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Cross-border dimensions of Arctic climate change impacts and implications for Europe

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Abstract

The Arctic has warmed almost four times faster than the rest of the globe during the past four decades. This has led to multiple impacts in the Arctic such as the melting of glaciers and the Greenland ice sheet, sea ice retreat, permafrost thaw, altered species distribution and abundance, changes in hydrology and snow conditions, and altered wildfire regimes. These documented and projected impacts in the region can also propagate across borders, creating risks and opportunities requiring adaptation responses well beyond the Arctic. By undertaking a systematic literature review that uses a conceptual framework for cross-border climate change impacts, we demonstrate how local impacts of the type described above, which are often analyzed separately in the literature, may initiate knock-on effects that can be transmitted and transformed across borders. We illustrate examples of six categories of cross-border risks resulting from this impact transmission and potentially requiring adaptation. These concern biophysical impacts, trade, infrastructure, finance, geopolitical relationships and human security and social justice. We examine potential adaptation options for responding to such cross-border risks that are of relevance for Europe. The systemic approach taken in this paper promotes improved understanding of trade-offs between potential benefits and risks, assists priority-setting for targeting adaptation interventions, and can account for the important role of non-climatic drivers in amplifying or dampening the cross-border risks of climate change impacts in the Arctic.

This article is categorized under:

- Trans-Disciplinary Perspectives > Regional Reviews
- Assessing Impacts of Climate Change > Observed Impacts of Climate Change
- Assessing Impacts of Climate Change > Evaluating Future Impacts of Climate Change
- Vulnerability and Adaptation to Climate Change > Learning from Cases and Analogies

KEYWORDS

adaptation, Arctic, climate change, cross-border, impact transmission, risks

1 | INTRODUCTION

The Arctic is warming much faster than the global average. Observations show that this Arctic amplification of surface air temperature has been about four times the global mean over the last four decades (Rantanen et al., 2022). This aligns with the high end of projections from global climate models, which show a range of amplification between two and four times, an uncertainty range that has not narrowed across four generations of model development (Douville, 2023; Lee et al., 2021).

Arctic warming has multiple impacts on the cryosphere, ecosystems, and societies (Ibarguchi et al., 2018). Several studies have examined how impacts of a changing Arctic climate can interact and may be transmitted into additional impacts, sometimes far away and of greater complexity than the original impacts (Edwards & Evans, 2017; Esau et al., 2023; Falardeau & Bennett, 2020; Instanes et al., 2016; Wrona et al., 2016). The propagation of impacts thus has the potential to extend beyond the Arctic region and create risks and opportunities for regions lying outside the Arctic (Alvarez et al., 2020; Kelmelis, 2011).

The paucity of literature on exposure to cross-border impacts was first highlighted in the context of national and European Union climate change risk assessments (Benzie et al., 2019), an observation reinforced in the IPCC Sixth Assessment Report (AR6), which identifies knowledge gaps with respect to inter-regional risks (O'Neill et al., 2022). To address this analytical shortfall, a framework for examining cross-border climate change impacts was developed by Carter et al. (2021), which represents impacts that propagate over space and time as an "impact transmission system." The starting point is a climate trigger, which can be an abrupt event, such as an extreme weather event, or a slow-onset event unfolding gradually over time, such as a long-term warming trend. The trigger causes an initial impact that propagates via different transmission mechanisms, eventually reaching a recipient region. Seven categories of impact transmission mechanisms were identified: trade, finance, people, psychological, geopolitical, biophysical, and infrastructure.

In this paper, we review some of the specific cross-border transmission mechanisms by which Arctic impacts are linked to non-Arctic regions. The IPCC AR6 describes climate drivers, impacts and risks requiring adaptation in polar regions, noting that "the implications of climate change impacts in the Arctic and Antarctic extend beyond their boundaries" (Constable et al., 2022, p. 2325). These are impacts as typically treated by Working Group II of the IPCC, and which we define here as "the effects on natural and human systems of extreme weather and climate events and of climate change" (Agard et al., 2014). Specifically, these are "effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services) and infrastructure." (IPCC, 2022). They are impacts, or potential impacts (risks), for which there may be adaptive responses that could be deployed by regions in receipt of such risks, beyond mitigation of the main drivers of anthropogenic climate change. Other interventions to influence climate feedback mechanisms, such as solar radiation modification (IPCC, 2023, p. 72), are not considered here.

A challenge for our study is to determine when an impact can be considered to propagate beyond the Arctic, not least because there are several definitions of the Arctic based on climatic, vegetational or jurisdictional criteria (e.g., compared in map form by Nilsson & Christensen, 2019, p. 2). Recognizing that these nuances in definition of the southern boundary of the circumpolar north pervade the literature on the Arctic reviewed here, we adopt a pragmatic rather than strict definition, noting that in most of the sources we cite, the region rarely departs greatly from that defined by the Arctic Monitoring and Assessment Programme (AMAP, 1998, p. 9).

The cross-border impacts that we focus on here are distinct from those that may arise through feedbacks in the global (or regional) climate system. These effects are largely captured, implicitly, in the climate trigger (see above). For example, it has been suggested that enhanced warming at high latitudes (Arctic amplification), in combination with reduced sea ice, may influence large scale and cross-border atmospheric circulation patterns and hence mid-latitude weather extremes (e.g., Cohen et al., 2020; Crawford et al., 2022), though the observational and model-based evidence for this is divergent (Doblas-Reyes et al., 2021). In the context of cross-border climate change impacts as defined here, climate extremes at lower latitudes attributed to slow-onset warming would be classified as teleconnected climate triggers (Carter et al., 2021). Unless they too occur in the Arctic, any initial impacts that they induce (i.e., outside the Arctic), while locally important, are largely beyond the scope of this paper. Of course, the two phenomena are not fully independent, as it is possible that cross-border impacts originally triggered in the Arctic and propagated outside may also be affected by teleconnected climate extremes attributable to the same climate trigger. For example, slow onset warming is opening up Arctic sea routes for trade with potential cross-border impacts on trade in mid-latitudes, which in addition may be affected by changing extreme weather related to Arctic climate systems.

