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Review

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Drivers of change in Arctic fjord socio-ecological systems: Examples from the European Arctic

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Abstract

Fjord systems are transition zones between land and sea, resulting in complex and dynamic environments. They are of particular interest in the Arctic as they harbour ecosystems inhabited by a rich range of species and provide many societal benefits. The key drivers of change in the European Arctic (i.e., Greenland, Svalbard, and Northern Norway) fjord socio-ecological systems are reviewed here, structured into five categories: cryosphere (sea ice, glacier mass balance, and glacial and riverine discharge), physics (seawater temperature, salinity, and light), chemistry (carbonate system, nutrients), biology (primary production, biomass, and species richness), and social (governance, tourism, and fisheries). The data available for the past and present state of these drivers, as well as future model projections, are analysed in a companion paper. Changes to the two drivers at the base of most interactions within fjords, seawater temperature and glacier mass balance, will have the most significant and profound consequences on the future of European Arctic fjords. This is because even though governance may be effective at mitigating/adapting to local disruptions caused by the changing climate, there is possibly nothing that can be done to halt the melting of glaciers, the warming of fjord waters, and all of the downstream consequences that these two changes will have. This review provides the first transdisciplinary synthesis of the interactions between the drivers of change within Arctic fjord socio-ecological systems. Knowledge of what these drivers of change are, and how they interact with one another, should provide more expedient focus for future research on the needs of adapting to the changing Arctic.

Impact statement

It is now well documented that the Arctic, the northern polar region of our planet, is changing rapidly. It is likely that as soon as 2050 the Arctic Ocean will be largely ice-free over the summer. The consequences of this are vast and merit our effort to discern how we may best adapt to the coming changes that a melted Arctic cryosphere will mean for human habitation across the globe. Within the European Arctic (i.e., Greenland, Svalbard, and Northern Norway), fjord ecosystems are particularly important because they serve as loci for ecosystem functioning and human settlement. In this transdisciplinary review, we synthesise the knowledge that exists for the socio-ecological systems within European Arctic fjords. It is necessary to review the complete scope of knowledge on these systems for the past, present, and possible future projections because as the climate changes, the interactions within these systems will themselves likely change. Meaning that European Arctic fjords will experience both externally and internally driven pressures. The 14 key drivers of change within European Arctic fjords are identified here and classified into five categories. The scope of these relationships, and how they may change across the European Arctic, are discussed. The aim of this review is to provide future research projects with a more complete foundation upon which they can orient their research questions for how best to adapt Arctic fjord socio-ecological systems to the changing climate.

Introduction

Fjord systems are characterised as deep narrow inlets of water, usually created by glaciers and sometimes harbouring a sill, a physical barrier that creates inner and outer deep areas. These systems are of particular importance in Greenland, Svalbard, and Northern Norway; hereafter referred to as the European Arctic (25°W–60°E and 66°N–90°N; Figure 1), because they host highly productive ecosystems that may be exploited by humans (e.g., aquaculture; Hermansen and Troell, 2012; Aanesen and Mikkelsen, 2020), act as carbon sinks (Smith et al., 2015; Cui et al., 2022), and provide suitable areas for spawning grounds and nurseries (e.g., Spotowitz et al., 2022). These regions are also well studied, with the necessarily large body of attendant literature required for the following review (see also Cottier et al., 2010).

The European Arctic is not one monolithic entity. Indeed, there are many differences between the fjords found throughout the region and therefore a wide range of possible interactions between the forces responsible for the changes therein are possible. The three study regions (and sites therein) focussed on to frame the review of these differences are Greenland (Qeqertarsuup Tunua, Nuup Kangerlua, and Young Sound), Svalbard (Kongsfjorden, Isfjorden, and Storfjorden), and Northern Norway (Porsangerfjorden). Where relevant to the text, additional sites are also mentioned. While all are classified geographically as Arctic, many fjords in Northern Norway lack sea ice and glaciers altogether, and the west coast of Svalbard is in the process of transitioning from Arctic temperatures to boreal (Hop and Wiencke, 2019). It is the fjords along the east coast of Greenland that have persisted as cold Arctic, for the time being.

The terminology used throughout the literature to describe the processes that cause changes in Arctic fjords is varied; therefore, we have decided to refer to them here as *drivers*: “Any natural- or human-induced factor that directly or indirectly causes a change in a system” (*sensu* Möller et al., 2022). There is a general hierarchy to the scale and directional forcing of these drivers; however, there are many feedback processes between them and many non-linear relationships. For example, warming induces a loss of sea ice, increasing light availability, which stimulates primary production, thereby promoting the progressive abundance of zooplankton to fish to birds, the overall species richness of the fjord, and the ecosystem services that provide to the human settlement(s) along the fjord. Some drivers, especially those in the biology category, tend to drive changes within themselves, rather than impacting drivers in other categories.

The drivers are classified into five categories and separated into sections below: cryosphere, physics, chemistry, biology, and social. Subsections for each driver provide a review of the current state of knowledge, which are followed by a summary of the present and future uncertainties for the category. The focus of the summaries varies between categories, reflecting the differences in the scientific sub-disciplines of the natural and social sciences. Any references within the text to a specific subsection are

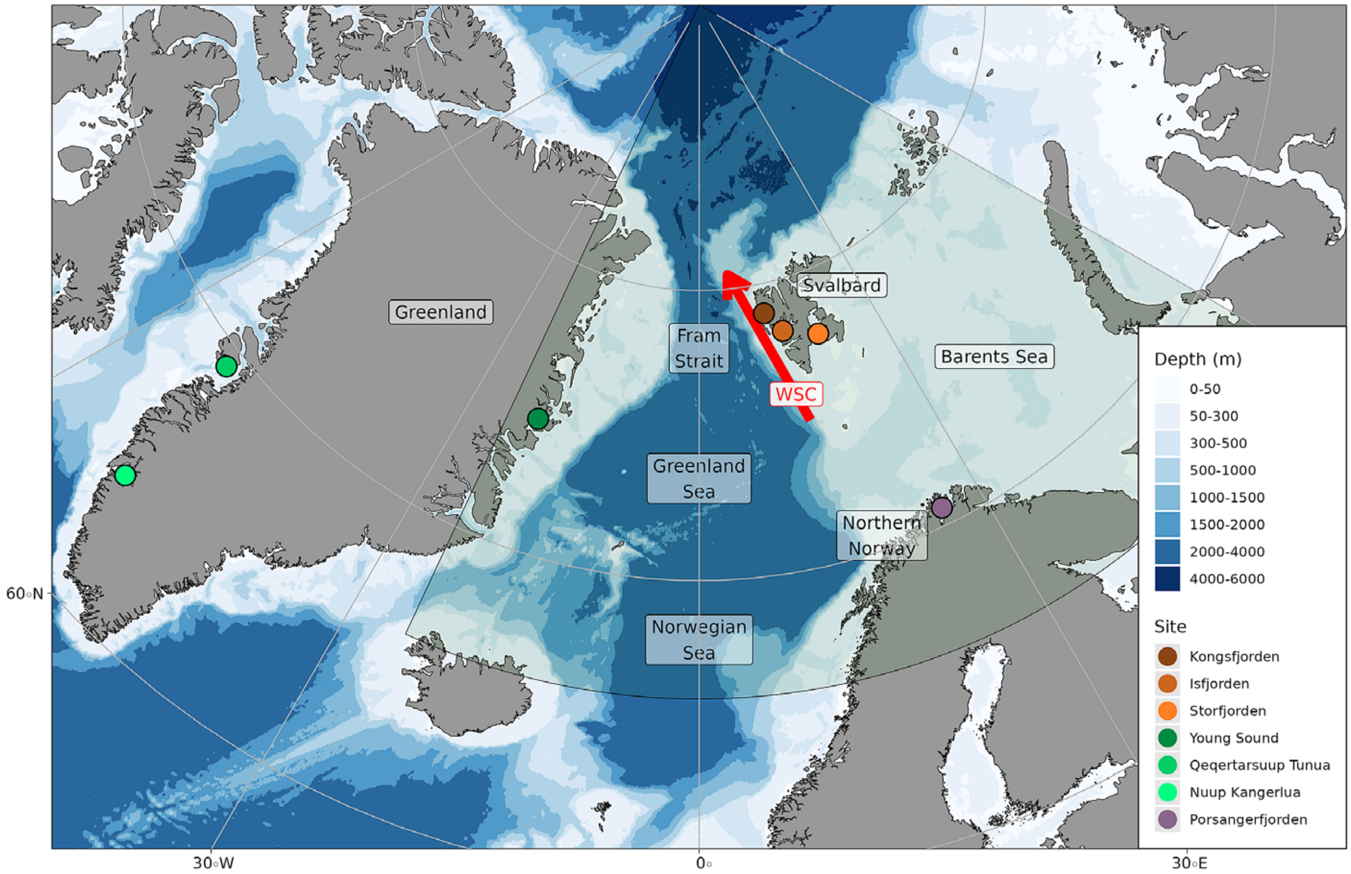

Figure 1. The extent of the European Arctic (25°W–60°E and 66°N–90°N; *sensu* Copernicus Marine Environment Monitoring Service) highlighted here *via* a polygon, with the seven focal sites for this review paper shown as coloured points grouped into the regions: Svalbard (brown), Greenland (green), and Northern Norway (purple). Areas referenced in the text are indicated with black labels. The general position of the West Spitsbergen Current (WSC) is shown with a red arrow.

