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Climate Impacts on Arctic Lake Ecosystems

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2.1 Introduction

Lakes and ponds are major features of the Arctic landscape, and span a diverse range of environmental conditions, from dilute, glacier-fed meltwaters to nutrient-rich tundra ponds and perennially ice-capped, stratified lakes with anoxic bottom waters. According to the global lakes and wetlands data base, the majority of the world's lakes with surface areas in the range 0.1 to 50 km^2 occur above latitude 45.5 °N (Lehner and Döll 2004), and 73% of these lie within the permafrost zone (Smith, Sheng, and MacDonald 2007). The most abundant freshwater ecosystems in the north are small and shallow; however, their total area and volume is substantial (Rautio *et al*. 2011 and references therein), and collectively they may influence biogeochemical dynamics at a global scale (Walter *et al*., 2006). In parts of the Arctic, these numerous shallow waters can account for up to 90% of the total land surface area (Pienitz, Doran, and Lamoureux 2008).

Thermokarst processes (permafrost thawing and erosion) play an important role in many of these lake systems throughout the Arctic, and over a wide range of soil and climate regimes (e.g., Jørgenson and Osterkamp 2005; Jones *et al*. 2011). Grosse *et al*. (2011) estimate that more than 61 000 lakes $>0.1\,\text{km}^2$ with a total lake area of

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more than 200 000 km^2 occur in the circumarctic region in permafrost with high to moderate ground ice content, and are likely to be thermokarst lakes. Using correction factors to account for smaller lakes too, the total thermokarst lake area is likely to be in the range 250 000–380 000 km^2. Beringian thermokarst lakes, defined here as located within the largely unglaciated region from the Mackenzie River, Canada, west to the Lena River, Russia, constitute about 30% (75 000–114 000 km^2) of the total pan-Arctic thermokarst lake area.

Large lakes >500 km^2 are also found throughout the circumpolar Arctic. One of the largest above the Arctic Circle is Lake Taymyr (lat. 74.1 °N, 4560 km^2, average depth of 2.5 m; Robarts *et al*. 1999) in northern Russia. Large, deep lakes in the Canadian North include Great Bear Lake (lat. 65–67 °N, area of 114 717 km^2, maximum depth of 446 m), Nettilling Lake (66.5 °N, 5066 km^2, 132 m; Oliver 1964), Amudjuak Lake (64 °N, 3115 km^2, maximum depth unknown), Lake Hazen (81.8 °N, 542 km^2, 267 m; Köck *et al*. 2012); Lac à l'Eau Claire (Clearwater Lake; 56.2 °N, 1239 km^2, 178 m; Milot-Roy and Vincent 1994), and Pingualuit Crater Lake (61.5 °N, 9 km^2, 267 m). Like the latter two lakes, El'gygytgyn Lake (67.5°N, 110 km^2, 174 m), in Siberia, also lies in a meteoritic impact crater, and has attracted considerable paleolimnological interest (Melles *et al*. 2007).

Despite this great limnological diversity, northern lakes also have a number of features in common (Vincent, Hobbie, and Laybourn-Parry 2008). Firstly, as a result of their high latitude location, these ecosystems experience extreme seasonal variations in incident solar radiation. Above the Arctic Circle, this translates into three months of continuous winter darkness and three months of continuous light in summer, which in turn give rise to high-amplitude fluctuations in primary production and all related food-web processes. Secondly, these seasonal effects are compounded by snow and ice, which cover these lakes for at least six months each year. For a small and decreasing number of extreme Arctic lakes, thick perennial ice persists throughout the year. The solid ice cap over the lakes influences all aspects of their limnology, including the availability of light for photosynthesis, rates of gas exchange with the atmosphere, interactions with the surrounding watershed, and their stratification and mixing regimes. Thirdly, persistent low temperatures exert a strong control on all physiological and ecological processes within high latitude lakes, and also in their surrounding catchments. This effect on chemical and biochemical reaction rates contributes to a fourth feature—the slow rates of soil-weathering processes in Arctic catchments. These lakes thereby receive only sparse inputs of nutrients, which maintain their water columns in an oligotrophic status of low algal biomass. As a result of all of these constraints, and exacerbated by their remoteness from temperate latitudes, an additional feature of northern ecosystems is their low biodiversity of aquatic plants and animals, many of which are specialized towards extreme cold, low energy supply, and oligotrophy.

