feeding, and causes oxygen depletion. Bloom-forming cyanobacteria are likely to be favored in a warming climate by several mechanisms. First, their temperature for

optimum growth tends to be high (25°C or above), and warmer conditions will favor their more rapid accumulation and dominance. Second, these species can regulate their position in stable water columns by way of gas vacuoles that allow them to sink or rise to the optimal depths for photosynthesis or nutrient uptake. As noted above, future climate change scenarios predict increased stratification and water column stability that would favor this strategy. Third, a warmer climate may lead to increased anoxia and internal phosphorus loading (perhaps also in external loading in some circumstances), and bloom-forming cyanobacteria tend to become increasingly prevalent with increasing degree of phosphorus enrichment. Finally, a highly toxic species from tropical and subtropical regions, *Cylindrospermopsis raciborskii*, has been increasingly observed in temperate lakes. This apparent invasion has been ascribed to climate change, with warmer temperatures favoring the early germination of its resting spores (akinetes).

Fish Communities and Migration

Many fish species are sensitive to even small changes in the temperature of their surroundings, and the warming trend associated with climate change is likely to cause a shift in the geographic distribution of many taxa. Cold water species such as walleye and trout may be driven to extinction in some lake waters because their thermal tolerance is exceeded, while other species may be able to colonize new habitats as a result of warmer conditions. In Toolik Lake, Alaska, a bioenergetics analysis showed that a 3°C rise in summer lake water temperature could cause the young-of-the-year lake trout to consume eight times more food that is currently necessary to maintain their condition, which greatly exceeds the present food availability. In Ontario lakes, the northern range of smallmouth bass is currently limited by temperature because the length of the growing season determines the winter survival of the young-of-the-year. Under a climate change scenario, this species could invade some additional 25 000 northern lakes, and because of its strongly negative effects on other fish, such invasions would likely cause the extirpation from these lakes of four native cyprinid species.

Climate change may affect the migratory behavior of some fish species. Arctic char for example migrate from lakes to the sea where the higher food availability allows them to grow to a large size. If arctic lakes become more productive as a result of climate change, then char migrations are projected to decrease, and the resultant lake char would be of smaller size and less suitable as a food resource for northern aboriginal communities.

Microbial Processes

Many lakes are net heterotrophic, with the respiration (R) of organic materials derived from autochthonous (within the lake) and allochthonous (outside the lake) sources exceeding photosynthesis (P). Heterotrophic microbial activity is likely to be enhanced in a warmer climate because of the direct physiological effects of temperature, and in some environments by the increased availability of organic carbon and nutrients, e.g., from increased catchment runoff. Photosynthesis on the other hand is strongly regulated by light availability and may be less responsive to the temperature increase, or even negatively affected via the mechanisms noted earlier. This combination of effects would exacerbate the negative P/R balance in lakes, and may result in lakes becoming even greater net sources of CO₂ to the atmosphere. Production of the more powerful greenhouse gas methane will be favored by prolonged anoxia in some environments, and in high northern latitudes by its release from permafrost surrounding thaw ponds. The production and release of greenhouse gases from arctic thaw lakes has been identified as a potentially important feedback mechanism that will accelerate climate warming.

See also: Aquatic Insects – Ecology, Feeding, and Life History; Cyanobacteria; Eutrophication; Fish, Populations; Littoral Zone; Reservoirs.

Further Reading

- Austin JA and Colman SM (2007) Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. *Geophysical Research Letters* 34: L06604, doi:10.1029/2006GL029021.
- Brooks AS and Zastrow JC (2002) The potential influence of climate change on offshore primary production in Lake Michigan. *Journal of Great Lakes Research* 28: 597–607.
- Coe MT and Foley JA (2001) Human and natural impacts on the water resources of the Lake Chad basin. *Journal of Geophysical Research Atmospheres* 106(D4): 3349–3356.
- Jackson DA and Mandrak NE (2002) Changing fish biodiversity: Predicting the loss of cyprinid biodiversity due to global climate change. In: McGinn NA (ed.) *Fisheries in a Changing Climate*, pp. 89–98. Bethesda, Maryland, USA: American Fisheries Society.
- Korhola A, Sorvari S, Rautio M, et al. (2002) A multi-proxy analysis of climate impacts on the recent development of subarctic Lake Sannajaärvi in Finnish Lapland. *Journal of Paleolimnology* 28: 59–77.
- Lemke P, Ren J, Alley RB, et al. (2007) Observations: Changes in snow, ice and frozen ground. In: Solomon S, Qin D, Manning M, et al. (eds.) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
- Mackay AW, Ryves DB, Morley DW, Jewson DH, and Rioual P (2006) Assessing the vulnerability of endemic diatom species in Lake Baikal to predicted future climate change: a multivariate approach. *Global Change Biology* 12: 2297–2315. doi: 10.1111/j.1365-2486.2006.01270.x.
- McDonald ME, Herschey AE, and Miller MC (1996) Global warming impacts on lake trout in Arctic lakes. *Limnology and Oceanography* 41: 1102–1108.
- McKnight D, Brakke DE, and Mulholland PJ (eds.) (1996) Freshwater ecosystems and climate change in North America. *Limnology and Oceanography* 41(special issue): 815–1149.
- Mueller DR, Vincent WF, and Jeffries MO (2003) Break-up of the largest Arctic ice shelf and associated loss of an epishelf lake. *Geophysical Research Letters* 30: 2031 doi:10.1029/2003GL017931.
- O'Reilly CM, Alin SR, Plisnier PD, Cohen AS, and McKee BA (2003) Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature* 424: 766–768.
- Prowse TD, Wrona FJ, Reist JD, Hobbie JE, Lévesque LMJ, and Vincent WF (2006) Climate change effects on hydroecology of arctic freshwater ecosystems. *Ambio* 35: 347–358.
- Quayle WC, Peck LS, Peat H, Ellis-Evans JC, and Harrigan PR (2002) Extreme responses to climate change in Antarctic lakes. *Science* 295: 645.
- Quesada A, Vincent WF, Kaup E, et al. (2006) Landscape control of high latitude lakes in a changing climate. In: Bergstrom D, Convey P, and Huiskes A (eds.) *Trends in Antarctic Terrestrial and Limnetic Ecosystems*, pp. 221–252. Dordrecht: Springer.
- Schindler DW and Smol JP (2006) Cumulative effects of climate warming and other human activities on freshwaters of arctic and subarctic North America. *Ambio* 35: 160–168.
- Smol JP and Douglas MSV (2007) Crossing the final ecological threshold in high arctic ponds. *Proceedings of the National Academy of Sciences USA* 104: 12395–12397.
- Smith LC, Sheng Y, MacDonald GM, and Hinzman LD (2005) Disappearing Arctic lakes. *Science* 308: 1429. doi: 10.1126/science.1108142.
- Vincent WF, Rautio M, and Pienitz R (2007) Climate control of underwater UV exposure in polar and alpine aquatic ecosystems. In: Orbaek JB, Kallenborn R, Tombre I, Hegseth E, Falk-Petersen A, and Hoel AH (eds.) *Arctic Alpine Ecosystems and People in a Changing Environment*, pp. 227–249. Berlin: Springer.
- Walter KM, Zimov SA, Chanton JP, Verbyla D, and Chapin FS (2006) Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature* 443: 71–75.
- Wiedner C, Rucker J, Brüggemann R, and Nixdorf B (2007) Climate change affects timing and size of populations of an invasive cyanobacterium in temperate regions. *Oecologia* 152: 473–484. doi: 10.1007/s00442-007-0683-5.