made via the name of the section (i.e., section “Seawater temperature”). The review finishes with a discussion of the relationships between the categories and their drivers in the past, present, and future before providing concluding remarks. An analysis of the *in situ* data available for the key drivers reviewed below is available in a companion paper (Schlegel and Gattuso, in review).

Cryosphere drivers

Sea ice

Sea ice is a globally unique ecosystem that hosts a diversity of endemic flora and fauna, and whose presence in fjords provides an array of services to society (Eamer et al., 2013). Indeed, the presence of sea ice, or lack thereof, forms the basis through which many of the drivers in this review interact with one another.

The primary conditions for the formation of sea ice are air temperature and salinity (Pavlov et al., 2013), but other complex factors also play an important role. Wind stress can fragment forming sea ice and prevent water stratification, freshwater inputs allow freezing at less negative temperatures, and snow cover can insulate against colder air temperatures which prevents further growth (Merkouriadi et al., 2017). The amount of sea ice formation and its location in late winter and spring determines the bottom temperature over the shelf when melted water is mixed with bottom water by storms (Hunt et al., 2011), which has implications for benthic life (see section “Biomass”).

Large pulses of warm and salty Atlantic water (AW) have been increasing in the fjords along the North/West Svalbard Archipelago over the last three decades (Skogseth et al., 2020). The combination of AW with increased air temperatures (e.g., winter trend of +3°C dec^{-1}; Maturilli et al., 2019) have severely restricted sea ice formation (Kongsfjorden: Cottier et al., 2007; Tverberg et al., 2019; Isfjorden: Muckenhuber et al., 2016; Skogseth et al., 2020; Gronfjorden: Zhuravskiy et al., 2012). Pronounced warming in the temperature of AW inflow (see section “Seawater temperature”) itself has been recorded during the summer from 1912 to 2019 (Bloshkina et al., 2021).

Unlike North/West Svalbard, most of Greenland is not exposed to rapidly warming ocean currents. The tidewater glaciers (see section “Glacier mass balance”) of Nuup Kangerlua (W Greenland) introduce large amounts of icebergs to the fjord, creating a dense ice melange stretching over several kilometres and freezing together in winter (Mortensen et al., 2020). As of this writing, there was a scarcity of *in situ* time series measuring sea ice cover for West Greenland, but satellite measurements (NSIDC, 2022) from 2006 to 2020 show trends of increasing cover within fjords and embayments (Schlegel and Gattuso, in review). The ice-free season in Young Sound (E Greenland) has been increasing, primarily driven by later formation of sea ice in autumn, accompanied by increased interannual variability since 2000 (Middelbo et al., 2019). On the southern border of the Barents Sea, Porsangerfjorden (N Norway) does not freeze over in the winter, with only the very inner reaches of the fjord occasionally covered by seasonal sea ice (Petrich et al., 2017).

Glacier mass balance

Glaciers are mountainous bodies of land-borne ice that have formed and persisted over millennia. Glaciers have such a dominating downstream effect on fjords that the ecosystems therein are generally defined by whether there is a glacier present and, if there is, whether it is land-terminating or marine-terminating (Lydersen et al., 2014).

Most of the large reservoirs of glacial ice in the Arctic, including the Greenland ice sheet (GrIS), are losing mass by surface melt, basal ice melt, and solid ice discharge at marine-terminating glacier fronts (Kochtitzky and Copland, 2022). The rate of this loss is projected to double by 2100 (Geyman et al., 2022). While the GrIS gained mass between 1972 and 1980 ($+47 \pm 21$ Gt yr^{-1}), since 1980 the GrIS has lost mass at an accelerating rate until a peak of 286 ± 20 Gt yr^{-1} between 2010 and 2018 (Mouginot et al., 2019). This process of ice loss (in both solid and liquid form) has also been well documented for fjord glaciers on Svalbard, such as those in Kongsfjorden (Schuler et al., 2020).

Terrestrial runoff

The Arctic Ocean holds ca. 1% of the world’s seawater, but receives 11% of global freshwater runoff (Shiklomanov, 1997). Meltwater from land-terminating glaciers enters the fjord at the surface, resulting in strong stratification that drives estuarine circulation. This also increases turbidity (Konik et al., 2021), which may have consequences for benthic life (see section “Biomass”). At marine-terminating glaciers, freshwater input comes mostly from below as subglacial discharge, often several hundred metres below the sea surface (Hopwood et al., 2020). Due to its low density, the subglacial meltwater can drive upwelling, thereby resupplying nutrient-rich but potentially warmer deep water to shallower depths (Meire et al., 2016; Hopwood et al., 2020) and stimulating primary production (see section “Primary production”; Hopwood et al., 2020). Icebergs, which originate from the calving of marine-terminating glaciers, can add freshwater at the surface, increasing stratification. As the cryosphere warms, glaciers do not melt at a linearly increasing rate, rather the melt rate eventually slows as they lose mass (Huss and Hock, 2018). On Svalbard, glacial meltwater is already decreasing due to mass loss below a critical tipping point (Nowak et al., 2021).

In addition to the melting of glaciers, river runoff is a major input of freshwater into Arctic fjords. River runoff is similar to land-terminating glacier melt in that it decreases the penetration of light, surface heating, stratification, oxygen content, nutrient input, and finally primary production (Wassmann et al., 1996; Aksnes et al., 2009). However, it differs in that the content of terrigenous material in Arctic rivers is highly variable and depends on the catchment type (Slagstad et al., 2015; Frigstad et al., 2020). Glaciers and ice sheets can dominate catchments in Greenland, Canada, Alaska, and archipelagoes such as Svalbard and Franz Joseph Land, but tundra dominates on the Eurasian and American continents, where catchments extend beyond the Arctic region. The organic carbon content in the large Eurasian rivers can be 10-fold higher than in glacial meltwater, partly reflecting thawing permafrost (Wild et al., 2019). The nitrogen input (see section “Nutrients”) from land (rivers and eroding coasts combined) is also substantial and has been estimated to sustain a third of the net primary production (see section “Primary production”) of the Arctic Ocean (Terhaar et al., 2021).

Summary

The cryosphere, a defining characteristic of the Arctic (Pavlova et al., 2019), is vanishing at an alarming rate (Meredith et al., 2019), driven primarily by warming air and seawater temperatures (see section “Seawater temperature”; Isaksen et al., 2022). There is also a robust linear relationship between the increase in atmospheric CO_2 and the decrease in sea ice extent (Stroeve and Notz, 2018). Many West Svalbard fjords are already experiencing increasingly longer sea ice-free periods (Dahlke et al., 2020), and given the current emissions trajectory most Arctic fjords will very likely follow this trend in the near future (Meredith et al., 2019). Sea ice volume over the entire Arctic has already diminished by 75% (Overland et al., 2019). Within the Svalbard fjords, sea ice has reduced by 50% on average from the periods 1973–2000 to 2005–2019, with a further reduction down to ca. 90% in the next 10 to 20 years (Urbański and Litwicka, 2022).