Responses to warming in the Arctic need to be based on a systemic view of the complex interactions between the resulting climate change impacts (Callaghan et al., 2020; Mavisakalyan et al., 2023; Overland, 2022). Moreover, there is a high likelihood that propagation and subsequent amplification of impacts cause "surprising outcomes" (Falardeau & Bennett, 2020, p. 2). Aside from their effects on the natural environment, cross-border impacts can affect numerous different actors, including indigenous peoples, a multitude of countries, national and international organizations, and commercial interests (Ibarguchi et al., 2018; Shake et al., 2018; Shijin et al., 2023; Smieszek et al., 2021), posing novel challenges for coherent and integrated policy responses (Kivimaa et al., 2024).

This paper seeks to contribute to the understanding of cross-border impacts in two ways. First, it offers an extensive survey of cross-border climate change impacts originating in the Arctic that propagate beyond the Arctic, based on a review of peer-reviewed and gray literature. Second, it examines implications of cross-border risks for Europe and how the European Union (EU), as a recipient region, might consider them in adapting to climate change.

2 | DATA AND METHOD

We used the conceptual framework of Carter et al. (2021) to frame our review. In this framework, the focus is on the interactions and transmission of impacts requiring adaptation responses within and across Arctic boundaries, as explained in the introduction.

We conducted a scoping review (Stratton, 2019) of peer-reviewed and gray literature (i.e., non-peer-reviewed sources judged to be reliable, such as industry journals, government reports, working papers or conference proceedings), using Google Scholar and complemented by an analysis of the IPCC AR6. Through an initial scan, we identified the main cross-border climate change impacts originating in the Arctic. Following Carter et al. (2021) we searched for climate triggers, multiple initial impacts caused by those triggers and the subsequent propagation of impacts across systems and borders. This initial scan helped to guide a systematic literature review based on the methodology of Shaffril et al. (2021), using the Web of Science Core Collections database as recommended by Gusenbauer and Haddaway (2020). The time frame for the search was 2001–2023. Boolean operators were combined with truncation of terms (Shaffril et al., 2021). Some priority keywords were identified from the scoping phase: *climate change*, *impacts*, *Arctic*, *cross-border*, *adaptation*, *Europe*, with all relevant synonyms included in the search (upper part of Table A1). The search covered the full text of the articles and provided 255 references.

A second search was conducted that retained the terms related to climate change, impact and Arctic from the general search and added topical terms identified as relevant during the scoping review phase (middle part of Table A1). This focused only on the abstracts, with a goal to identify studies that contribute to an understanding of the chain of impacts. A total of 504 additional non-duplicate references were found.

Finally, a third search was conducted with the aim to find specific articles on how to adapt to cross-border impacts of climate change. To do so, this search combined the keywords *cross-border* and *impact*, retained keywords on *adaptation* and *climate change* and added a new set of terms around the notion of *method* (lower part of Table A1). Only abstracts were searched, yielding 264 references.

All results were then screened by examining, in sequence, the title, abstract, and in cases requiring further clarification, full article (Figure 1). To verify that our inclusion and exclusion criteria were being applied consistently, members of the author team undertook independent screening of overlapping samples, with any discrepancies resolved by consensus. Articles were excluded if they were too narrowly focused (e.g., on a particular species or location, without consideration of cascading or cross-border impacts), addressed mitigation, or were completely out of scope (for example, on the Alps or Tibet, which occasionally were identified as "Arctic" studies). An important aspect of the screening, responsible for the majority of discrepancies between the author team once inclusion and exclusion criteria were defined, was the fact that many articles only infer a potential of impacts to cross borders without explicitly stating this. For example, impacts on transport and energy infrastructures were not necessarily explicitly mentioned as cross-border impacts in some of the papers (Da Cunha et al., 2022; Porfiriev et al., 2019; Romero Manrique et al., 2018), whereas their consequences would clearly cross boundaries. Similarly, many studies referring to impacts on ecosystems and trophic levels mention cascading impacts, but do not necessarily explain if

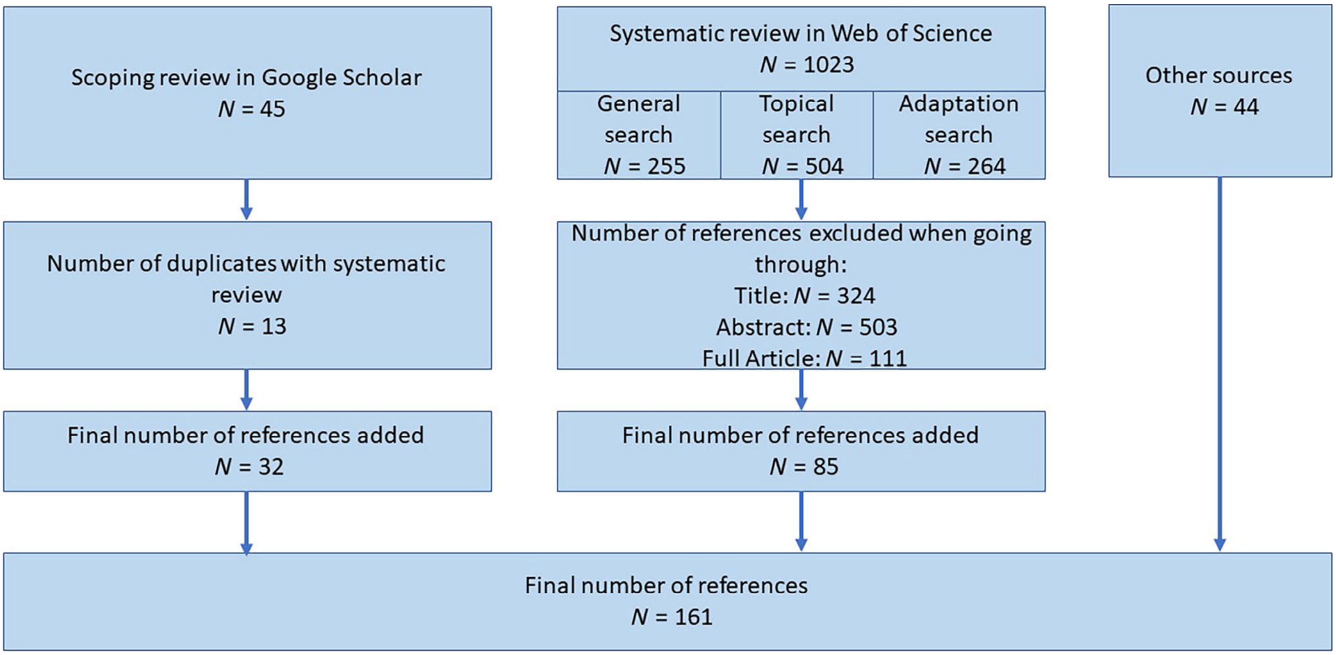

FIGURE 1 Method for the literature review.

the cascade might extend beyond the Arctic region. In such cases, it was necessary to read articles thoroughly to analyze whether cross-border impacts might be involved. Note also that articles that were not in English or not readily accessible were excluded from the study. After screening, our main data for the systematic literature review consisted of 161 references (Figure 1).