There is now compelling evidence of rising atmospheric temperatures at a planetary scale, and the greatest amplitude of change has been recorded at high northern latitudes (IPCC 2007). While global average annual air temperatures have increased by around 0.4 °C since the early 1990s, the North American Arctic over the same period has warmed by 2.1 °C (ACIA 2005). These observations are consistent with results from global circulation models, which predict that the most severe ongoing warming will be in the Arctic, to temperatures up to 8 °C above present values by the end of the twenty-first century. This magnitude of change will have drastic effects on Arctic

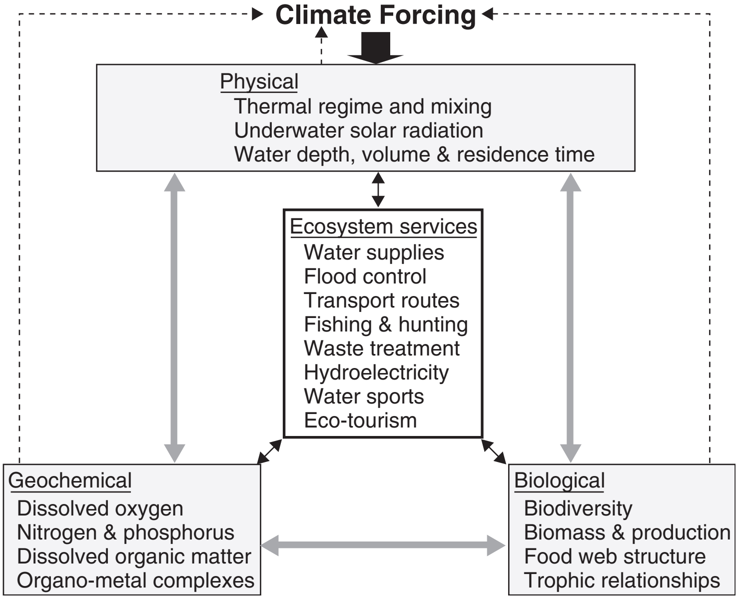

Figure 2.1 Impacts of climate change on northern lakes and their ecosystem services. Dotted lines indicate positive feedback effects. Modified from Vincent (2009).

freshwater ecosystems, given that many of their limnological features are dependent on prolonged sub-zero air temperatures each year.

The aim of the present review is to summarize the primary mechanisms of climate-induced change in northern high latitude lakes (Figure 2.1). We first examine the direct physical impacts of climate warming, ranging from loss of ice cover to complete loss of freshwater ecosystems by drainage or evaporation. We then review the biogeochemical mechanisms of change including shifts in organic matter loading and de-oxygenation, the formation and release of microbial methane from thermokarst lakes associated with permafrost thaw, the biological response mechanisms including loss of cold-adapted taxa and arrival of invasive species, and the local anthropogenic effects accompanying climate change. We conclude this review with a brief analysis of strategies to reduce the impacts of climate warming on northern lakes and their vital ecosystem services.

2.2 Physical impacts of climate change

The circumpolar Arctic has experienced large spatial variations in climate in the past, and similarly large variations in the physical impact of climate on lakes are to be expected among different sectors of the North. There is paleolimnological evidence of such variability, with shifts in diatom community structure in many lakes over the last century consistent with climate change, but to differing extents among sites and sectors (Smol *et al*. 2005). The climate and lake characteristics of northern Québec (Nunavik)-Labrador (Nunatsiavut) region in the low Arctic appear to have been especially stable for hundreds of years, perhaps longer (Pienitz *et al*. 2004), but from the early 1990s onwards have been undergoing rapid change (Bhiry *et al*. 2011).