Marine-terminating glaciers in the northern hemisphere have been losing mass at such unprecedented rates that 7% of them have transitioned to land-terminating over the last 20 years (Kochtitzky and Copland, 2022). Such a change in glacier status restructures the entire local ecosystem and its services. Moreover, it is worth noting that rapid glacial melt may also be driving further increases in atmospheric CO_2 (Wadham et al., 2019; Christiansen et al., 2021).

Precipitation rates in the Arctic have been increasing, and are projected to continue to increase, and by the end of the century (except Greenland) the majority of this precipitation is projected to be rain rather than snow (Bintanja and Andry, 2017). Indeed, from 1979 to 2009, the average trend throughout the Arctic for snow days per year has been −2.49 days per decade (Liston and Hiemstra, 2011). This has resulted in increases of river runoff (Mankoff et al., 2020), associated with a peak date occurring earlier in the calendar year (Holmes et al., 2018). This increasing discharge intensifies the freshwater cycle and increases the connectivity between land and sea (Hernes et al., 2021) through the increased delivery of nutrients, organic matter, sediments, and contaminants. This is especially pronounced for Eurasian rivers (Shiklomanov et al., 2021). Within Arctic fjords specifically, we see that this process is beginning to affect the surface waters in Greenland fjords (Paulsen et al., 2017), and has a larger impact on Svalbard fjords (Wiedmann et al., 2016; Santos-Garcia et al., 2022) and their adjacent ecosystems (Delpech et al., 2021), with an even greater effect on northern Norwegian fjords (McGovern et al., 2020).

Physics drivers

Seawater temperature

One of the primary controlling factors of the extent of the Arctic cryosphere is the earth's temperature (Meredith et al., 2019). This also has a dominating effect on the presence of species thriving in a given location (see section "Species richness"; Willis et al., 2006; Vihtakari et al., 2018). It has been established that the rate of warming in the air is four times more rapid in the Arctic than elsewhere (Rantanen et al., 2022). However, changes in seawater temperature are not always linear, nor are they uniform in scale temporally or spatially. Rather, disturbances may materialise as non-linear phenomena, such as shifts of ocean currents or the ephemeral appearance of extreme ocean temperature events.

AW, which is warmer and more nutrient-rich than Arctic waters, is circulated to Svalbard via the Fram Strait as part of the West Spitsbergen Current (WSC) where it forms much of the bottom layer of the West Svalbard fjords in summer. However, starting in 2006, AW has begun occupying much more of the water column (Tverberg et al., 2019; Skogseth et al., 2020), a process referred to as "Atlantification". This occurs in part due to changes to patterns of the wind stress field in the area (Pavlov et al., 2013) and the wandering of large-scale ocean currents. In addition to increasing temperatures, changes to the inflow of AW are so critical because this water body is the main nutrient contributor (see section "Nutrients") to the European Arctic (Duarte et al., 2021).

In contrast to the warming in Western Svalbard, driven largely by increased AW temperature, Hanna and Cappelen (2003) observed a significant cooling trend in southern Greenland seawater surface temperatures in eight meteorological stations from 1958 to 2001 (−1.22°C in 44 years), while the rest of the world was warming (+0.55 °C in 44 years). They suggested that this cooling could be attributed to a positive phase in the North Atlantic Oscillation (NAO), which leads to northerly winds over Greenland pushing cold air masses down to the south, and was highly positively correlated ($r = 0.76$) to the historic seawater temperature trend (Hanna and Cappelen, 2003). However, after 2001, southern Greenland air and seawater temperatures began increasing and a more recent study by Jiang et al. (2020) found that in addition to climate indices, such as the NAO, that greenhouse gas concentrations are key drivers for seawater temperature changes in Greenland.

Salinity

The salinity of seawater creates bounding limits for the presence of many, but not all, marine species found throughout the Arctic (see section "Species richness"; Węsławski et al., 2011) and salinity changes can have impacts on the trophic structure of local fjord ecosystems (Bridier et al., 2021). Changes in salinity also induce changes in total alkalinity, a key parameter of the carbonate system (see section "Carbonate system"). In general, fjords have three distinct strongly stratified water masses (Stigebrandt, 2012):

1) *Surface water*: generally, the lowest salinity due to local freshwater supply.
2) *Intermediate water*: mirrors the stratification of adjacent coastal waters but with some phase delay.
3) *Basin water*: rests below the sill level and contains the densest waters, which may enter from outside the fjord (*NB*: not all fjords have a sill).

The increasing rates of rainfall, glacial melt, and river discharge into fjords (see section "Terrestrial runoff") may hypothetically impact the thickness and extent of the low-salinity layer in their inner regions so greatly that it slows the rate of the overturning circulation and deep-water renewal (Bianchi et al., 2020). High precipitation in temperate fjords can create a persistent low-salinity layer in surface waters (Gillibrand et al., 1995; Gibbs, 2001) that accentuates salinity stratification and limits phytoplankton access to nutrient-rich saline bottom waters (see section "Primary production"), except during wind-induced mixing episodes (Sakshaug and Myklestad, 1973; Goebel et al., 2005; Bianchi et al., 2020). A decrease in salinity of the surface water (0–50 m) in Young Sound (E Greenland) and on the adjacent shelf has been observed (Sejr et al., 2017). The lower density of the freshening surface means that bottom water in the deeper part of the fjord is isolated from exchange with shelf water (Boone et al., 2018).

Light (PAR and UV)

The light available throughout the water column, here specifically photosynthetically active radiation (PAR), is a key driver of the presence and composition of benthic and pelagic phototrophic communities due to their need to photosynthesise (see section "Biomass"). Assuming the availability of necessary nutrients (see section “Nutrients”), this means that light plays a major role in the global carbon cycle by controlling the geographical and depth distributions of primary producers (see section “Primary production”; Gattuso et al., 2020). In the Arctic, three processes linked to climate change that affect the penetration of light into the water column have been well researched:

1) Current and future projected sea ice loss (see section “Sea ice”) creates longer sea ice free periods that allow for greater penetration of light (Pavlov et al., 2019).
2) Projected increases in freshwater input (see section “Terrestrial runoff”) reduce light penetration in the coastal zone by increasing turbidity via the delivery of particulate and dissolved organic matter (DOM; Frigstad et al., 2020; Nowak et al., 2021).
3) If summer cloudiness increases as the Arctic warms, it will decrease incident PAR above the sea surface (Bélanger et al., 2013).

Largely due to increased freshwater inputs, most fjords in Western Svalbard (1997–2019; Konik et al., 2021), and many fjords on mainland Norway (1935–2007; Aksnes et al., 2009) have experienced a regime shift towards darker water, a phenomenon referred to as “darkening” or “browning”. It is hypothesised that this darkening of water may cause a reduction in primary production (see section “Primary production”; Aksnes et al., 2009). Areas distant from sources of freshwater input (e.g., glaciers and rivers; section “Terrestrial runoff”) could, however, experience an increase in light penetration as is occurring in the open Arctic Ocean where reduced sea ice leads to increased PAR and thereby primary production (see section “Primary production”; Arrigo and van Dijken, 2011).

For atmospheric radiation conditions, further stratospheric ozone loss will result in a higher UV-B burden in the Arctic (Manney et al., 2011). The impact of UV-B on benthic communities in Arctic fjords has been extensively studied; however, the results with respect to the ecological implications are still somewhat inconclusive (see Bischof and Steinhoff, 2012, for review). UV-B may negatively affect biological processes in shallow waters, as experimentally tested for the germination of seaweed spores (Wiencke et al., 2006). However, under natural field conditions, kelp spores germinating under parental canopies might not be exposed to harmful UV-B, and it remains questionable to what extent biologically significant UV-B fluxes will propagate into subtidal communities (i.e., deeper than 10 m; Laeseke et al., 2019).

Summary

Models show that a global temperature rise of +2°C will translate to +4°C of warming in the air temperature of the Arctic (Overland et al., 2019), with the worst-case scenario showing +15°C of winter air warming by 2100 (Overland et al., 2019). One must also consider the disproportionately larger surface heat fluxes into the Arctic (Bischof et al., 2019) that may inhibit the stabilisation of the global climate even if an effective emissions reduction strategy is implemented (Overland et al., 2019). There is therefore a high level of certainty that the rate of increasing seawater temperature will further accelerate in the future (Meredith et al., 2019).