3 | CROSS-BORDER TRANSMISSION FROM THE ARCTIC

This section describes impacts of climate change of Arctic origin that may propagate to affect regions outside the Arctic. We first identify the main climate triggers for the Arctic, and show how these, on their own or in combination, may lead to a range of initial impacts. For each of six classes of initial impacts, we then highlight pathways by which they can propagate beyond the location of their original occurrence.

3.1 | Climate triggers and initial impacts in the Arctic

Three main Arctic climate triggers were considered:

- *Regional warming*, as a slow onset event that unfolds gradually over time. It is the primary and underlying climate trigger in the Arctic (Pedersen et al., 2022) that is attributable to anthropogenic causes, magnified by numerous and not fully understood feedback mechanisms (Rantanen et al., 2022). It is closely associated with the two other climate triggers.
- *Increased rain*, as a slow onset event characterized not only by a projected increase in precipitation but also by a shift towards more precipitation falling as rain (Cherry et al., 2017; Hansen et al., 2015; Kelman & Næss, 2019; Waits et al., 2018).
- *Changes in extreme weather events*, characterized by an altered magnitude and frequency of events towards the tails of frequency distributions, such as for variables related to seasonal and daily temperature, precipitation (including snow and freezing rain) and storminess (Esau et al., 2023; Pascual et al., 2021; Walsh et al., 2020).

Regional warming affects the cryosphere by causing *melting of glaciers and ice sheets*, *sea ice retreat* and *permafrost thaw* (IPCC, 2019). Recent warming has caused the Greenland Ice Sheet to lose around 5000 Gt of ice (equivalent to about 13.5 mm of global sea level rise) during the period 1992–2020 and the loss is expected to continue throughout the 21st century (Fox-Kemper et al., 2021). Similarly, glaciers throughout the Arctic are losing mass and projected to continue doing so (Fox-Kemper et al., 2021). The main driver of sea ice retreat since the late 1970s is very likely anthropogenic forcing (Eyring et al., 2021), and projections indicate that there will be at least one occurrence of a practically ice-free Arctic Ocean in September by 2050 (Fox-Kemper et al., 2021). Permafrost covers about 14.8 million square kilometers in the northern hemisphere, mainly in the circumpolar Arctic (Ran et al., 2022). An average decrease of 25% $\pm$ 5% $^\circ C^{-1}$ in the global volume of perennially frozen ground up to 3 m below the surface is projected for global warming of up to 3°C (Fox-Kemper et al., 2021).

Regional warming also *alters species distribution and abundance*. In marine systems, increasing temperatures and acidification (caused by increased absorption of carbon dioxide) are affecting species abundance, growth, and phenology (Barange et al., 2018; Crépin et al., 2017; Fassbender et al., 2017). Northward migration of marine species changes the species composition in Arctic waters and the risk of invasive species may increase (Burgass et al., 2019; Mueter et al., 2021; Yool et al., 2015). On land, a general increase in productivity and greenness is observed with open tundra changing to shrubland and the tree line moving to higher altitudes and latitudes (Box et al., 2019; Maliniemi et al., 2018; Pedersen et al., 2022). Evidence of the causal link between Arctic warming and Arctic greening has become increasingly compelling over the years (Berner et al., 2020; Callaghan et al., 2022), though other vegetation impacts are also observed. These include "browning" of vegetation, characterized by physical damage or mortality due to extreme events, and/or to reductions in productivity brought about by warming outpacing the ability of species to shift their ranges geographically or altitudinally. Satellite observations from 1985 to 2016 indicate that "37.3% of the Arctic has greened, 4.7% has browned, with 58% showing no change." (Callaghan et al., 2022, p. 1035).

Increasing precipitation and a shift from snow to rain *changes the state of surface water and snow conditions*. First, rain-on-snow events create ice crusts on snow cover (Pedersen et al., 2022). Second, increased rain on the surface of ice bodies accelerates glacial melting induced by warming (Vincent, 2020). Third, increased liquid precipitation increases runoff, which varies by season due to concurrent shifts in the timing of snow melt, and river and lake ice cover as the climate warms (Bokhorst et al., 2016).

Extreme weather events, such as heatwaves, intense precipitation, drought or storms, can have many effects on the cryosphere and ecosystems in the Arctic, with an altered *risk of wildfires* being a particularly important consequence. The frequency and intensity of wildfires are related to wind conditions, lightning, droughts, soil dryness as well as vegetation changes that affect fuel load (McCarty et al., 2021). They are treated as an initial impact occurring within the Arctic, though distinctions can be blurred. The risk of a climate-triggered fire is conditional on the state of the forest and fuel load, themselves affected by impacts of previous fires, so feedbacks apply that may also have cross-border dimensions. In recent years, the frequency and extent of wildfires in the Arctic region have been unprecedented for at least the past 10,000 years (Constable et al., 2022).

3.2 | Impact propagation across borders

In this section we examine propagation pathways and potential cross-border risks caused by the initial impacts of climate change identified in section 3.1. We focus on the propagation of impacts from the Arctic to the rest of the world through the transmission systems we have identified, recognizing that there can also be feedbacks that may amplify or dampen the climate trigger and its impacts at any step of the transmission (Esau et al., 2023; Smith et al., 2019).

