Permafrost slump in Northwest Territories, Canada.
Photo: Jennifer Lento

3. Drivers of Change in Arctic Freshwaters

3.1. Introduction

Freshwater ecosystems are highly abundant and diverse throughout the circumpolar region and include lakes, ponds, rivers, streams, and associated wetlands, all interconnected in the hydrological cycle of the Arctic (Wrona et al. 2005, Prowse et al. 2006b, Wrona et al. 2006b, Vincent and Laybourn-Parry 2008). Arctic freshwaters are generally nutrient-poor and ice-covered during a large part of the year. Key environmental and anthropogenic drivers in the Arctic, operating singly or in concert, affect the distribution and abundance of freshwater ecosystems, their water chemistry and related habitats, and structural (i.e., community composition) and functional (i.e., drinking water and food supply) ecological properties. In this chapter we summarize the major drivers of change that act on freshwater ecosystems in the Arctic, and provide examples of the effects of several key drivers of change.

3.2. Major Environmental and Human Impacts on Arctic Freshwaters

The Freshwater Monitoring Plan identifies nine major environmental and anthropogenic stressors to freshwater ecosystems (Culp et al. 2012a, Table 2) that can be summarized as (1) permafrost thaw and changes in the hydrological regime resulting in higher loads of nutrients, solids and organic matter (e.g., Kokelj et al. 2013), (2) long-range transboundary air pollutants and point source pollution originating from industrial development and urbanisation, (3) fisheries over-harvesting, (4) climate-driven changes to riparian vegetation from grasses to shrub-dominated flora (e.g., Elmendorf et al. 2012), i.e., greening of the Arctic (Jia et al. 2003, 2009), and (5) flow alterations and regulation due to hydropower dams and other forms of development that leads to substantial habitat fragmentation and destruction. As the water quality and biota of lakes and rivers reflect local- and landscape-scale processes in their catchment, these freshwater ecosystems are highly suitable for the monitoring and detection of both diffusive and point-source pollution. For example, increased nutrient loads from agricultural land use or point-source pollution will result in higher primary production and higher abundances of grazing benthic invertebrates in lakes and rivers. Conversely, increased loads of suspended solids or dissolved organic matter can decrease light penetration and cause a decline in primary production (Karlsson et al. 2009). Permafrost thaw will result in increased turbidity and a leakage of soil organic carbon (Kokelj et al. 2009). Large-scale thawing of permafrost layers can dramatically alter Arctic landscapes through the drainage of lakes on permafrost, resulting in the disappearance of these water bodies and large-scale landscape transformations.

3.2.1. Key Examples of Environmental Drivers Affected by Climate

Many of the environmental factors that affect the physical-chemical environment of lakes and rivers are primarily driven by climate. This includes changes in the duration and thickness of ice cover as well as snow pack conditions (Borgstrøm 2001, Schindler and Smol 2006, Christoffersen et al. 2008, AMAP 2011, Prowse et al. 2011b). For example, long-term shifts in ice cover duration have been observed in lakes and rivers in Fennoscandia. In the Torne River located in Northern Sweden, ice-on is 10 days later and ice-out 10 days earlier than in the early 1900s, meaning that on average the present-day duration of river ice cover is some 20 days shorter than a century ago (Figure 3-1). A similar long-term trend in seasonal ice duration is evident for Lake Torneträsk, Sweden (Figure 3-1). Such changes in ice cover affect the thermal budget of freshwater ecosystems. For example, long-term temperature data from Utsjoki Nuorgam in the Tana River (69°N, in Finland) show that there has been a gradual increase in the number of days exceeding a daily mean temperature of 5°C between 1970 and 2017 (Figure 3-2). The trend was most evident from 1995 to 2017, when the number of days above 5°C increased significantly, at a rate of 0.56 days per year (Sen's slope of trend; Mann-Kendall trend test for 1995- 2017 significant at $p = 0.01$). Overall, this has led to an increase to 21 more days of temperatures over 5°C since 1970 (Figure 3-2). Warmer water and subsequently shorter ice cover will allow more sunlight and heat to enter freshwaters, thus resulting in more degree days (i.e., the cumulative heat that organisms experience), and drive photosynthesis,