Rapidly increasing seawater temperatures appear to be accelerating the phenomenon of Atlantification, a process that will potentially decrease the density differences between polar surface water and the AW that rest below, which in turn may lead to more mixing and larger ocean heat fluxes towards the surface (Polyakov et al., 2020). The changes to the salinity itself may also cause trophic restructuring of the ecosystems throughout many Arctic fjords (see section “Biomass”), with inherent knock-on effects to the human societies that are structured around present ecosystem services (see section “Fisheries”).

Less clear than the increases in temperature and changes in salinity are the changes to light penetration in Arctic fjords. While it appears evident that light penetration in the open Arctic Ocean will increase over time (Pavlov et al., 2019), it is still unclear whether or not this will hold true within fjords. While sea ice is melting rapidly within most fjords, there is also an increased rate of turbid water runoff. So while there is a longer period in which light may contact the sea surface, it is becoming more difficult for light to penetrate these waters. This is an area of investigation that still requires much research (e.g., Walch et al., 2022).

Chemistry drivers

Carbonate system

Increased atmospheric carbon dioxide (CO_2) globally raises the partial pressure of CO_2 in seawater (pCO_2). The ocean has absorbed >25% of anthropogenic CO_2 emissions since the industrial revolution (Friedlingstein et al., 2022), which moderates climate change at the cost of ocean acidification, a process that describes the increase in dissolved inorganic carbon (DIC), the concomitant decline of pH, and the saturation state of calcium carbonate ($CaCO_3$; Gattuso and Hansson, 2011). The projected decrease in pH and $CaCO_3$ saturation state will lead to undersaturation of surface waters with respect to aragonite-type $CaCO_3$ in the entire Arctic Ocean by 2040 (Steinacher et al., 2009). This undersaturation has already been observed *in situ* throughout many Arctic Seas from 2008 onwards (e.g., Zhang et al., 2020; Fransner et al., 2022). This is due in part to the decrease of salinity (see section “Salinity”), which lowers the buffering capacity of these systems (Qi et al., 2022). Aragonite undersaturation has negative consequences on ecologically important aragonite-shelled organisms in Arctic fjords (see section “Biomass”; Comeau et al., 2012), which may have large knock-on consequences for a number of other taxa (see section “Species richness”; Bednaršek et al., 2021; Niemi et al., 2021).

Nutrients

Besides light, macronutrients (e.g., nitrate [NO_3], nitrite [NO_2], ammonium [NH_4], phosphate [PO_4], silicate [SiO_4], and iron [Fe]) are the key drivers of primary production (see section “Primary production”). Within the euphotic zone, the shallower depths where light levels are sufficient for photosynthesis, nutrients are typically the limiting factor for primary production (generally used up by algae, depending on the season). Organic matter sinking out of the euphotic zone is slowly degraded and nutrients are regenerated; however, these nutrients stay at depth, unavailable for primary production, unless deep water is mixed up to the surface (see section “Salinity”; Valiela, 2015). The process of deep water mixing is particularly important because nitrogen may enter fjords via organic matter that is not directly available to primary producers (see section “Primary production”) and must be degraded by bacteria and archaea into bioavailable forms while at depth (e.g., NO_3 and/or NH_4; Valiela, 2015).

Four well-studied processes that can bring deep nutrient-rich water masses to the euphotic zone are the following (Cottier et al., 2010):

1) melting at the marine-terminating face of glaciers that drives local upwelling (see section "Glacier mass balance"),
2) reduced stratification of the water column in winter, typically weakened by decreased meltwater runoff (see section "Terrestrial runoff"), allows deeper mixing of the water column by physical forces (e.g., winds and tides),
3) surface currents exiting fjords over steep slopes (e.g., shelf breaks), and
4) icebergs melt from below driving local upwelling similar to marine-terminating glacier fronts (Moon et al., 2018).

Glacial meltwater is one of the primary sources of nutrient input into fjords and may be rich in SiO_4 and Fe depending on bedrock geochemistry (Halbach et al., 2019; Hopwood et al., 2020). PO_4 may also be introduced by meltwater where it is quickly scavenged (Hopwood et al., 2020). Land-terminating glaciers may provide even higher levels of nutrients and organic matter in systems with high levels of snowmelt and/or soil/permafrost leaching, which has large implications for local fjord ecology and adjacent coastal communities (Harris et al., 2018; Kotwicki et al., 2018; McGovern et al., 2020; Delpech et al., 2021).

River runoff is another primary input, with nutrient and organic loads that tend to be similar to neighbouring glaciers. A consideration for riverine inputs that differ from glacial is the increased nutrient load attributed to wastewater from human activities (Tuholske et al., 2021). In Isfjorden, for example, where one may find the largest human settlement on Svalbard, nutrient concentrations in river runoff (i.e., $NO_2 + NO_3$) can be 12-fold higher than in the uninhabited regions of the fjord (McGovern et al., 2020). Very rapid and sudden precipitation events may also lead to high-nutrient freshwater plumes in fjords, but whose effects on local ecosystems tend to remain very localised (McGovern et al., 2020).

Summary

If the concentration of CO_2 in the atmosphere keeps increasing as it has done in past decades (IPCC, 2021), the impacts of the seawater CO_2 system on shell-forming organisms will almost certainly become more severe. The weakening or possible local extinction of these organisms may lead to an entire trophic restructuring of ecosystems both within and adjacent to fjords due to the trophic importance of these organisms to small pelagic fish and birds (see section "Biomass"; Bednaršek et al., 2021).

Nutrient loading of Arctic fjord waters is likely to increase in the future due to higher rates of river runoff, glacial melt (see section "Terrestrial runoff"; Santos-Garcia et al., 2022), and precipitation (Frigstad et al., 2020), in combination with increased human activities. Therefore, the biogeochemical properties of fjords are projected to change apace with the climate (McGovern et al., 2020). As more glaciers transition from marine- to land-terminating, their fjords will have fewer methods through which deep water mixing resupplies nutrients to the surface. The loss of icebergs caused by the change in a glacier's status may reduce the transport of nutrients further out towards its mouth, resulting in a tighter concentration at the points of entry for freshwater runoff. These reductions to nutrient input may be offset by increased rates of terrestrial runoff, another point of research whose future outcome remains uncertain.

Lastly, and perhaps most dramatically, future warming may result in a winter melt, thereby preventing the normal seasonal recirculation of nutrients from deep waters and creating a situation where the nutrients in sinking biological matter are no longer resupplied to fjord ecosystems in the euphotic zone. Taken all together, the dramatic warming in the Arctic will likely lead to many fjords losing three of their four primary processes of deep water recirculation. The remaining process, surface currents exiting fjords, may become stronger due to increased river runoff.

Biology drivers

Primary production

Primary productivity in Arctic fjord ecosystems is a foundational measure of the trophic energy available in an ecosystem and has extreme interannual variability due to the multitude of non-linear interactions between physicochemical processes in nearshore systems (Hopwood et al., 2020). Increasingly frequent warm water intrusions and glacial melt are affecting the inter-annual duration and stability of the pycnocline (i.e., surface salinity; section "Salinity") and biological pump (i.e., deep water upwelling; section "Nutrients"), thereby modifying phytoplankton bloom periods and their species composition (see section "Species richness"; Piwosz et al., 2009; Wiencke and Hop, 2016).

Arctic fjord primary production is heavily seasonal, with the highest levels typically reached during phytoplankton bloom events in spring and occasionally autumn. The spring bloom occurs when the nutrients supplied by the deep mixing in winter (see section "Nutrients") are joined by the sufficient light availability of the spring (see the section "Light (PAR and UV)"). A second bloom may develop in late summer when upwelling driven by marine-terminating glacial melt (see section "Nutrients") supplies enough additional nutrients to the euphotic zone (Juul-Pedersen et al., 2015). The separate autumn bloom is driven by the seasonal weakening of water column stratification that leads to an increased deep water mixing while light is still sufficient for photosynthesis (e.g., Eilertsen et al., 1989).