The most drastic limnological impact of climate change is the complete loss of certain aquatic ecosystems. This may occur through geomorphological effects such as the breaching of an ice dam, or erosion of permafrost soils. For example, many epishelf lakes (freshwater lakes underlain by seawater and dammed by ice shelves) occurred along the northern coast of Ellesmere Island in the Canadian High Arctic in the early twentieth century (Veillette *et al.* 2008), but the warming and break-up of the northern ice shelves has resulted in their drainage and loss (e.g., Mueller *et al.* 2003), and now only one such ecosystem is known to occur in the Arctic (Veillette *et al.* 2011a). Thermokarst lakes on permafrost soils are expanding in size and number in certain parts of the Arctic (e.g., Payette *et al.* 2004), but at other locations they have been observed to suddenly drain as a result of thawing and erosion (Smith *et al.* 2005; Jones *et al.* 2011). Thaw lakes appear to have natural cycles of expansion, erosion, drainage, and reformation (Kessler, Plug, and Walter Anthony 2012; van Huissteden *et al.* 2011), which may accelerate under warmer climate conditions.

Shifts in water balance will also give rise to major changes in lake extent and persistence. Over the past 50 years there has been an overall trend of increasing snow precipitation in the Arctic, but with large spatial variability in current and projected future trends (Brown and Mote 2009). Global climate models predict that there will continue to be large differences in precipitation trends among regions, with decreases in snow water equivalent over Scandinavia and Alaska, no change over the boreal forest region, and increased precipitation over northern Siberia (by 15–30%) and the Canadian Arctic Archipelago (Brown and Mote 2009). However, these trends are offset by warmer temperatures in summer and decreased duration of ice cover, both of which favor water loss by evaporation. Lakes at several locations appear to have shifted to a negative net precipitation-evaporation balance, and for some pond waters, this has led to complete drying up, perhaps for the first time in millennia (Smol and Douglas 2007). Many high Arctic wetlands are dependent on perennial snow banks and glaciers, and are vulnerable to the rapid warming of the cryosphere. The potential changes in northern wetlands and lake extent as a result of increased evaporation and potential drainage are a major source of uncertainty for models of methane release from Arctic permafrost (Koven *et al.* 2011).

The loss of ice cover, or increased duration of ice-free conditions has wide-ranging effects on the limnology of northern waters (Vincent, Hobbie, and Layboum-Parry 2008; Mueller *et al.* 2009; Prowse *et al.* 2011; see also Chapter 3). The increased availability of light for photosynthesis may enhance the annual rate of primary production, and may also result in a vertical extension of the active photosynthetic communities to deeper parts of the water column, thereby allowing a greater proportion of the total volume of the lake to be available for net primary production. An example of this latter effect is given in Antoniades *et al.* (2009) who concluded that the deep layer of photosynthetic sulfur bacteria in high Arctic meromictic Lake A appeared to be more extensive and active under conditions of decreased snow and ice cover. The absence of ice also allows wind-induced mixing that may entrain nutrients from deeper in the water column. For example, during 2008, an unusually warm year, Lake A lost its perennial ice cover (Vincent *et al.* 2009), and the halocline slightly deepened, bringing up nutrients that stimulated phytoplankton production at the base of the mixolimnion (Veillette *et al.* 2011b). Loss of ice may also result in changes in algal community structure, for example an increase in the ratio of planktonic to benthic diatom taxa (Smol 1988).

For phytoplankton communities in the surface waters of Arctic lakes, loss of snow and ice cover may also result in damage by bright ultraviolet radiation (Gareis, Lesack, and Bothwell 2010). Exposure to UV radiation has multiple impacts on phytoplankton cells and communities, although these may be offset by a variety of photoprotection and repair strategies (Vincent and Roy 1993). Model calculations indicate that loss of ice and its overlying snow can have a greater effect on increasing underwater UV exposure than stratospheric ozone depletion (Vincent, Rautio, and Pienitz 2007). In a perennially ice-covered lake in the High Arctic, for example, experimental removal of snow resulted in a thirteenfold increase in the photosynthetically active radiation (PAR) beneath the ice, but also a sixteenfold increase in biological UV exposure (Belzile *et al.* 2001).