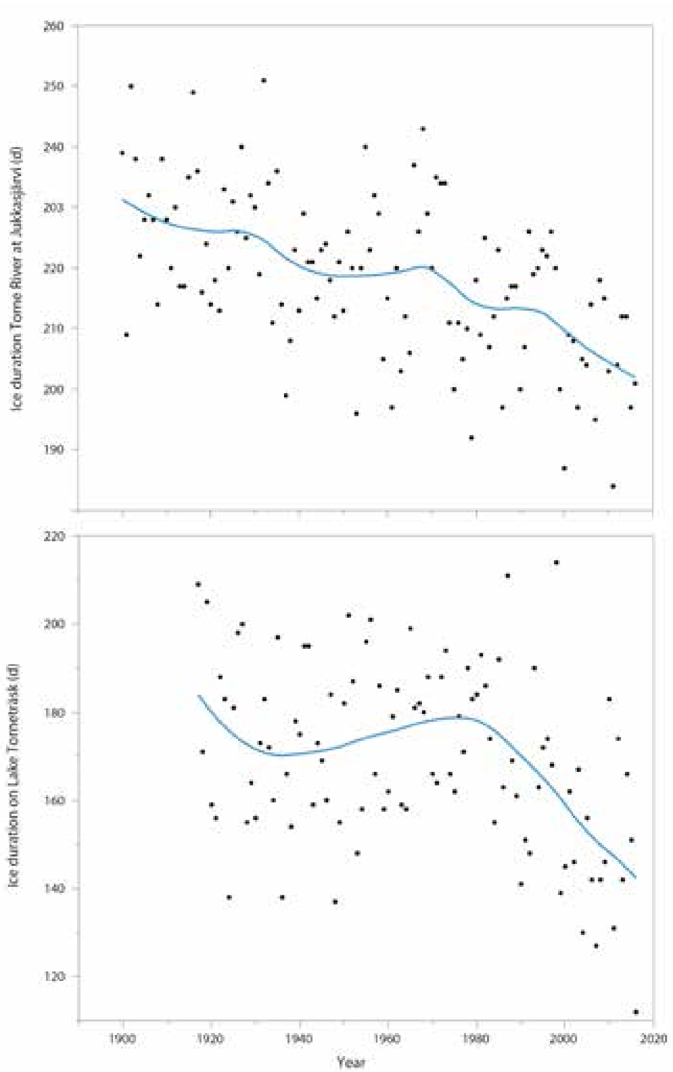

Figure 3-1 Long-term trends in ice duration (as days) in the River Torne (upper plot) and Lake Torneträsk (lower plot) at 68° north on the Scandinavian peninsula. Lines show smooth fit. Data source: Swedish Meteorological and Hydrological Institute.

leading to higher primary production and subsequent effects on production at higher trophic levels. Higher water temperatures may also allow the northward movement of species with a more southerly distribution, thus increasing the biodiversity of lakes and rivers (Culp et al. 2012b).

The climate-change-driven impact on the Torne River ice regimen has been accompanied by a gradual decrease in concentrations of total phosphorus, a key nutrient that limits the photosynthesis rates of primary producers in aquatic ecosystems. Phosphorus concentrations in the Torne River have declined on average by some 7 µg/L per year and, although small, these declines are highly significant. Similar, but slightly more pronounced declines in total phosphorus concentrations, i.e., 0.14–0.26 µg/L per year, have been found for other major unregulated rivers that drain the Boreal Highlands of Sweden (Figure 3-3). Declines in total phosphorus concentrations have also been found for lakes at northern latitudes in Finland (Arvola et al. 2011), Canada (Eimers et al. 2009, Stammler et al. 2017), and Sweden (Huser et al. 2018). Large-scale catchment processes that contribute to reductions in nutrient run-off to lakes and rivers are (i) the observed changes in tundra vegetation cover, a.k.a. the "Greening of the Arctic" (Pouliot et al. 2009, Elmendorf et al. 2012) mediated by an increased nutrient uptake by and storage in rooted plants (Aerts et al. 2006), and (ii) the more efficient trapping of P in soils that originates from soil pH increases induced by declines in acid precipitation (Geelhoed et al. 1997, Gérard 2016). The concerted action of these large-scale changes contributes to the gradual transformation of northern lakes toward more nutrient-poor conditions and is expected to increase in the predominance of N2-fixing cyanobacteria. Long-term declines in total phosphorus concentrations have repercussions on the primary production in these rivers and lakes and may push them towards more ultra-oligotrophic conditions. These declines in nutrient concentrations partly counteract the positive effects of a longer growing season due to changes in the ice regimen.