3.2.1 | Melting of glaciers and ice sheets

Glacial melting causes cross-border impacts through sea level rise, which leads to risks of coastal flooding and related impacts such as saline intrusion (Fox-Kemper et al., 2021; IPCC, 2019). In this case, the transmission system is simple: relative sea level rise (in regions where absolute sea level rise is not compensated by isostatic uplift) creates similar risks in the Arctic and elsewhere. Coasts can become increasingly vulnerable to waves, storms, erosion and flooding. Globally, population and infrastructure on low-lying coasts and small islands are most at risk (Bertelsen & Gallucci, 2016; Byravan & Rajan, 2022; Olsen et al., 2011). In the Arctic, the melting of land glaciers and sea ice retreat can aggravate the impacts (Frezzotti & Orombelli, 2014; Kelmelis, 2011; Smith et al., 2019). This is particularly the case along the Beaufort Sea coast of the US and Canada, as well as along coasts of the Russian East Siberian Sea and Laptev Sea (Walsh et al., 2020). The melting of glaciers can also lead to aesthetic degradation of Arctic landscapes, which may impact cross-border tourism (Milner et al., 2017). In addition, receding glaciers can alter river flow, potentially decreasing water availability, affecting indigenous and local livelihoods as well as hydropower, which is increasingly supplied across borders (Milner et al., 2017).

3.2.2 | Sea ice retreat

Arctic sea ice retreat creates opportunities with cross-border implications in two interacting ways. First, shipping routes are becoming increasingly navigable (Huntington et al., 2023; Ng et al., 2018; Wan et al., 2018). The two shipping routes that have historically been plied are the Northern Sea Route (NSR) along the north coast of Russia and the Northwest Passage (NWP) through the Canadian Arctic Archipelago. A third, the Transpolar Sea Route (TSR), is a shorter route between Asia and Europe via the North Pole. With accelerating climate change, it may become potentially navigable in summer by mid-century and is arguably politically less sensitive than the NSR and NWP as it passes through international waters (Bennett et al., 2020). However, practical obstacles, such as dependence on icebreakers, fees and customs clearance, and limited weather forecasting services, search and rescue capabilities, and relief ports, still limit the use of the northern sea routes (Bekkers et al., 2018). Therefore, cross-Arctic transit shipping is projected to become more profitable only after the 2030s (Boylan, 2021; Karahalil et al., 2021; Liu & Kronbak, 2010; Yumashev et al., 2017). Impacts on global trade flows between Asia and Europe and between America and Eurasia are hence likely to be manifested over long time horizons (Stephen, 2018; Sur & Kim, 2020; Tiller et al., 2022). For instance, it has been estimated that under conditions that would allow year-round commercial navigation (not regarded as plausible for another century even under high emissions scenarios), the NSR could carry up to 5% of global shipping (Yumashev et al., 2017).

Second, sea ice retreat improves access to natural resources and locations in the Arctic seas and the central Arctic Ocean. This can benefit cross-border commercial fisheries (see Section 3.2.4), tourism (Burgass et al., 2019; Edwards & Evans, 2017) and exploitation of non-renewable resources. The opportunities are of global interest as the Arctic is estimated to hold 13% of the world's oil reserves, 30% of undiscovered gas resources, as well as substantial deposits of metals such as palladium, nickel and iron ore, all of which are made more accessible by retreating ice (Gautier et al., 2009). In 2016, Russian oil and gas exploration in the Yamal Nenets region was expected to export 16.5 million tons of liquefied natural gas per year (Bertelsen & Gallucci, 2016). Significant growth was planned thereafter, along with renewal and expansion of the nuclear icebreaker fleet, developments that have subsequently been delayed by sanctions and uncertain market access related to the Russian invasion of Ukraine (Moe, 2023). Norway is currently planning to grant licenses for deep sea mining of critical minerals (Smieszek et al., 2021). Opening Arctic seas also enhance transit opportunities for land-based resources made accessible by retreating ice and permafrost thaw (Ng et al., 2018).

The transmission of impacts occurs via economic activities that are part of international trade, involving many non-Arctic states and complex supply chains. Global financial systems are also closely involved, through investments by non-Arctic states and insurance and reinsurance for infrastructure and activities (Bertelsen & Gallucci, 2016; Boylan, 2021; Edwards & Evans, 2017; Johannsdottir et al., 2021; Meier et al., 2014). Tensions may arise between countries as competition over and protection of resources gain importance (Kaltenborn et al., 2020; Zagorskii, 2016). For example, it has been argued that new fisheries management regimes are needed to avoid the “tragedy of the commons” (Zou & Huntington, 2018, p. 132). Moreover, a militarization of the region to protect resources could escalate into geopolitical security risks (Li et al., 2022; Parsons, 2011; Vylegzhanin et al., 2021).

The new accessibility to both transport and economic activities in the Arctic has potentially important consequences for the livelihoods of indigenous peoples. In some cases, they have participated as equal stakeholders in deciding on how to benefit from emerging opportunities (Kelman & Næss, 2019). However, the responses of non-Arctic actors to such opportunities frequently disregard the interests of indigenous groups, with exploitation for cross-border benefits often reducing their access, for example, to ancestral land (Shake et al., 2018). Furthermore, negative effects on marine ecosystems, through accidental oil spills, disturbance of marine mammals, and transport of invasive species, disrupt traditional livelihoods (Bennett et al., 2020; Edwards & Evans, 2017; Huntington et al., 2023; Mueter et al., 2021; Tiller et al., 2022). Finally, in the case of tourism, indigenous and local communities must often cope with its negative repercussions, which may also disrupt cultural traditions while benefits are reaped by tour operators (Stephen, 2018). Such examples demonstrate how cross-border opportunities can easily create cross-border conflicts in the Arctic, through extractive and exploitative practices, environmental injustice, inequality, and environmental degradation (Hanaček et al., 2022).