Earlier breakup dates for ice cover and increased duration of exposure of the water column to incident sunlight will also result in radiative heating, and the water columns will thereby have more time to heat up. This is particularly important for high latitude lakes where temperatures are often at or below the 3.98 °C critical threshold of maximum density of water. Even modest warming can shift a lake that stratifies during winter but not summer (cold monomictic) to one that stratifies during both seasons, with periods of mixing in fall and spring (dimictic). We have observed, for example, that Char Lake, the classic cold monomictic lake studied during the International Biological Program in the 1970s (Schindler *et al.* 1974) has recently warmed above the maximum density threshold, and is now thermally stratified in summer. For deep windswept lakes that are only weakly stratified and readily mixed by storms during summer (for instance, the western basin of Clearwater Lake, Nunavik, Canada; Milot-Roy and Vincent 1994), the nonlinear decrease in water density with warming may result in less frequent episodes of summer mixing, or even a shift from polymixis to dimixis. Shorter periods of mixing in spring and autumn can be expected in thermokarst ponds, which already have stratified waters for a large portion of the year (Laurion *et al.* 2010).

Increased stratification has a variety of effects, including positive feedbacks via warming of the surface layer, possible increases in phytoplankton and zooplankton growth rates, and an increased propensity to deep water oxygen depletion. Such changes in stratification and mixing have been inferred from fossil diatom records in Lapland, which suggest an increase in biological productivity and a shift in the zooplankton community toward cladocerans (Sorvari, Korhola, and Thompson 2002). Such shifts can also potentially result in the increased retention of contaminants within Arctic food webs (Chételat and Amyot 2009). Additionally, warming can impair coldwater fish oxythermal habitats, especially when combined with eutrophication (Jacobson, Stefan, and Pereira 2010).

2.3 Biogeochemical impacts of climate change

Climate warming affects the biogeochemistry of lake ecosystems, directly by increasing the reaction rates of all chemical and biochemical processes, and indirectly by a variety of effects on water column and catchment processes. As noted above, one such example of the latter is the depletion of hypolimnetic oxygen under conditions of increased stratification, and less exchange of gases between the bottom waters of the lake and the atmosphere during stratified periods, with peak gas emissions at spring melt and autumnal overturn (Striegl *et al.* 2001; Kortelainen *et al.* 2006). Under extreme conditions, and exacerbated by increased nutrient and organic carbon inputs (see below), these bottom waters may be driven to anoxia. This in turn may result in the liberation of inorganic phosphorus, iron and manganese from the sediments, thereby stimulating additional biological production (Wetzel 2001).

The warming of Arctic catchments will have a variety of effects. Firstly, increased thawing of the permafrost results in increased erosion and transport of tundra soils and organic carbon to thermokarst lakes, and thereby increases the microbial production of carbon dioxide and methane (Walter *et al.* 2006; Mazéas, von Fischer, and Rhew 2009; Laurion *et al.* 2010). This source of organic matter results in the formation and release of methane with radiocarbon ages ranging from modern to several thousand years old, reflecting the age of the Holocene soils decomposing in near surface lake sediments (Walter *et al.* 2008). Of greater concern is the mobilization of hundreds of teragrams of permafrost organic carbon when permafrost thaws underneath lakes (see also Chapter 1). The zone of thaw beneath a lake, called a talik or thaw bulb, is an anaerobic environment in which microbes readily decompose organic matter that was locked up in permafrost for tens of thousands of years (Figure 2.2). This thawing results in the rapid production and emission of methane and carbon dioxide predominately in the form of ebullition (bubbling) and with radiocarbon ages of 30 000–43 000 years (Walter *et al.* 2006, 2008). Given the tremendous size of the permafrost carbon pool (~1700 petagrams; Tarnocai *et al.* 2009), which is more than twice the size of the atmospheric carbon pool, permafrost thaw associated with thermokarst lake cycles could result in the release of more than 50 000 teragrams of ^{14}C-depleted methane in the future (Walter, Smith, and Chapin 2007; Walter Anthony 2009). This is more than ten times the amount of methane in the current atmosphere. The release of this potent greenhouse gas from thermokarst lakes sets up a positive feedback cycle in which methane causes global climate warming, which in turn causes permafrost to thaw, and more methane to be formed and released.