Another important environmental driver of change in Arctic freshwaters is the thawing of ground ice across landscapes as climates warm and precipitation increases (Kokelj et al. 2015). For example, permafrost degradation via retrogressive thaw slumps can increase transport of solutes, including nutrients, and sediments into Arctic lakes and rivers (Kokelj et al. 2009, Chin et al. 2016). Shoreline slumps on lake ecosystems appear to reduce DOC and increase water clarity as a result of the adsorption of nutrients onto settling sediment particles (Thompson et al. 2012). Such environmental change is associated with reduced phytoplankton productivity and increases in rooted macrophyte biomass (Mesquita et al. 2010). In contrast, shoreline slumps in rivers increase turbidity and suspended sediments by multiple orders of magnitude (Figure 3-4) and can lead to overwhelming sediment effects including reduced benthic algal biomass (Levenstein et al. 2018) and macroinvertebrate abundance (Chin et al. 2016). Furthermore, climate models indicate that increasing permafrost degradation will lead to a loss of wetlands in the Arctic as meltwater from thawing ground ice drains to deeper soil levels rather than contributing to surface soil moisture (Avis et al. 2011). It is clear that biological communities in Arctic freshwaters are at risk from environmental changes that can affect food web dynamics, biological production, and biodiversity, thereby having potential effects on the ecosystem services valued by northerners.

The retreat of glaciers and ice sheets provides a unique example of how climate change can have both positive and negative effects on freshwaters and freshwater biodiversity. Glacier retreat and accompanying shifts in glacial outflow can lead to river piracy when flowing waters are dependent on the glacier for source water. River piracy is the re-routing of headwater streams into different river systems, significantly altering flow regimes and even causing rivers to dry up, and a recent example from the Yukon in the Canadian Arctic showed such events happening on an accelerated time scale in response to glacier retreat (see Shugar et

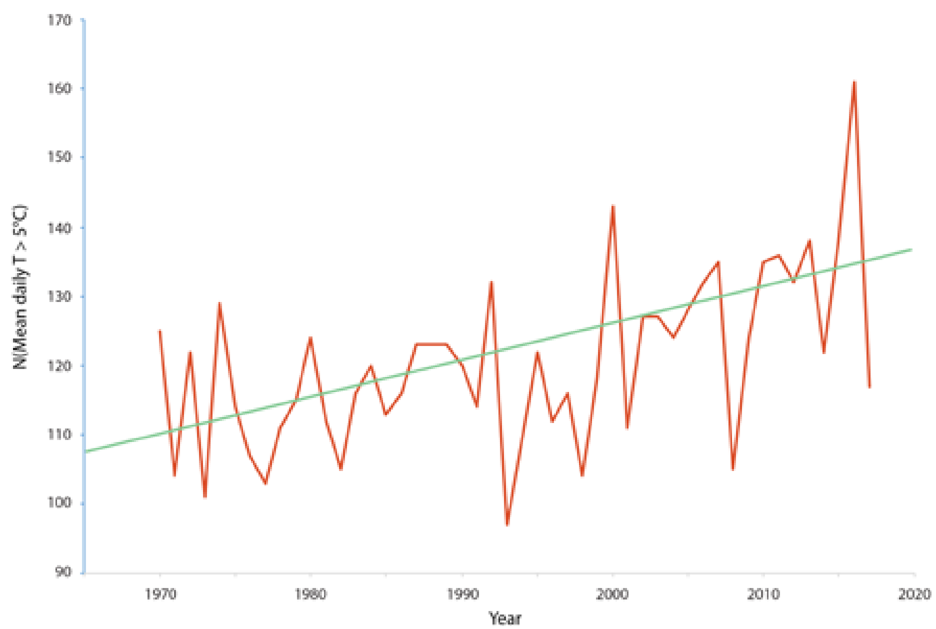

Figure 3-2 Long-term water temperature trends (1970–2017) for the Utsjoki Nuorgam station in the River Tana (69°N in Finland). The diagram shows the number of days per year with a mean temperature exceeding 5°C. The data show that from 1995 to 2017, this indicator increased by over 0.5 days per year. Data source: Finnish Meteorological Institute.