Even though primary productivity is undoubtedly an important ecological factor in the shallow margins of Arctic fjord systems, with only a few exceptions, it has not been comprehensively quantified. In Kongsfjorden (W Spitsbergen), the loss of sea ice (see section "Sea ice") has led to changes in spring bloom dynamics, with higher light levels in the water column (see section "Light (PAR and UV)") earlier in the year driving earlier spring blooms with higher biomass and diversity (see section "Species richness"; Hegseth and Tverberg, 2013). Pelagic primary productivity in this fjord has been estimated across multiple studies conducted over a 20-year period (1979–1999) and ranges from 4 to 180 $mg\,C\,m^{-2}\,yr^{-1}$ with no clear predictive trend or continuity (Hop et al., 2002 and references therein; Duarte et al., 2019). Primary production in Nuup Kangerlua (W Greenland) follows a recurring seasonal pattern with the highest production and biomass during the spring bloom or late summer (Juul-Pedersen et al., 2015; Krawczyk et al., 2018). Primary production in Godthåbsfjorden (Nuup Kangerlua, W Greenland) has smaller interannual variability with ranges between 84.6 and 139.1 $g\,C\,m^{-2}\,yr^{-1}$ (Juul-Pedersen et al., 2015).

Biomass

Phytoplankton biomass is directly related to primary production (see section "Primary production"); however, loss of this biomass can be related to grazing, viral or fungal lysis (e.g., Hassett et al., 2019), or sedimentation. Thus, high primary production does not necessarily lead to high phytoplankton biomass. Due largely to Atlantification (see section "Salinity"), a significant northward advance of temperate phytoplankton and changes of the planktonic organism size distribution towards smaller organisms (i.e., pico- and nanoplankton) have been observed (Oziel et al., 2017; Neukermans et al., 2018; Konik et al., 2021). This means that climate change may be mediating trophic shifts in fjord ecosystems, a process referred to as "borealisation".

The biomass of zooplankton communities in Arctic fjords relies heavily on the seasonal availability of highly productive phytoplankton (Vereide, 2019), making zooplankton one of the main pathways connecting pelagic primary production (see section "Primary production") to larger predators. Zooplankton biomass is also affected by local scale perturbations in temperature (see section "Seawater temperature"), salinity (see section "Salinity"), and light availability (see section "Light (PAR and UV)"); all of which are in flux due to the changing climate. The borealisation of West Svalbard fjords, due to Atlantification, is already affecting seabirds via its impacts on zooplankton (Descamps et al., 2022).

The shifting of the large ocean currents in the Arctic will have widespread effects on pelagic macrozooplankton (i.e., copepods, euphausiids, and amphipods). It was found that the warming occurring in the Kongsfjorden ecosystem (W Svalbard), largely due to increased AW inflow (see section "Seawater temperature"), is having a positive effect on the abundance of euphausiids and amphipods (Dalpadado et al., 2016), which are key prey for target fishery species (see section "Fisheries") such as capelin and polar cod (Dalpadado et al., 2016). As the borealisation of the fjords along Western Svalbard continues, it may alter the population dynamics of key prey macrozooplankton species so dramatically that the changes may be tracked by monitoring the diets of local black-legged kittiwakes (Vihtakari et al., 2018).

Although macrophytobenthos (seaweeds and seagrass) are mostly restricted to a narrow spatial stretch along fjords, being dependent on either rocky substrate (seaweeds) or light-flooded sandy sediments (seagrass), their local biomass can be considerable. The vertical structures they create as ecosystem engineers also translate into a strong bottom-up effect in Arctic fjords. Increases in the biomass of these communities over time have been observed (Kędra et al., 2010; Bartsch et al., 2016), and even though the *in situ* sampling in the study was spatially limited, the findings were striking enough to conclude that a regime shift of the rocky-bottom community occurred via a sharp increase in macroalgae cover in 1995 (Kortsch et al., 2012). Indeed, a pan-Arctic study of 38 sites showed a general increase in abundance, productivity, and/or biodiversity, with a poleward migration rate of 18–23 km per decade (Krause-Jensen et al., 2020). An *in situ* study in Kongsfjorden (W Svalbard), which compared macroalgae biomass records from 2012 to 2014 against those from 1996 to 1998, found that biomass at the 2.5 m depth had increased by 8.2-fold, and that the community had shifted to shallower waters (Bartsch et al., 2016). The two forces driving shallower shifts in macrophytobenthos biomass are

1) decreases in sea ice cover (see section "Sea ice") mean less ice scour and more PAR penetration at the shallow depths macroalgae like to inhabit (Fredriksen et al., 2019 and citations therein) and
2) increased turbidity, which inhibits PAR penetration (see section "Light (PAR and UV)") to the historically deeper range where macroalgae have been found (Bartsch et al., 2016).

Demersal fish have a strong top-down effect on fjord ecosystems via predation, and their distribution in fjords is strongly driven by along fjord salinity and temperature gradients (Mérillet et al., 2022). Fjords with a sill (i.e., physical barrier) that guard the inner waters from external oceanic forces create very cold habitats that harbour specific communities (Kędra et al., 2010; Węsławski et al., 2011). These are hypothesised to offer a refuge for Arctic endemic species against increasing seawater temperatures (see section "Seawater temperature"; Węsławski et al., 2011; Drewnik et al., 2017). This may be particularly important as continuing poleward expansion of boreal communities and corresponding decreases in dominance of Arctic communities is being observed (see section "Species richness"; Jørgensen et al., 2019), which will likely have widespread impacts on the established fisheries in the Arctic (see "Summary" of "Social drivers" section).

Species richness

In addition to the primary production of an ecosystem and the biomass therein, the richness of species, their diversity, and evenness are critically important for stable functioning (Díaz and Cabido, 2001; Gamfeldt et al., 2015; Isbell et al., 2018). Meaning that the more diverse the assemblage of species in an ecosystem is, the more likely that system will be able to withstand a range of external stressors, based on the insurance hypothesis that some species will have redundant characteristics (i.e., biological traits) and that the ones that will survive will be able to maintain the ecosystem functions performed (Yachi and Loreau, 1999; Lamy et al., 2019). A consideration of paramount importance given the massive and rapid impacts that climate change and other human activities are having on Arctic fjords.

The first impacts of climate change on flora or fauna within the European Arctic (i.e., Greenland, Svalbard, and Northern Norway) were noted by Blacker (1957), followed by a long pause until research on the species richness of rocky shore communities within European Arctic and sub-Arctic fjords showed that they had increased (Hansen and Ingólfsson, 1993; Włodarska-Kowalczuk et al., 2012; Fredriksen et al., 2019 and references therein). Due primarily to warming seawater (see section "Seawater temperature"), an increase in species richness of rocky littoral microorganisms has also been recorded on Svalbard (Węsławski et al., 2010). Similarly, fish species richness has significantly increased in Porsangerfjorden (N Norway) over 2007–2019, facilitated by reductions in sea ice cover (see section "Sea ice") and the freshening of water (see section "Salinity"; Mérillet et al., 2022).

While seawater temperatures in Arctic fjords remain below the present mean of 3°C, rising temperatures are projected to *decrease* species richness; however, upon passing that 3°C threshold, species richness is projected to begin to *increase* (Benedetti et al., 2021). Plankton species richness in particular is expected to see an overall increase with global warming as species shift poleward (see section "Biomass"; Benedetti et al., 2021). However, most decreases are expected in East and Southwest Greenland and West Svalbard (Benedetti et al., 2021). The temperature of seawater (see section "Seawater temperature") is described as the primary cause of the overall increase to species richness in the Arctic, with nutrients (see section "Nutrients") playing an additional role in some areas (Benedetti et al., 2021). Due to the almost certain continued increases to both of these drivers, it is likely that while species richness in fjords may decrease in the short term, on a multi-decadal scale it is likely that borealisation of fjord species (see section "Biomass") will lead to an overall increase in species richness (with the possible exception of plankton). Unfortunately, this will not necessarily equate to a more resilient ecosystem because the incoming boreal species may lack the same diversity of functional traits found in Arctic species (Kędra et al., 2015; McGovern et al., 2020).