Secondly, thawing of the tundra may also release and mobilize inorganic nutrients (see also Chapter 1), previously immobilized in deep permafrost soil horizons, which then stimulate biogeochemical processes in the receiving waters. Thirdly, there is increasing evidence that Arctic warming is leading to increased plant growth across the tundra, with the northward expansion of shrubs and trees (Tape, Sturm, and Racine 2006; Hudson and Henry 2009; Grant *et al.* 2011). Snow over these erect plants has a much lower albedo than snow on tundra, and their expansion over northern landscapes is likely to cause a positive feedback of increased heating, as well as increased soil weathering during higher temperatures, the expansion of root biomass, and increased microbial activity in the rhizosphere (Vincent, Hobbie, and Laybourn-Parry 2008). The appearance and densification of shrubs and trees in the landscape can also result in a substantial increase in terrestrial organic carbon production and its export to lakes as dissolved and particulate organic matter. Paleolimnological studies suggest that these large changes may have occurred in the past as a result of climate-induced tree line migration, resulting in changes in the colored dissolved organic matter (CDOM) content of lakes, and associated shifts in underwater spectral UV and PAR irradiance (Pienitz and Vincent 2000; Saulnier-Talbot, Pienitz, and

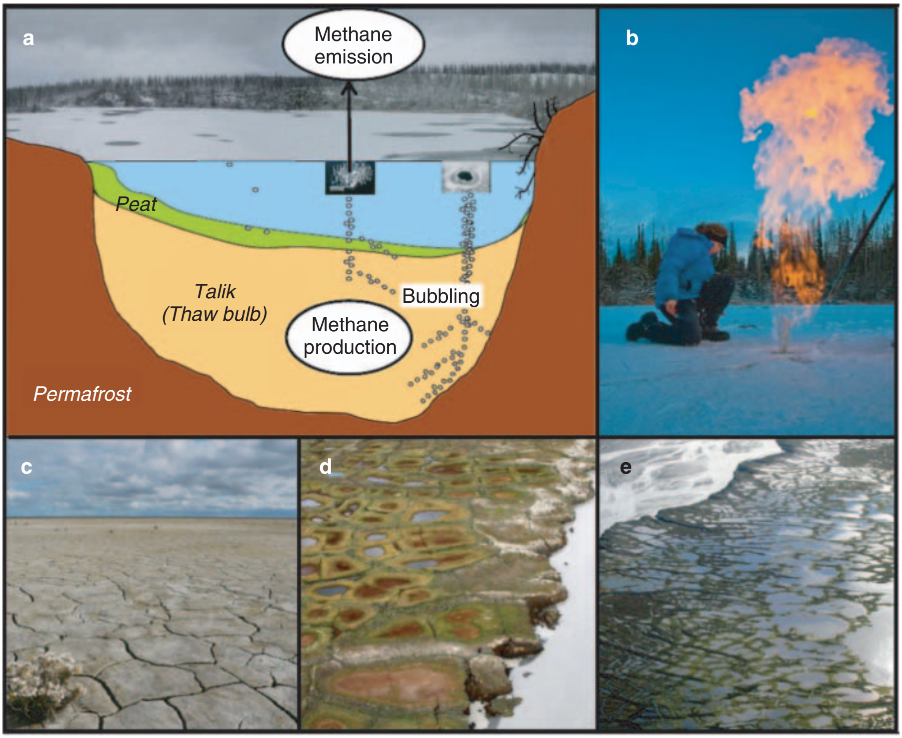

Figure 2.2 Arctic thaw lakes in the changing Arctic. (a) These waterbodies are biogeochemical hotspots on the tundra in which soil and lake organic matter is broken down by microbial activity in the thaw zone beneath the lake, resulting in the liberation of methane and carbon dioxide. Large quantities of these gases are released to the atmosphere via bubbling, which can produce and maintain holes in the ice. Modified from Walter *et al*. (2007). (b) The methane can accumulate as gas pockets beneath the ice, such as here in an Alaska lake where the gas has been vented through a hole made in the ice and then ignited. Photocredit: Todd Paris, November 2009; from Walter Anthony *et al*. (2010). Reproduced with permission. (c) In parts of the Arctic, thaw lakes are expanding in number and size, while in other areas, such as here in the Nettilling Lake region of Baffin Island, landscape erosion has resulted in complete drainage of some waterbodies. Photocredit: Reinhard Pienitz, August 2010. (d) Long-term as well as interannual variations in climate strongly affect the water balance and persistence of lakes on the permafrost. Many of these polygon ponds on Bylot Island, Canada evaporated to dryness in a warm, low precipitation year. Photocredit: Isabelle Laurion, July 2007. (e) The Bylot Island polygon ponds were numerous and extensive during a preceding cool, wet year. Photocredit: Isabelle Laurion, July 2005. (See insert for color representation.)