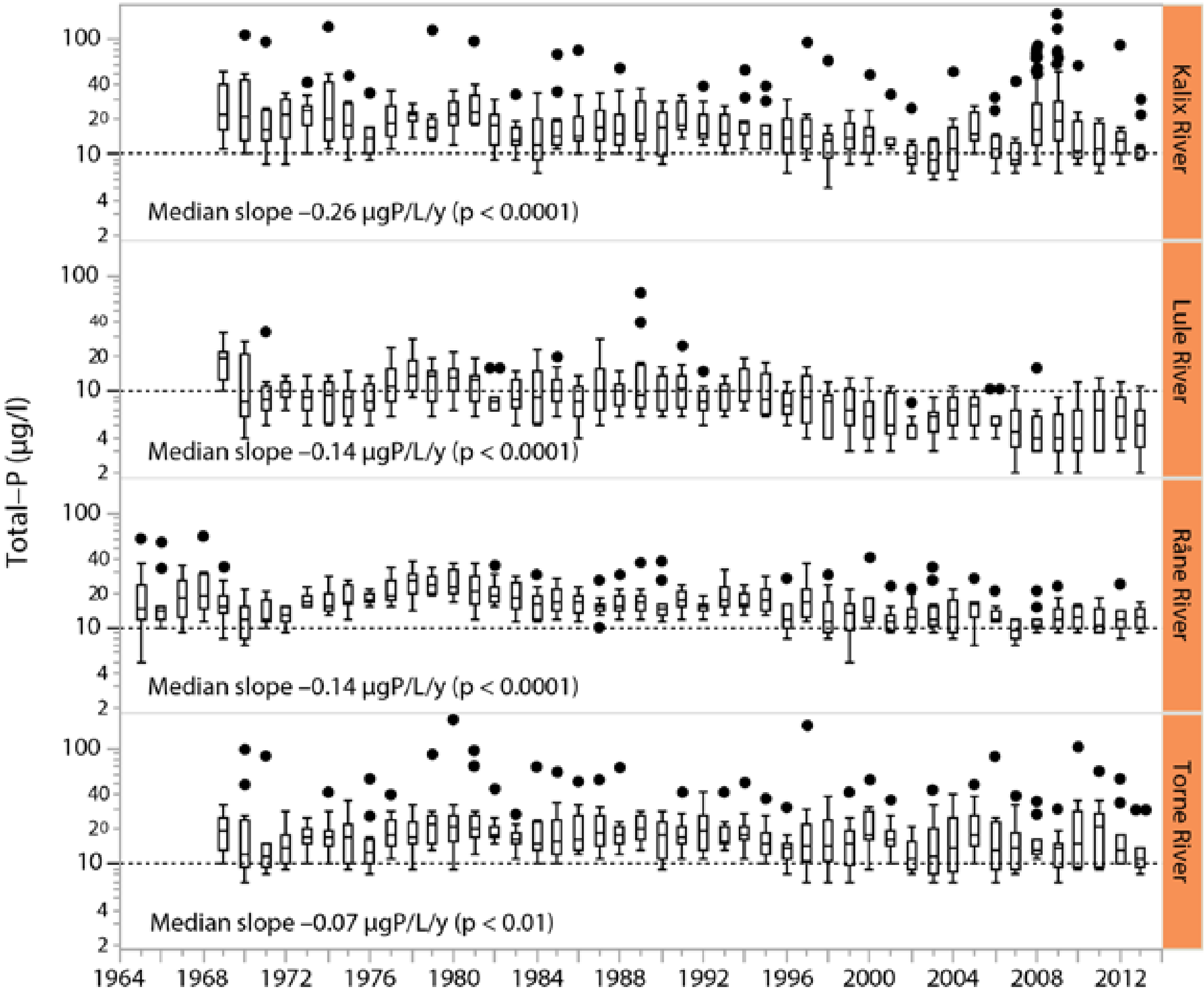

Figure 3-3 Long-term trends in total phosphorus water concentrations (µg/L) in four major, unregulated rivers that drain the subarctic Arctic/alpine ecoregion of the Scandinavian peninsula, the Kalix river, The Lule river, the Råne river, and the Torne river. Slopes and p-values are given in the different panels. Boxes indicate medians and 25th and 75th percentiles, while whiskers give the 10th and 90th percentiles.