Climate change and increased anthropogenic activities are expected to contribute to the potential increases to species richness largely by elevating the potential for the introduction of non-indigenous species (NIS; Chan et al., 2019), which when established in novel ecosystems are often able to outcompete local species (Wood et al., 2011). There is a particular risk of this along the coasts of Northern Norway and West Svalbard, where warming water masses and high potential for advection via the North Atlantic Current and WSC are good preconditions for the introduction of NIS (Węsławski et al., 2011; Tarling et al., 2022). In the Greenland Sea/East Greenland area, three known NIS have already been introduced (among them the Pacific diatom *Neodenticula seminae*) and five in the Barents Sea/Svalbard area. Among those, the following have become established: the Japanese skeleton shrimp *Caprella mutica*, the copepod *Eurytemora americana*, the Chinese mitten crab *Eriocheir sinensis*, and the red king crab *Paralithodes camtschaticus* (Chan et al., 2019). Of these, king crabs were intentionally introduced to the east of Porsangerfjorden (N Norway) in the 1960s to establish a commercial fishery (see "Summary" of "Social drivers" section), and are now spreading west over the north of Norway, causing widespread trophic perturbations (Dvoretsky and Dvoretsky, 2015).

Summary

Decreases of sea ice cover (see section "Sea ice") in the open Arctic Ocean have been associated with increased primary productivity (Ardyna and Arrigo, 2020), but this relationship has not yet been conclusively measured in fjords. It is, however, hypothesised that this will eventually become a measurable relationship because further warming of seawater (see section "Seawater temperature") within fjords will almost certainly result in prolonged sea iceice-free periods and larger volumes of meltwater (see section "Terrestrial runoff"), which will provide more nutrients that fuel primary productivity (Piquet et al., 2014).

It is generally agreed that most Arctic fjords ecosystems will experience radical community changes, with many going through stable state shifts from Arctic to boreal (Kortsch et al., 2012; Fossheim et al., 2015; Pecuchet et al., 2020), though how these changes will look remains unclear. For example, it is known that demersal fish communities have an inherent adaptive capacity to survive long periods of seasonally low food availability (Sun et al., 2009), which in combination with their opportunistic feeding strategy (Iken et al., 2010; Węsławski et al., 2011) might translate to some degree of stability in the face of the climate-driven changes to fjord ecosystems. Modelling efforts to predict the impact of potential warming and acidification scenarios by 2100 on demersal fish showed that habitat loss would be small (0–11%), with no appreciable difference between losses for Arctic and Arctic-boreal species (Renaud et al., 2019). The extent of marine forests (macrophytobenthos) within the Arctic basin is also predicted to remain stable (Bringloe et al., 2022), if not increase due to the changing climate (Krause-Jensen et al., 2020). The depth structure of these forests, however, is likely to shift to shallower waters (Bartsch et al., 2016).

Until recently, the climatic conditions around Svalbard acted as a barrier to the spread of NIS, but the Atlantification (see section "Salinity") of the marine environment has partly removed this (Øian and Kaltenborn, 2020). The encroachment of NIS, due to borealisation, is currently squeezing Arctic species further northward (Fossheim et al., 2015; Kortsch et al., 2015). A process that will almost certainly continue into the future (Filbee-Dexter et al., 2019). It has been noted, however, that assemblages in Svalbard will likely remain different from those in Northern Norway due to the greater direct human influence on the continent (Kujawa et al., 2021).

Social drivers

Governance

There are many ways that changes to the drivers detailed above may affect Arctic livelihoods, culture, identity, economy, health, and security, especially for Indigenous Peoples (IPCC, 2021); however, these are not the only drivers of change in the Arctic. Through its top-down control of human societies, governance may have broader impacts on Arctic fjord socio-ecological systems than nearly all other aspects of climate change by controlling the rapid and dramatic direct local impacts that human actions may have on the natural world (Tyler et al., 2007; Hovelsrud and Smit, 2010).

Self-determination in managing climate change impacts has inspired Greenlandic politicians to contemplate joining the Paris Agreement and to look for investors to expand the hydro-power resource enabling the storage and export of green energy within a decade (Bjørst, 2022). In parallel, the national strategy for oil and gas exploration has been abandoned. As another way to grow and diversify its economy, Greenland is in the process of building two international airports to improve transport and connectivity, specifically around tourism (see section "Tourism"). These two examples showcase how the Government of Greenland is managing the right to resources, subsurface and hydropower installation, and how regional governments are becoming key players for domestic development that are increasingly empowered to act on negative trends affecting the regional population, but in ways that may have negative ecological consequences.

In 2018, the Norwegian government decided to close most of its coal mines on Svalbard (the primary original reason for human settlements there) and identified tourism (see section "Tourism") as a new cornerstone industry (NMJ, 2016). Concurrent with this recent shift is the goal for Svalbard to ensure the best wilderness management in the world (MoCE, 2020). Strict regulations have been followed, and currently underway is a major overhaul and tightening of the environmental protections and tourism management for the archipelago (Granberg et al., 2017; NEA, 2022).

Tourism

In recent decades (until the onset of COVID-19 countermeasures in early 2020), there has been an increasing global interest in the Arctic as a tourist destination, particularly fjords. Promoting this increase in tourism has been an intentional governance choice (see section "Governance"), with the stated goal being the development and diversification of the economies of the sparsely populated peripheral regions of Nordic countries (Ren et al., 2021a). This has, however, led to growing human impacts on small and remote destinations where signs of human activities had yet been scarce, and where these anthropogenic disturbances may have wide-ranging consequences.

Ironically, the changing climate is currently serving as a net benefit to Arctic tourism, with tourist arrivals via cruise ship in Longyearbyen (W Svalbard) doubling from 2010 to 2018 (Port of Longyearbyen, 2018; Epinion, 2019). This has led to calls for opportunity-based adaptations to the cruise tourism influx (Dawson et al., 2016) because the warming Arctic and its melting sea ice (see section "Sea ice") will ensure that coastal destinations remain the most accessible. This is an important consideration because in addition to the impacts of the humans themselves, the ships they use for transport to and from the Arctic may drive changes in a number of different ways. Some of these may be more apparent, like the introduction of nutrients (i.e., via human waste; section "Nutrients") and pollutants (Øian and Kaltenborn, 2020), but some less so, like the introduction of NIS (see section "Species richness"; Hellmann et al., 2008; Goldsmit et al., 2018). These are transported on the hulls of ships, via the emptying of ballast water (Chan et al., 2013), or by the tourists themselves. Weaver and Lawton (2017) argue that the potential economic benefits of cruise tourism in small coastal communities may be outweighed by their social and environmental stressors, and Ren et al. (2021b) stress the need for more locally based management of Arctic cruise tourism.

While human activities in the permanent settlements of Svalbard do have an environmental footprint, this is easily rivalled by that of tourism, where residents are outnumbered by tourists during the high season (Hovelsrud et al., 2021). Tourists arriving in Isfjorden (W Svalbard) tend to spend less than 3 days on the archipelago (Hovelsrud et al., 2021), but the increase in tourist arrivals has meant a doubling of total tourist nights per year (Visit Svalbard, 2020). Management decisions (see section "Governance") to deal with this issue are ongoing (Hovelsrud et al., 2020). Of the cruise ships arriving on the archipelago, the average number of overseas arrivals per year has decreased (Stocker et al., 2020), most likely due to a ban on heavy oil fuel in most of the coastal waters of Svalbard. This is endemic to a shift towards smaller expedition cruises and pleasure craft vessels, which have increased by 42% from 2008 to 2018 (NEA, 2022). These smaller vessels benefit more from the retreating sea ice edge (Palma et al., 2019; Hovelsrud et al., 2020) due to their ability to sail closer to the ice-edge and glaciers, a demand for which has become a recent market trend (Hovelsrud et al., 2021).

Accounting for about a third of all foreign visitors, cruises have for many years been a central part of tourism in Greenland. The country has previously set annual growth targets for cruises as a whole. However, Visit Greenland announced in late 2022 that it will abstain from marketing to conventional cruises after a summer with cruise tourism numbers matching the record year of 2019 (Visit Greenland, 2022). Whether this may actually enable a move from conventional cruises to cleaner and socially less impactful expedition cruise tourism remains to be seen but will have crucial implications for the fjord systems of Greenland as a return to mass tourism will mean greater anthropogenic impact in the future.