3.2.3 | Permafrost thaw

Permafrost thaw causes changes in water quality and affects geomorphological processes in the Arctic. It increases nutrients and organic matter in freshwater systems (Pedersen et al., 2022), it changes landscapes and hydrology with potential drying in some areas and appearance of ponds and lakes in others (Box et al., 2019; Meinander et al., 2022; Nitzbon et al., 2020), and it can release pathogens and toxins (Borgå et al., 2022; Evengård et al., 2021; Larsen et al., 2021; Waits et al., 2018). These impacts create multiple risks for indigenous peoples within the Arctic who are directly exposed, but pathogens and toxins can also be transported beyond the Arctic by means of air, water, animals and humans (Waits et al., 2018). Arctic permafrost stores twice as much carbon as the atmosphere, and thawing releases carbon dioxide (CO_2) and methane, both greenhouse gases, that become well mixed in the atmosphere, affecting the global climate (Canadell et al., 2021). Moreover, elevated CO_2 concentration attributable to feedback processes in the Arctic, as in the case of sea level (Section 3.2.1), has a global reach. It affects the productivity, nutritional quality and water use efficiency of terrestrial plants and contributes to marine and freshwater acidification, with impacts that vary depending on the recipient system (e.g., Beach et al., 2019; Bezner Kerr et al., 2022).

Loss of ground stability, erosion and resulting coastal flooding are other important local impacts of permafrost thaw with far reaching consequences for roads, railroads, and also cultural sites (Da Cunha et al., 2022; Esau et al., 2023; Falardeau & Bennett, 2020; Hjort et al., 2018; Hjort et al., 2022; Instanes et al., 2016; Vincent, 2020). Soil instability can also affect industrial sites for extraction of oil, gas and minerals increasing the risk of accidents (Langer et al., 2022) and disrupting exports (Porfiriev et al., 2019; Vincent, 2020). By mid-century, 30%–50% of critical circumpolar infrastructure is projected to be at high risk due to permafrost thaw (Hjort et al., 2022) and annual damage is estimated at between \$182 billion and \$276 billion depending on climate scenario, with Russia being the most affected (Streletskiy et al., 2023). This would have cross-border repercussions for financial systems with increasing investment risks of many Arctic activities (Bouffard et al., 2021; Gädeke et al., 2021; Larsen et al., 2021; Revich et al., 2022).

3.2.4 | Altered species distribution and abundance

Warming and changes in species distribution and abundance increase the risk of transmission of diseases and infections (Laaksonen et al., 2010; Lemieux et al., 2022; Townhill et al., 2022; Vollset et al., 2021; Waits et al., 2018). In terrestrial systems there are strong seasonal cross-border connections between the Arctic and other regions associated with the movement of key vectors of disease, in particular migratory birds (Wauchope et al., 2017). Changing breeding conditions or disease outbreaks such as the avian flu in Northern Norway in 2023 (De La Hamaide, 2023; Lane et al., 2023) have far reaching consequences for regions outside the Arctic.

In addition, widespread shifts and redistribution of vegetation, with feedbacks between the biosphere and the atmosphere as well as interactions with permafrost thaw and wildfires, can be transmitted up the food chains and trophic levels, impacting ecosystem services such as food production, access to natural resources, climate regulation and traditional culture in the Arctic (Pearson et al., 2013; Post et al., 2009). Such impacts could propagate beyond the Arctic region to lower latitudes, for example through changes in population size or migration patterns of migratory birds reliant on specific Arctic habitats (Pearson et al., 2013). Moreover, future adaptation at lower latitudes could be informed by such rapid changes in vegetation and related trophic relationships that "may be a bellwether of changes to come at lower latitudes" (Post et al., 2009, p. 1355).

Species impacts also affect marine food webs (Burgass et al., 2019; Esau et al., 2023; Papastavridis, 2018). Trade in fisheries is a key mechanism for transmitting the impacts across borders. Some projections suggest new opportunities with parts of the Arctic waters potentially becoming more productive because of the northward migration of commercial species (Mueter et al., 2021; Papastavridis, 2018). Some invasive species such as snow crab also have an important commercial value (Esau et al., 2023). At the same time, native Arctic species are at risk of declining (Burgass et al., 2019; Jonsson & Setzer, 2015; Vollset et al., 2021). This shows how risks and opportunities are intertwined in

Arctic regions with cross-border impacts on global food systems (Constable et al., 2022; Falardeau & Bennett, 2020; Ford et al., 2015; Hossain et al., 2017; Troell et al., 2017).

Cross-border ecological impacts are linked to questions of social justice. For example, local small-scale fisheries that are bound to a region may lose out in competition with large enterprises that can switch locations and target species (Oostdijk et al., 2022). Changes in fish stocks and fish migration can also trigger cross-border tensions between stakeholders. Lack of clarity in transboundary regulations concerning bycatches, the size and distribution of fishing quotas and the definition of the exclusive economic zones can all cause disputes (Crépin et al., 2017; Mendenhall et al., 2020; Spijkers et al., 2021).

3.2.5 | Changes in surface water and snow conditions

Changing surface water and snow conditions affect local and indigenous livelihoods. Local transportation corridors are lost due to changes in ice dynamics (Ford et al., 2014) and communities dependent on reindeer and caribou herding are strongly impacted by rain-on-snow events with ice crust formation that inhibit foraging (Bokhorst et al., 2016; Fohringer et al., 2021; Forbes et al., 2022).

Changes in surface water and snow conditions affecting mining operations can have cross-border impacts by disrupting global trade and supply chains (Ford et al., 2014). Increased runoff may potentially benefit the hydropower industry (Instanes et al., 2016; Olsen et al., 2011), but changing timing of peak run-off may create need for storage.

3.2.6 | Wildfires

Some of the largest areas burnt by wildfires are located at high latitudes in Siberia, Canada and Alaska, often in remote permafrost zones of the taiga, (Kharuk et al., 2021), where future fire occurrence is projected to increase due to climate change (de Groot et al., 2013). Changes in wildfire regimes may cause atmospheric and landscape changes with cross-border impacts, aside from the negative global impacts of reduced carbon sinks (Chuffart & Raspotnik, 2019). Black carbon deposition from wildfires enhances snow melt and permafrost thaw (Nitzbon et al., 2020). Smoke affects air quality with local aerosol concentrations sometimes exceeding 1000 times the background level. This creates health risks for local populations (Kharuk et al., 2021; Romero Manrique et al., 2018), and can become an international, cross-border issue during extreme events, when smoke plumes may spread over thousands of kilometers (Clarke et al., 2023; Kharuk et al., 2021; Lowe & Garfin, 2023).