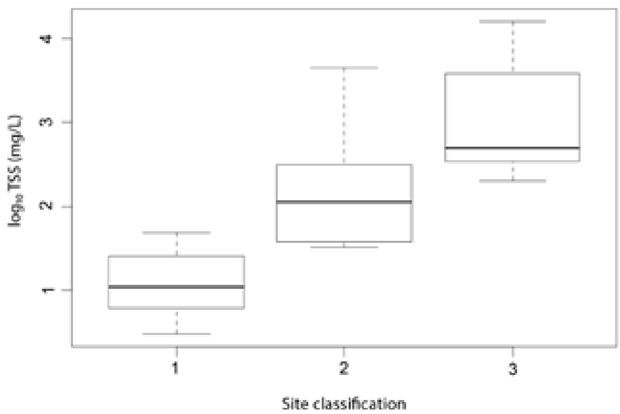

Figure 3-4 Effects of permafrost thaw slumping on Arctic rivers, including (upper) a photo of thaw slump outflow entering a stream on the Peel Plateau, Northwest Territories, Canada, and (lower) log10-transformed total suspended solids (TSS) in (1) undisturbed, (2) 1-2 disturbance, and (3) > 2 disturbance stream sites, with letters indicating significant differences in mean TSS among disturbance classifications Plot reproduced from Chin et al. (2016).

al. 2017). In contrast, meltwater from ice sheets in west Greenland has led to an increase in the number and size of lakes on the landscape, increasing available freshwater habitat (Carrivick and Quincey 2014). Climate-induced glacier loss alters hydrological regimes, sediment transport, and biogeochemical and contaminant fluxes from rivers to oceans (Brown et al. 2018). Declining glacial cover will initially cause a decline in alpha diversity (number of species) in receiving waters as glacial meltwater inputs increase and water temperature drops (Figure 3-5), leading to stronger differences in assemblage composition (beta diversity). A further reduction of glacial influence will alter cold river biodiversity, leading to increased alpha diversity and functional diversity (Figure 3-5), and will completely reshape many river systems (Brown and Milner 2012, Milner et al. 2017, Brown et al. 2018). With the loss of glaciers, hydrologic regimes of rivers and lakes will be more reliant on inputs from other water sources, such as snowmelt, groundwater, and rain events (Milner et al. 2017). This will profoundly influence the natural environment, including many facets of biodiversity, and the ecosystem services that glacier-fed rivers provide to humans, particularly provision of water for agriculture, hydropower, and consumption.

3.3. Predicted Scenarios of Species Richness Response to Climate Warming

Scenarios of species richness response to increased temperatures in Arctic lakes and rivers were proposed by Culp et al. (2012b). These biodiversity predictions specifically address changes in the relative share of eurythermic species (i.e., those that can function at a wide range of temperatures) and stenothermic species (i.e., those that are adapted to a narrow range of temperatures). As temperature regimes in Arctic freshwaters warm, the northward movement of eurythermic species will affect biodiversity at all scales from species composition within rivers, lakes and ponds (alpha biodiversity) to changes in regional assemblages (gamma biodiversity), with the overall state change depending on the relative rates of gains and losses in eurythermic and stenothermic species (Vincent et al. 2011). These changes in species richness can also be expected to modify functional diversity in Arctic freshwaters (Brown et al. 2018). A rapid increase in the abundances of eurythermic species and a slow loss of stenotherms will produce a pulsed increase in gamma biodiversity that likely will settle at a new equilibrium dominated by eurythermal species (Figure 3-6a). In contrast, a more moderate dispersal rate by eurythermal species (assuming that barriers to dispersal are limited) coupled with the rapid loss of stenotherms will produce a pulsed decrease in gamma biodiversity that will also eventually settle at a new equilibrium dominated by eurythermal species (Figure 3-6b). An equilibrium dominated by eurythermal species is reached more rapidly through a rapid increase in eurytherms coupled with a rapid decrease in stenotherms (Figure 3-6c). In contrast, a slow increase in eurytherms coupled with a slow decrease in stenotherms will lead to a slow increase in gamma biodiversity that eventually will settle at a new equilibrium dominated by eurytherms (Figure 3-6d). The actual changes in species diversity will, therefore, depend critically on the relative rates of change in eurythermal and stenothermic species, with the panels in Figure 3-6 representing possible response scenarios. Declines in eurytherms are expected as temperatures increase beyond thermal tolerance levels (not shown in Figure 3-6) (Woodward et al. 2010).