Fisheries

Besides adding nutrients (see section "Nutrients") and pollutants, humans also engage in extractive behaviours that can upset natural trophic balance. These disturbances are generally monitored via target species and regulated by the management of fisheries (see section "Governance"). However, fishing also affects non-targeted species as well as the structure of the habitats, such as the use of bottom trawls (Gray et al., 2006; Kaiser et al., 2006). While the impacts of tourists are generally inferred via head counts at ports of call, the proxy for tracking the impacts of fishing vessels in the Arctic is by monitoring ship mileage. This value has been increasing in the waters around Svalbard as the ice edge steadily retreats (see section "Sea ice"; Stocker et al., 2020), and the duration of the operational season extends (i.e., longer sea iceice-free period per year). Unsurprisingly then the overall number of ships in the Arctic increased by 25% from just 2013 to 2019 (Stocker et al., 2020).

In Porsangerfjorden (N Norway), the shrimp fishery, which used the ecologically damaging method of bottom trawling, was closed in the early 1970s after intensive fishing caused the over-exploitation of cod as well as small and young fishes (Søvik et al., 2020). This fishery was, however, opened again in 2021 for trial with only a few boats allowed to fish in the outer part of the fjord (G. Søvik, pers. comm.), a demonstration of the direct impact that governance (see section "Governance") can have on a local ecosystem. Fishing for cod (*Gadus morhua*), saithe (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*), and red king crab (*P. camtschaticus*) had always been allowed in the fjord with other less damaging gear. Red king crab in particular has become an important commercial fishery with 921 t landed in 2018 (Søvik et al., 2020). Originally a NIS (see section "Species richness"), the adaptation of a fishery for red king crab (Sundet and Hoel, 2016), has potentially aided the recovery of kelp forests in Northern Norway by reducing sea urchin grazing pressure (Christie et al., 2019), and is a good example of how governance can help to adapt to the inevitable changes that Arctic fjord ecosystems will experience.

The largest city of Greenland lies at the mouth of Nuup Kangerlua, where hunting for seals and seabirds, as well as fishing for cod, halibut, and redfish is common. Humpback whales have been protected inside the fjord since 2021, while other species remain open for hunting. As of today, fishing is the main economic sector for the country (Grønlands Økonomiske Råd, 2021). And while fisheries are affected by the changing climate, government regulations (see section "Governance") and changes to the international prices on fish and shrimp likely have a greater impact. In 2021, for example, (because of COVID-19) the prices for cod dropped suddenly compared to previous years, leading to widely felt economic hardships (Andersen, 2022). To limit this reoccurrence, development in the formal economy is seen as important by decision-makers and business owners. However, fishing, hunting, and gathering activities remain a key part of the region's mixed economy and hold great cultural and social value. This means that it is particularly difficult for the government of Greenland to tightly regulate the extractive behaviour of its citizens, and thereby the ecological impacts they may have. It is in part to address issues like this that many governments of Arctic nations have been leaning away from extractive economic strategies in favour of tourism (see section "Tourism").

The northernmost fisheries on the planet, found in the fjords and waters around Svalbard, have been strictly regulated since 1977 when Norway claimed the right to regulate fishing 200 nautical miles around Svalbard under the Norwegian Economic Zone Act (reduced slightly in 2010 when a final dividing line agreement with Russia was made). Since 1980, the Directorate of Fisheries has collected detailed information on landings from Norwegian fishers in the Svalbard zone (Misund et al., 2016), and the main fisheries are Atlantic cod *G. morhua* with close to 75 million tonnes fished in 2021 with an estimated value of 1.2 billions NOK (or 114.2 million €), followed by shrimp (*Pandalus borealis*; 27.3 million tonnes; 550 million NOK or 52.3 million €), haddock (*M. aeglefinus*; 22.1 million tonnes; 331 million NOK or 31.5 million €) and snow crab (*Chionoecetes opilio;* 6.3 million tonnes; 586 million NOK or 55.7 million €; Fiskeridirektoratet, 2022). Within the coastal zone/fjords of Svalbard, the core areas for fishing (mostly for shrimp) are Isfjorden, Krossfjorden, and Hinlopen. At present, it is not possible to deliver landings directly to local communities on Svalbard, with most going to mainland Norway. While there is interest to develop the necessary local infrastructure, it has been inhibited by strict environmental regulations (see section "Governance"). A few local hunters provide seal meat and Atlantic cod to restaurants in Longyearbyen, and it is popular for the locals to fish cod and hunt seals for their own use.

Summary

It is very difficult to predict what the future social structure of Arctic communities will look like. One can, however, seek to understand how and why these societies have changed in the past and present (AMAP, 2017). Future policies that may be developed in order to adapt to the changing personal decisions of the inhabitants of the Arctic will in turn have top-down impacts on many of the drivers detailed in previous sections. One must also remember that the results of climate change research do not automatically translate into adaptive human behaviour (Hovelsrud et al., 2015). Indeed, the many international climate meetings (e.g., Conference of the Parties [COPs]) and IPCC projections on the changing climate have had seemingly little impact when introduced into national politics and everyday lives. The need for economic growth and the development of new infrastructure in Arctic communities may very well lead to an increase in CO_2 emissions, rather than a reduction, meaning that social drivers may negatively impact the Arctic climate system even more in years to come. For example, the increase in local pollution in the form of CO_2, sulphur, black carbon emissions, and nutrient runoff are directly affected by how northern communities decide to manage the tourism industry (see section "Tourism"). The failure (or success) of local ecosystems and key taxa are also directly influenced by choices in how to manage northern fisheries (see section "Fisheries") and the potential expansion of aquaculture endeavours (Heath et al., 2022), such as the farming of kelp forests.

Social drivers of change are generally perceived first and foremost to have local impacts, but they too are capable of having widespread feedback on the other categories of drivers. For example, while various aspects of climate change will likely have the largest impact on ecosystems and species in the future (Thierry et al., 2022), the greatest impacts historically have come from human overexploitation of species and destruction of their habitats (Caro et al., 2022). The melting Arctic will allow for even greater exploitation of the resources therein, which will have entirely new impacts that until present had not been possible.

Conclusions

Arctic fjords are changing rapidly at nearly every measurable level. Therefore, a clear understanding of the relationships of these drivers with each other in the past, present, and how they may change in the future is necessary for designing effective adaptation strategies (Søreide et al., 2021). Some of these changes, such as the increase in sea ice-free days, are easier to project than others, such as whether governance decisions to create economic growth will focus on developing industry over ecological protection. In this review, we have provided a summary of the knowledge of the key drivers of change in socio-ecological Arctic fjord systems (Table 1), and how those drivers interact with one another (Figure 2). Below, we provide a discussion on the choice of the drivers, gaps in knowledge, future changes, and concluding remarks.

The list of drivers in this review was very carefully considered. A much longer list of drivers was initially constructed, but many were cut when no literature supporting their importance within Arctic fjords was found. An illustrative example is dissolved oxygen in fjord waters. The general global trend shows oxygen levels are decreasing and will continue to do so in a changing climate (Breitburg et al., 2018). There is, however, very little research on this issue in the Arctic, leading the IPCC to give medium confidence

Table 1. The main point to consider for each driver of change, and the summary per category

Category	Driver	Main point
Cryosphere	Sea ice	Sea ice is melting so rapidly that ice-free periods are lasting for most if not all year long.
	Glacier mass balance	Glacier melt is so advanced that many are beginning to transition from marine-terminating to land-terminating.
	Terrestrial runoff	The increased rate of runoff from glaciers and rivers is increasing surface nutrients, turbidity, and stratification.
	Summary	*The Arctic cryosphere as a unique ecosystem may completely disappear.*
Physics	Seawater temperature	The temperature of seawater is increasing at the surface and depth much more rapidly almost anywhere else on Earth.
	Salinity	Changes of large ocean currents is causing the "Atlantification" (increased salinity and nutrients) of many W Svalbard fjords, which will likely increase in the future.
	Light	The loss of sea ice increases the potential for more light to enter the water, but increases in turbidity are counteracting this to an uncertain degree.
	Summary	*The rate of climate change to the physical environment will not abate and can only be reduced and perhaps stopped by implementing the Paris Agreement in a full and timely manner.*
Chemistry	Carbonate system	The waters of Arctic fjords will continue to acidify apace with, or more rapid than, global CO_2 emissions.
	Nutrients	Increasing terrestrial runoff and continued human development/tourism mean an almost certain increasing trend in nutrient inputs to Arctic fjords.
	Summary	*The chemical composition of seawater will continue to alter rapidly, likely having ecological impacts on the mid to lower trophic ranges.*

(*Continued*)