3.2.7 | Synthesis of impact propagation

The pathways of cross-border climate change impact propagation determined by this review as originating in the Arctic are summarized in Figure 2, based on a typology proposed by Carter et al. (2021). The resulting cross-border risks to human security and social justice ("people" in the original typology), trade, infrastructure, finance, geopolitical conditions and biophysical conditions could emerge from the propagation of impacts across borders. Their significance in the recipient region outside the Arctic will vary depending on the intensity of the trigger, the initial impact, and the way the impact is modified, intensified, or possibly attenuated in the transmission system.

4 | IMPLICATIONS FOR EUROPE

Europe is a major contributor to anthropogenic climate change and pollution in the Arctic and is one of the biggest users of Arctic resources (Koivurova et al., 2021; Smieszek et al., 2021). The EU has three member states with territories extending into the Arctic: Finland, Sweden and Denmark. Moreover, through the European Economic Area it has close ties with Norway and Iceland. Many non-Arctic observer states to the Arctic Council are European, including Switzerland and the United Kingdom and the EU member states France, Germany, Italy, the Netherlands, Poland and Spain. Our consideration of European adaptive responses is directed primarily at EU rather than national-scale responses.

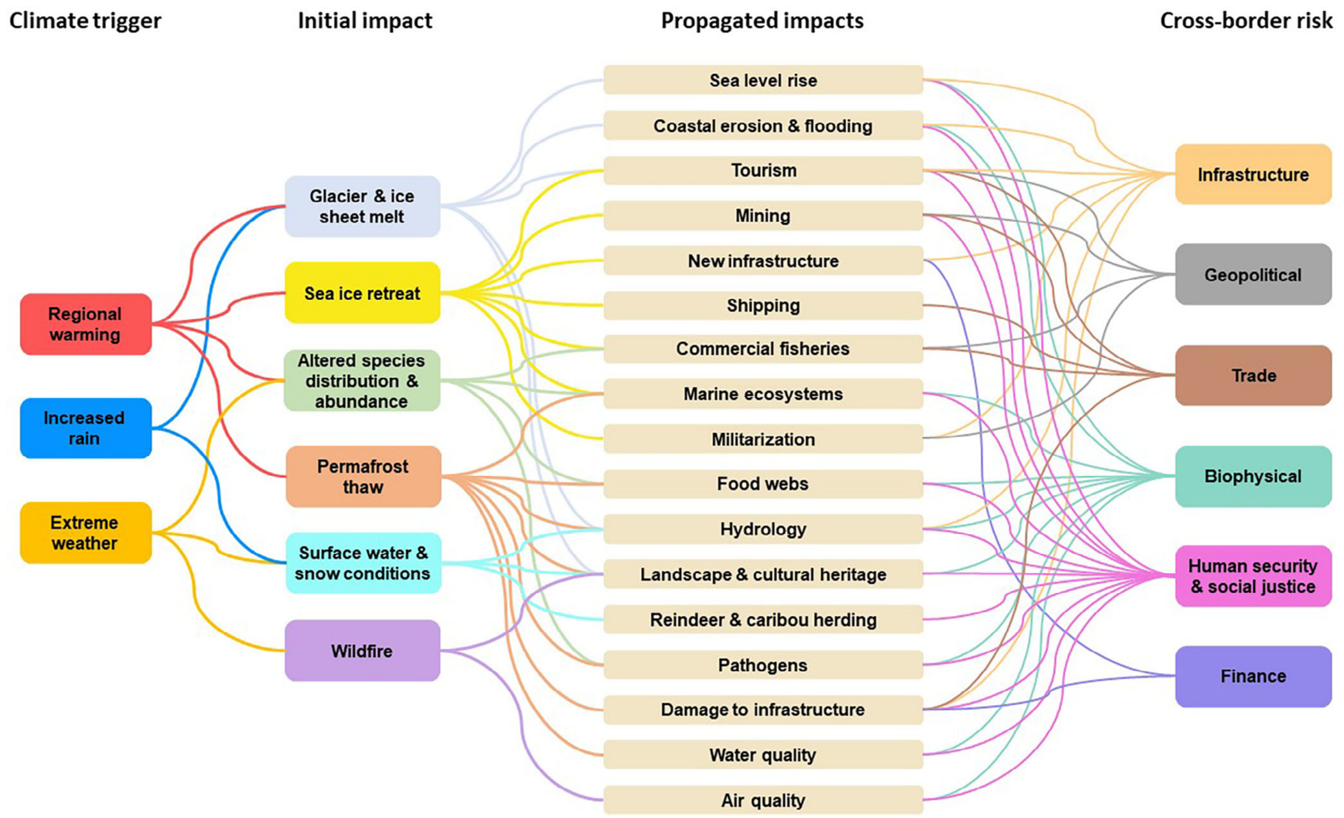

FIGURE 2 Transmission of cross-border climate change impacts originating in the Arctic. Climate triggers can initiate impacts in the Arctic that may be transmitted into regions outside the Arctic via systems of varying complexity, posing risks that may merit an adaptation response. Note that connections shown are based on the literature reviewed here and may not capture all potential linkages.

4.1 | Europe as a recipient region of Arctic cross-border climate change impacts

Some of the impacts of regional warming in the Arctic are global in nature. The melting of the Greenland ice sheet and other glaciers in the Arctic accelerate sea level rise, causing displacement of people and loss of assets in Europe and globally (Boest-Petersen et al., 2021; Vousdoukas et al., 2020). Wildfires in the Arctic may bring pollution and health impacts to Europe (Clarke et al., 2023). There are also several feedback mechanisms through which changes in the Arctic may accelerate global warming, such as increased emissions of CO_2 and methane caused by permafrost thaw (Alvarez et al., 2020). Elevated levels of atmospheric CO_2 themselves affect global terrestrial and aquatic ecosystems (Bezner Kerr et al., 2022; Oostdijk et al., 2022).

Europe will be both a recipient of risks and a potential beneficiary of climate induced changes in the Arctic (Alvarez et al., 2020; Bennett et al., 2020; Benzie et al., 2019; Koçak & Yercan, 2021; Li et al., 2022; Smits et al., 2014; Sur & Kim, 2020; Tiller et al., 2022; Yumashev et al., 2017). The EU Arctic policy communication reflects this dual position, with objectives to support resilience in the Arctic but also to develop imports of renewable energy instead of oil and gas, extract critical minerals and raw materials for the green transition, and practice sustainable fishing (European Commission, 2021; Koivurova et al., 2022). For example, one-third of the Arctic fish landings is sold on the European market (Papastavridis, 2018).