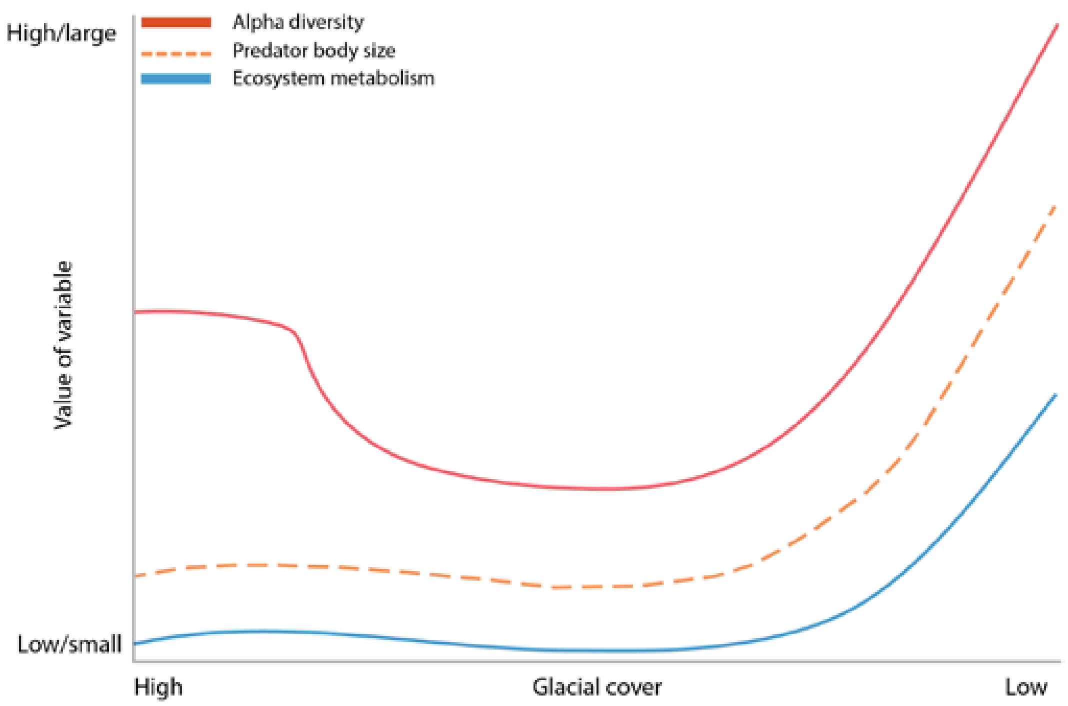

Figure 3-5 Changes in alpha diversity (red line), predator body size (blue dashed line), and ecosystem metabolism (blue solid line) with a shift in glacial cover from high (left) to low (right). Redrawn from Milner et al. (2017).

Where dispersal routes do not exist (e.g., isolated high Arctic or high-altitude water bodies), the climate-driven loss of stenotherms may not be compensated by eurythermic species invasion and an overall decline in gamma biodiversity is expected. The effect is expected to predominate more among vertebrates whose dispersal patterns rely on habitat connectivity, although the response of invertebrate composition and functional diversity to climate change may also be affected by dispersal limitations (Brown et al. 2018). Avian range expansion associated with climate warming, however, may lead to increased invertebrate diversity at local (alpha) and regional (gamma) scales via dispersal facilitation (Santamaría and Klaassen 2002).

Scenarios of biodiversity change in Arctic freshwaters (Figure 3-6), including glacially-fed systems (Figure 3-5), predict a net increase in biodiversity with warming temperatures, assuming dispersal routes exist for southern species to colonize northern regions. However, as water quality and habitat conditions shift to more closely resemble southern latitudes, this shift is expected to come with a reduction in the habitat range of cold-tolerant species endemic to the Arctic. Thus, along with an overall predicted increase in the number of species, there will be a net loss of unique Arctic-specific biodiversity. Alterations of habitat conditions originating from changes in air and water temperatures, permafrost extent, nutrient availability, and terrestrial vegetation will change the zonation of the Arctic region by globally decreasing the size of the sub-, low, and high Arctic regions and by reducing habitat critical to cold-tolerant Arctic species.

In summary, climatic regime change is likely to produce substantial effects on the physical and chemical habitat template of Arctic freshwater ecosystems. This change in the abiotic environment is expected to cause transformations in biological production and biodiversity as some existing resident taxa are selected against while others are favored such as the northerly dispersal of taxa previously unable to tolerate Arctic conditions (Wrona et al. 2006a, Vincent et al. 2011). Resulting alterations to aquatic biodiversity, therefore, have the potential to produce changes to freshwater fisheries around the Arctic, and to modify the distributions of aquatic invertebrates, vertebrates and plants. These changes to aquatic biodiversity and food webs will affect not only Arctic freshwater ecosystems, but also the ecosystem services that they supply to Arctic residents.