Vincent 2003). Changes in DOC may also influence the heat budget of lakes and the extent of stratification (Caplanne and Laurion 2008).

The processes described here may lead to a decreased rate of photosynthesis as a result of increased shading by CDOM and terrigenous particles (as in Watanabe *et al.* 2011), although this may be partially offset by increased nutrients and decreased exposure of the phytoplankton to damaging UV radiation. The increased allochthonous input of dissolved and particulate organic carbon by erosion and terrestrial plant growth, in combination with the increased inorganic nutrient supply, is likely to favor increased rates of heterotrophic activity and microbial food web processes in the receiving waters (Sobek *et al.* 2003; Sobek, Tranvik, and Cole, 2005). In combination, this implies that the photosynthesis to respiration ratio in northern lakes will shift downwards in the future, and that these ecosystems will become increasingly net emitters of carbon dioxide. Depending on the acid-neutralizing capacity (alkalinity) of the lake waters, such changes could also result in decreased pH.

2.4 Biological impacts of climate change

The warming of northern ecosystems is likely to impair cold-adapted specialists, such as psychrophilic microbes (Vincent 2010) and cold stenothermal fauna, for example Arctic char (see below). In the marine environment, changes across specific thresholds have led to a complete regime shift in food-web structure (Grebmeier *et al.* 2006). Similar discontinuities may be expected in the future in Arctic freshwater systems, especially with the arrival of invasive generalist species from the South. The local biodiversity of northern lakes may increase in terms of species richness, but at the expense of Arctic endemic species that may be driven to extinction by competition, parasitism or direct thermal stress (Vincent *et al.* 2011).

Paleolimnological analyses of sediment cores from lakes throughout the circumpolar Arctic have shown large changes in the composition of diatom communities over the last century, likely in response to climate change. These floristic changes varied in magnitude and exact timing (Smol *et al.* 2005; Rühland, Paterson, and Smol 2008), and ongoing changes in community structure at all trophic levels are similarly likely to vary greatly among different sectors of the Arctic.

The displacement of native fish in northern lakes is of particular concern to Inuit and First Nations communities, and will be an increasing priority of research and monitoring. For example, a modeling study of the range distribution of smallmouth bass (*Micropterus dolomieu*) showed that it could potentially invade some additional 25 000 northern lakes and, because of its strongly negative effects on other fish, cause the extirpation of four native cyprinid species from these lakes (Sharma *et al.* 2007).

2.5 Human impacts of climate change

Northern lakes provide a variety of key ecosystem services including transport routes, drinking-water supplies, habitats for aquatic wildlife of traditional value to northern communities, and water for industries including hydroelectricity, recreational fishing, eco-tourism and mining. The influence of climate change on water supply and quality is increasingly viewed with concern by Inuit and other indigenous communities (Moquin 2005). Additionally, the warmer temperatures may allow invading species to survive and complete their life cycles, causing the extinction of native biota and serious impairment of traditional hunting and fishing practices (Vincent *et al.* 2011).

Lake and river ice in the north provide winter transport routes that are important to northern indigenous people for access to their traditional hunting and fishing areas, as well as for the heavy transport of goods to remote communities and industries such as mining centers. For example, the Tibbitt to Contwoyto Winter Road in northern Canada, passes over 495 km of frozen tundra, lakes, and rivers, and is estimated to have an economic contribution of more than one billion US$ annually (Prowse *et al.* 2011). These ice roads and traditional routes are now subject to earlier break-up and unseasonal warming, which is reducing their economic value and creating dangerous conditions for freight haulers and northern communities (Ford *et al.* 2008).

Several climate-related effects may influence the future quality of drinking water in the North. Ongoing permafrost degradation may cause a rise in turbidity and dissolved organic matter levels in the raw source waters, which will require vigilance to ensure that chlorination and other disinfection treatments are adjusted appropriately, and that local residents that use the raw water are adequately advised. In a survey of Nunavik Inuit households in 2004, 29% of the consumed water was raw water taken directly from creeks, rivers and lakes (Martin *et al.* 2009). The arrival of new species may also bring with them disease-related problems for drinking water; for example the northward migration and increased population densities of beavers and associated protozoan parasites in eastern Canada (Jarema *et al.* 2009). High-latitude freshwaters are mostly free of toxic bloom-forming cyanobacteria that create a broad spectrum of water quality problems in the temperate zone, but ongoing warming and stratification of Arctic and subarctic lakes combined with climate-related increases in nutrient loading may encourage the development of these taxa (Vincent 2009).