Resource exploitation by the EU and all the other actors in the Arctic can, however, create risks for indigenous peoples and their livelihoods. This is increasingly recognized as a question not only of trade and economic interests but also one of basic human rights (Hanaček et al., 2022). Cross-border management conflicts can arise due to different views of the value of particular resources. For instance, there has been friction between EU and Norwegian authorities concerning exploitation of snow crabs, an invasive species considered valuable by Norway but observed to be spreading beyond the Norwegian exclusive economic zone (EEZ) due to changing water temperatures (Kaiser et al., 2018).

4.2 | A European perspective on adaptation to Arctic cross-border climate change impacts

In dealing with the complexity of the cross-border impacts originating in the Arctic, responses can, in principle, focus on any stage of the impact transmission system from supporting adaptation at the source of the initial impacts all the way to managing the cross-border risks (Carter et al., 2021). For a recipient region like Europe, it might appear rational to focus solely on the transboundary risks it experiences (Burgass et al., 2019). That way, it would be relatively straightforward to design internally coherent actions. However, what appears to be coherent policy within Europe (for example, by the EU) may not appear that way from an Arctic perspective, since it usually involves adaptation actions targeted at impacts in Arctic regions that fall under a range of jurisdictions (Kivimaa et al., 2024). At the same time, adaptation actions within the Arctic are often undertaken autonomously by local and indigenous people, for example, through modification of timing, travel routes and equipment for hunting and harvesting activities, and may not consider long-term adaptation, potentially leading to reduced adaptive capacity or maladaptation (Ford et al., 2014). This suggests a need for enhanced interaction between different levels of governance along the impact transmission system.

The right-hand column of Table 1 summarizes some indicative adaptation measures reported in the literature, and we can analyze these in the context of the governance challenges for EU policy described above. We do so according to categories of cross-border risks portrayed on the right hand side of Figure 2, which also appear in combinations under the same heading in Table 1.

Responses for addressing cross-border biophysical risks and risks to trade, infrastructure and finance focus in large part on technical and economic interventions to alleviate or anticipate physical damage and monetary costs. Entries in Table 1 include international research into and awareness raising of future changes and their likely impacts and development of improved transboundary monitoring and early warning systems (e.g., for extreme weather, sea ice and glacier retreat, marine pollution, disease transmission, fish abundance, wildfires and permafrost decay). They also highlight research and planning for enhanced resilience in new and existing industrial, transport, supply chain and tourism infrastructure, as well as describing the involvement of the insurance industry and international finance in building both local capacity and transboundary resilience. The EU is already allocating considerable funding to Arctic research in relation to many of these risks.

Human security and social justice are categorized together in our review, as a cross-border risk for "people" in the framework by Carter et al. (2021). Nearly all of the propagated impacts relate in one way or another to this category (Figure 2), which refers to two main types of risks. Human security alludes to risks for livelihoods, such as displacements, food scarcity, or water scarcity, as well as risks to personal safety, health and well-being. Social justice is related to how actors such as the EU address issues of inequality and fairness in responding to the risks, which are themselves fundamental determinants of human security.

For example, flood prevention and evacuation plans, relocation, legislation to protect water resources, supplementary feed, transport & herding of reindeer, or increasing monitoring capacity to protect homes and livelihoods from fire, are potential adaptation measures addressing human security risks (Table 1). Adaptive responses to cross-border impacts and opportunities, such as those exploiting newly accessible natural resources, frequently lead to a redistribution of vulnerability and risks, potentially with adverse, and socially unjust, impacts on human security in the Arctic (Atteridge & Remling, 2018). Many papers in the review refer to the need to account for traditional knowledge in the practice of research and policy making, and to enhance awareness of potential inequities related to economic impacts. For example, reindeer herding in Arctic EU countries is subject to both EU and national policies on agriculture and nature conservation, with financial steering mechanisms that have resulted in a shift towards a more sedentary approach and a loss of traditional practices (Landauer et al., 2021). As another example, if the EU response to changes in the availability of Arctic fish resources does not consider long-term ecological sustainability and impacts on indigenous populations, Arctic fisheries that depend on the European market may suffer (European Parliament, 2015). In both cases, the EU could mitigate these risks in a more socially just and coherent manner than hitherto (Kivimaa et al., 2024).

Geopolitical risks are an inherent feature of cross-border climate change impacts, with competition for resources creating potential conflicts that require stronger international and regional co-operation in governance, regulation, spatial planning, transboundary management and emergency preparedness (Table 1). Moreover, the role of non-climatic drivers and of "wildcard", surprise events in influencing policy is also highlighted in our review. For example, the war

TABLE 1 Indicative list of adaptation measures found in the literature, in relation to the transmission of impact across borders.