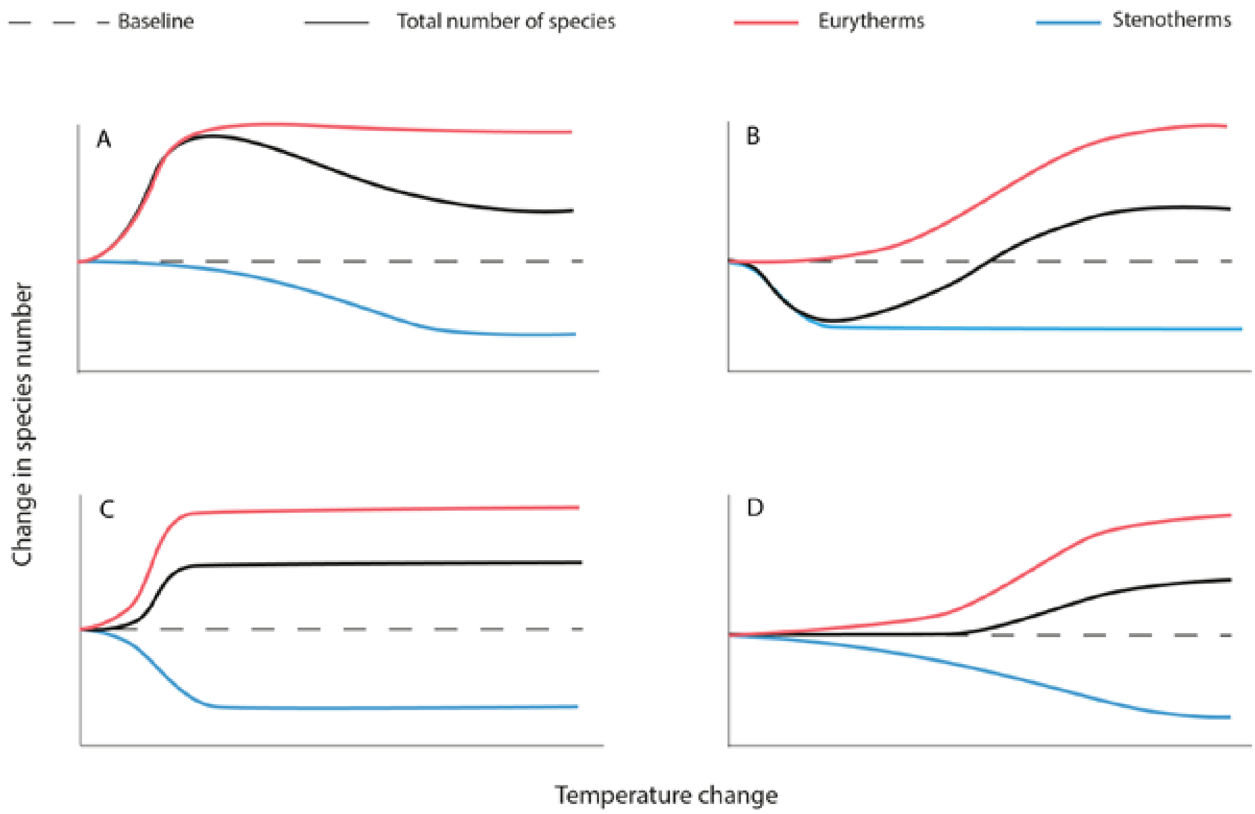

Figure 3-6. The hypothesized effects of rising mean water temperature on biodiversity (as total species number) of Arctic freshwater ecosystems. A pulsed increase in gamma biodiversity (a) results from the combination of high eurythermal invasion and establishment and low stenothermic loss with increasing water temperature. A pulsed decrease in gamma biodiversity (b) results from the combination of low eurythermal invasion and establishment and high stenothermic loss. Rapid increases (c) and slow increases (d) in species diversity occur, respectively, with high eurythermal invasion and establishment coupled with high stenothermic loss or low eurythermal invasion and establishment and low stenothermic loss as temperatures increase. For simplification, barriers to dispersal have been assumed to be limited in these models.