Table 1. (*Continued*)

Category	Driver	Main point
Biology	Primary production	Primary production will likely increase apace with rising temperatures, glacial melt, and nutrient inputs, even though surface waters will darken.
	Biomass	The low to mid-range trophic levels of many ecosystems will likely see extreme borealisation (i.e., replacement by species from the south), but the macrobenthos may remain relatively stable (e.g., demersal fish) or even increase (e.g., kelps).
	Species richness	Non-indigenous species (NIS) will likely outcompete Arctic endemics, causing short-term decreases to species richness, but this trend will likely reverse as ecosystems shift to a stable boreal state.
	Summary	*While some Arctic species may remain, future ecosystems will likely have mostly boreal characteristics, potentially weakening their overall resilience.*
Social	Governance	Because the need for economic development is large for most human communities, it is not clear whether ecologically responsible governance choices will be made.
	Tourism	Tourism and its impact will continue to increase, but a strong trend towards ecological responsibility is emerging.
	Fisheries	The shift towards tourism creates economic opportunities that may alleviate pressure from fisheries practices, which is a positive signal for increased ecological protection.
	Summary	*Governance can have greater impacts on local taxa/ecosystems than climate change, and it appears the future may be tipped more towards ecological choices rather than industry.*

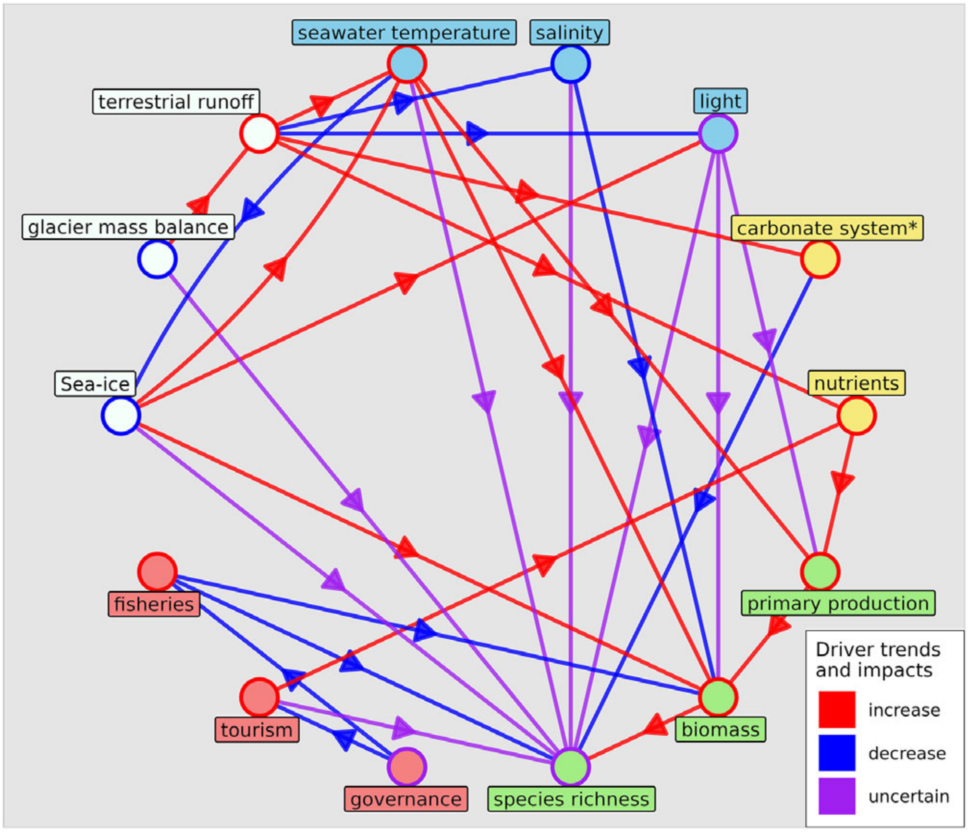

Figure 2. Network chart of the interactions between the drivers of change in Arctic fjord socio-ecological systems as determined from a review of the literature. The trend in the change of each driver (i.e., increasing, decreasing, or uncertain) is shown *via* the coloured borders of the labelled points. The impacts that the drivers have on each other are shown with coloured arrows. The categories of the drivers are shown with the internal colour of the points and their labels. Note that "positive"' governance is assumed here to be choices in favour of environmental protection rather than exploitation. It is for this reason that governance is shown here to have a negative impact on fisheries and tourism. The asterisk on the carbonate system is to note that it consists of several variables, including pCO_2, DIC, TA, pH, and $CaCO_3$ saturation state (see section "Carbonate system"), which do not vary in synchrony. The positive effect of increasing terrestrial runoff on the carbonate system refers to pCO_2 and DIC, whereas the negative effect on calcifying organisms refers to pH and $CaCO_3$ saturation state.

to the past trend (Arias et al., 2021). While decreasing oxygen levels will likely be deleterious for multicellular life in the global ocean (Storch et al., 2014), initial research in Arctic fjords shows they may be partially exempt (Kempf, 2020).

The melting Arctic will fundamentally reshuffle the biotic interactions within fjords, but will also increase the opportunity for fisheries and maritime traffic. For example, as multi-year sea ice becomes scarce to the north of Russia it will become an important arterial for shipping (e.g., Shanghai to Hamburg is 30% shorter than the Suez Canal route, saving 14 days of travel time/cost). Will Arctic communities adapt to these new logistical opportunities? Will they continue to exploit and extract from the natural world, or will the recent trends towards more ecologically responsible practices take root? One must also consider that once the Arctic cryosphere is mostly gone, tourism will almost certainly decrease. The main research gap then that persists in the social sciences is, in the face of the changing climate and the potential draw-down of tourism as a viable economic pathway, how can Arctic communities achieve sustainability given their need for long-distance travel and the increasing energy requirements to match economic development. In the natural sciences, a key unknown is how the light regime within Arctic fjord surface waters will change in the future, and how it will impact the borealisation of coastal communities.

Given that a range of data is collected in the Arctic via *in situ* measurements and remote sensing, it is possible to discern the numeric relationships for many of the drivers detailed above, and to project those relationships forward into the future based on different climate projections (Schlegel and Gattuso, in review). It is therefore possible to see where in the Arctic these historic relationships differ, and where the future projections may likewise diverge. Using the interplay of sea ice cover and seawater temperature as an example, while most fjords experience similar decreases in sea ice cover as fjord waters warm, the relationship at depth (>200 m) differs between Greenland and Svalbard due to the lack of Atlantification of fjord waters in the former (see section "Seawater temperature"; Schlegel and Gattuso, in review). It must be noted, however, that while the Arctic is becoming increasingly well sampled, data within most fjords remain scarce. The more thorough sampling of fjords, particularly for the 14 drivers covered in this review, should be an area of concerted future effort.

Without an immediate and massive reduction in anthropogenic emissions, accompanied by the rapid development and implementation of atmospheric CO_2 extraction technologies to limit global warming to 1.5°C by 2100, the Arctic cryosphere will be altered significantly (Meredith et al., 2019). Considering that the UN has concluded this is no longer possible, the work now is projecting when exactly massive significant shifts will occur (e.g., Wei et al., 2020). Of the published models for Arctic Ocean sea ice, the soonest predicted ice-free summer period over the North Pole is 2030, though most err towards 2050 (Wei et al., 2020). Taking into account the relationships between all of the drivers detailed in this review, and considering that the time scale of human governance only extends to 2050, we may conclude that many Arctic fjords will become entirely and irrevocably borealised in the coming decades. They may, however, continue functioning in some way resembling their current state, meaning that human strategies for adaptation will have to continue to change rapidly, but will likely not need to be fundamentally overhauled to match the types of ecosystems that are found below the Arctic circle. Taken all together, the drivers of change in socio-ecological systems weave a complex web of interaction, with no one driver or category being necessarily more or less important than another, and certainly, none of them can be excluded when one's aim is to create effective adaptation strategies for a changing future Arctic.

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Data availability statement. No data were generated or analysed for this review, however, this paper is accompanied by a sister paper (Schlegel and Gattuso, in review) that describes and analyses a data product whose compilation was directed by the knowledge generated during this review process. The data product itself is openly available on PANGAEA at: https://doi.org/10.1594/PANGAEA.953115.

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