Most northern communities are now equipped with water treatment plants but many do not have water reticulation systems because of permafrost soils and the difficulty of maintaining pipes and flowing water in their harsh winter climates. Throughout many parts of the north, water is delivered daily by truck to houses where it is kept in large tanks. The microbiological cleanliness of storage systems for this water will require increased attention as temperatures warm in the future (Martin *et al.* 2009).

Arctic char (*Salvelinus alpinus*) is a key element of the traditional diet of Inuit and other northern indigenous people, and changes in this and other fish species associated with climate change may have impacts on northern culture and health. Arctic char appears to be especially sensitive to high temperatures relative to other salmonids, and is also the most tolerant of low temperatures (Baroudy and Elliott 1994). With ongoing climate change, Arctic char will be unlikely to survive in the warmer surface and littoral waters of many northern lakes. The arrival of southern species such as Atlantic salmon (*Salmo salar*) and brook trout (*Salvelinus fontinalis*) could reduce or replace Arctic char, and the latter will likely be displaced from some habitats. There may also be climate-induced changes in the migratory behavior of Arctic char, which would potentially result in changes in their productivity and population size distribution (Reist *et al.* 2006; Power, Reist, and Dempson 2008).

Hydroelectricity plays an important role in some northern economies and will require careful attention to climate-related shifts in water supply, specifically the current and future magnitude of changes in precipitation gains and evaporative losses (likely to increase with warmer water temperatures, and longer ice-free conditions), as well as changes in water plant species and density that may influence storage volume and operating protocols. Future changes in reservoir ice conditions may also affect hydroelectric operations (Prowse *et al.* 2011).

The warming climate will also be accompanied by improved access to resources in the Arctic, and thereby increased human activities. There are many examples of severe local pollution effects of human development on northern lakes in the past (e.g., Laperrière *et al.* 2008; Antoniades *et al.* 2011b), and the current expansion of economic and resource extraction activities in the Arctic will require increasing vigilance and appropriate water management strategies to avoid and minimize such impacts in the future.

2.6 Conclusions

As a result of climate change, the northern landscape has now entered a state of rapid transition, and Arctic freshwater ecosystems are beginning to show shifts in their physical, biogeochemical and biological properties. These ongoing changes will affect the ecosystem services that they are able to provide to northern residents, industries and society at large. Many of these impacts are interconnected (Figure 2.1). For example, changes in climate affect water temperature and thereby stratification, which may lead to anoxia, a contraction of habitat for biota requiring highly oxygenated waters, and a deterioration in fishing yield for northern communities. Conversely, ongoing fishing pressure at some locations where food webs are already under thermal stress may hasten the demise of fish stocks and the more rapid establishment of invasive species from the south. Several of these effects may also result in positive feedbacks, at a variety of scales; for example, the local effects of stratification enhancing additional warming of the surface waters of lakes, and the global effects of increasing greenhouse gas emissions from northern waters.

Given that climate is such a powerful agent of change for aquatic ecosystems, it follows that the only effective strategy to minimize harm will be to reduce the rate and endpoint of global warming. This is especially urgent for Arctic ecosystems given that instrumental data records and global circulation models converge on the prediction that it is the highest northern latitudes that will continue to experience the fastest and most extreme increases in temperature. There is a compelling body of evidence that northern environments are already passing across major thresholds of change, and that this is due to the rise in greenhouse gases in the atmosphere caused by human activities. Arctic ice shelves, for example, appear to have broken up in the past (Antoniades *et al.* 2011a), but their current episode of collapse is co-occurring with the collapse of Antarctic ice shelves, implying an unprecedented, synchronized phase of polar deglaciation that would be consistent with human-induced, global climate change (Hodgson 2011). Northern glaciers are currently experiencing attrition at sharply accelerated rates (Gardner *et al.* 2011). Similarly, analyses based on sea ice, climate and ocean proxies imply that the current loss of Arctic sea ice (Perovich and Richter-Menge 2009) is without precedent for 1450 years, and is the result of increased advection of warm Atlantic water into the Arctic basin, also consistent with anthropogenically induced warming (Kinnard *et al.* 2011). The Arctic Ocean is predicted to be seasonally ice-free within decades (Wang and Overland 2009), and this could be a tipping point that triggers widespread degradation of permafrost, with implications for lake water quality, mobilization of permafrost organic carbon, and accelerated methane release.

Although climate mitigation, defined as the reduction of greenhouse gas emissions to the atmosphere, is an urgent priority to avoid dangerous excursions in climate, the unabated year-by-year increases in emission rates imply that adequate control at a planetary level seems unattainable in the short term. Current modeling analyses predict that if emissions continue to increase, a temperature threshold of 2 °C would probably be exceeded over large parts of Eurasia, north Africa and Canada by 2040, and possibly as early as 2030 (Joshi *et al.* 2011). At several locations in the circumpolar north, it appears that these thresholds have already been exceeded (for instance, Hudson Bay, Canada; Bhiry *et al.* 2011). In tandem with global efforts to slow the rates of emission, additional efforts are required at regional and local scales to minimize and manage impacts on natural waters and their surrounding ecosystems.

The most effective approach at the regional scale is that of conservation. High latitude ecosystems have less biodiversity, and therefore less functional redundancy, than those at temperate latitudes and are therefore inherently more sensitive to perturbation (Post *et al.* 2009). The creation of high latitude parks and other conservation zones provides a strategy to reduce the effects of multiple stressors that are superimposed on northern biota in a warming climate and to provide refugia for vulnerable species. These conservation practices may range from local protection from human activities, for example around municipal water supplies, to the creation of large-scale wilderness zones to preserve biological communities and entire ecosystems that are at risk. These northern parks and other protected areas are likely to come under increasing economic pressure as the drive to extract oil, gas and mineral resources from the Arctic continues to accelerate.

At the local scale, the ongoing effects of climate change must be addressed by adaptation strategies. The first requirement is an adequate surveillance system to monitor, communicate, and respond to changes. Strategies to address the increasing safety issues for ice roads include reductions in maximum allowable loads to be transported, modifications to the methods used for ice road construction, and rescheduling to concentrate transport during the coldest part of winter (Prowse *et al.* 2009). Satellite remote sensing (RADARSAT) has been implemented in northern Canada to provide timely warnings of unsafe ice conditions (Gauthier *et al.* 2010), and offers considerable potential throughout the circumpolar north in the future. For drinking water supplies, adequate surveillance and advisories are also critical to ensure water quality and safety. These essential resources require the development of integrated freshwater management plans, which include consideration of alternate water sources as traditional supplies change in quantity or quality. The likely shifting of thermal conditions in northern lakes and reservoirs to those conducive to growth by noxious cyanobacteria will also require ongoing attention, with emphasis on catchment control of phosphorus and other nutrient sources. For hydroelectric reservoirs, shifting ice conditions will have both positive and negative effects, and may require adaptive changes in operating procedures, with attention to minimize deleterious impacts associated with ice jams and ice breakup downstream of the spillway (Prowse *et al.* 2011). Fisheries management plans will also need to be adapted to the changes in migration and productivity of northern fish populations with ongoing climate change. The potential arrival of invasive species will create particularly challenging problems for ecosystem management, including fisheries, and will require increased surveillance and prevention measures as road access to the north continues to develop, along with increased industrial, eco-tourism and recreational boating activities.

In summary, northern aquatic ecosystems are a rich resource of enormous cultural, economic and ecological value. These waters are now undergoing rapid changes in their physical, biogeochemical and biological properties, and their abilities to provide ecosystem services are beginning to be compromised. These changes are likely to continue and to be amplified in the foreseeable future. Local adaptation strategies need to be put in place, and regional conservation and management plans are an important priority to reduce the effects of multiple stressors. At the planetary scale, ongoing efforts are required to reduce greenhouse gas emissions and slow global warming, allowing more time for adaptation. In all of these respects, northern ecosystems are an early warning system of major change that will occur throughout the global environment, and they are a natural laboratory in which to develop appropriate strategies to manage the world’s precious, and increasingly vulnerable, freshwater resources.

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