Initial impact & *climate trigger*	Propagated impacts	Cross-border risk	Adaptation measures
Melting glaciers due to *Regional warming* (Section 3.2.1)	Sea level rise [1] Coastal erosion & flooding [2,3]	Human security & social justice & Critical infrastructure [4–6] Biophysical [6,7]	• New imagery/technologies for accurate glacier mass loss mapping [8]* • Robust observing systems; improved climate & cryosphere models [6]* • Adaptation plans addressing cryosphere changes incl. variability, surprises & unanticipated events [6] • Flood prevention & evacuation plans [9] • Adequate resources for prevention of critical infrastructure damage and/or relocation [4, 10]
	Landscape, hydrology & tourism [8]	Human security & social justice & Trade [8]	• Continuous biogeochemical, contaminant & biodiversity monitoring; development of early warning systems [8, 11] • Adaptation plans for critical ecosystem services & international legislation to protect water resources [8]
Sea ice retreat due to *Regional warming* (Section 3.2.2)	Increased shipping [12, 13] Militarization [14–18] Increased access to commercial fisheries [19, 20] Tourism [19, 21, 22] Mining [5, 9, 19, 20]	Trade [23–26] Geopolitical conditions [14–18]	• Improve transboundary Arctic observation systems for monitoring sea ice & Arctic amplification [27, 28]* • Bolster coordination of integrated research to advance prediction [29] • Reduce lag between identifying impacts & implementing responses [15, 20] • Global cooperation among relevant actors [16, 30] • Seek robust & sustainable sovereignty to reduce security risks [17] • Policy coherence in jurisdictional & sectoral governance [19] • Pursue economic activity & development that maximizes benefits & minimizes adverse effects, e.g., by investing in local capacities [30, 31] or combining, during Arctic cruises, tourism with data collection & monitoring for research [28]
	Development of economic activities & its impacts on marine ecosystems [1, 12, 32]	Human security & social justice [19, 25, 33] Biophysical [12, 19, 25, 32, 33]	• Include traditional knowledge in science; co-create knowledge for policy [10, 25, 34–41] • Enhance awareness of inequities in economic impacts across local & global stakeholders & need to integrate social justice in policies [12, 42, 43]
	Development of infrastructure [5, 19, 44]	Critical infrastructure & Finance [5, 19, 22, 44]	• Account for non-market aspects in environmental policies [45] • Involve the insurance industry in awareness raising & embedding of risk & insurance-related terms & conditions in decision-making [22]
Permafrost thaw due to *Regional warming* (Section 3.2.3)	Water quality & geomorphological processes [45–47] Release of pathogens [39, 49–51] Local infrastructure [27, 52, 53] CO2 effects on food webs & marine ecosystems [43, 88–89]	Human security & social justice [34, 39, 40, 51] Biophysical [45–47, 54, 55]	• Enhance data sharing & analysis for improved permafrost models [40, 56] • Prioritize investment in concrete adaptation actions for indigenous people & infrastructure & stress innovative visual & oral methods over conventional methods to avoid research fatigue [51, 57, 58] • More research on potential disease transmission in the Arctic; adaptation of health monitoring & health care infrastructure [23, 39, 49] • Relocation [56]
	Damage to critical infrastructure [56]	Trade (exports) [58, 60]	• Operational monitoring & early warning for timely infrastructure adaptation of new industrial facilities & sites currently in operation [59]

(Continues)

TABLE 1 (Continued)

Initial impact & *climate trigger*	Propagated impacts	Cross-border risk	Adaptation measures
		Critical infrastructure & Finance [51, 56, 61, 62] Human security & social justice [56]	• Bring more people to the Arctic region which will bring more interest in investments & security [10, 63]
Altered species distribution & abundance due to *Regional warming* (Section 3.2.4)	Changes in important food webs [21, 27, 32, 54, 55, 64–69] Transmission of pathogens [49, 67, 70–75]	Human security& social justice [10, 11, 19, 32, 43, 53, 63, 73–76] Geopolitical [64, 77, 78] Biophysical [54, 55]	• Assess resilience using carefully selected indicators [47, 64] • Enhance understanding of fish species abundance to inform regulation of sustainable fisheries stocks [66] • Port State control measures, flag State measures, fishing vessels' registration and inspection at sea by third States [65] • Establish shared management regimes between national actors to implement common measures & ensure stakeholder cooperation [32, 77, 79] • Pan-Arctic effective marine spatial planning [19, 64]
Changes in surface water & snow conditions due to *Increased rainfall* (Section 3.3.5)	Reindeer & Caribou herding [36, 80–82] Landscape & hydrology [31, 83]	Human security & social justice [6, 36, 52, 80, 81] Biophysical [6, 52]	• Invest in local hydropower plants designed using state-of-the-art streamflow projections [52] • Support supplementary feed, transport & herding of reindeer, conserve existing grazing habitats to assure landscape connectivity & remediate & restore sites of former resource extraction [80] • Include herder knowledge of impacted systems in evaluating new exploitative land uses [80]
Increased risk of wildfires due to *Changes in extreme weather events* (Section 3.2.6)	Atmospheric and landscape changes [84]	Human security & social justice [34, 85–87] Biophysical [48, 84]	• Manage fuel at risk of ignition & implement controlled burning [41] • Increase transdisciplinary research & pan-Arctic collaboration to understand & predict fire & guide adaptation [41] • Improve understanding of ecological landscape changes & long-term economic & social development to assess fire risk [41] • Focus fire suppression in areas with high social, natural or economic values while allowing beneficial wildfire to burn in dense forest areas like Siberia [86] • Increase monitoring capacity of Indigenous peoples to protect homes & livelihoods from fire & adapt to the changing fire regime [41]

Note: The asterisk (*) shows when an adaptation measure is directed to the initial impact; other measures are directed more generally to the propagation of impacts and the cross-border risks. 1 Fox-Kemper et al. (2021); 2 Smith et al. (2019); 3 Frezzotti & Orombelli (2014); 4 Marino & Lazrus (2015); 5 Bertelsen & Gallucci (2016); 6 Olsen et al. (2011); 7 Cooley et al. (2022); 8 Milner et al. (2017); 9 Da Cunha et al. (2022); 10 Ford et al. (2015); 11 Wrona et al. (2016); 12 Huntington et al. (2023); 13 Wang et al. (2018); 14 Zagorskii (2016); 15 Kaltenborn et al. (2020); 16 Vylegzhanin et al. (2021); 17 Parsons (2011); 18 Li et al. (2022); 19 Edwards & Evans (2017); 20 Smieszek et al. (2021); 21 Burgass et al. (2019); 22 Johannsdottir et al. (2021); 23 Stephen (2018); 24 Sur & Kim (2020); 25 Tiller et al. (2022); 26 Yumashev et al. (2017); 27 Esau et al. (2023); 28 De La Barre et al. (2016); 29 Jung et al. (2016); 30 Petrov et al. (2021); 31 Ford et al. (2014); 32 Mueter et al. (2021); 33 Bennett et al. (2020); 34 Romero Manrique et al. (2018); 35 Smith & Sharp (2012); 36 Bokhorst et al. (2016); 37 Buschman & Sudlovenick (2022); 38 Dawson et al. (2020); 39 Evengård et al. (2021); 40 Natali et al. (2022); 41 McCarty et al. (2021); 42 Kaiser et al. (2018); 43 Oostdijk et al. (2022); 44 Boylan (2021); 45 Mavisakalyan et al. (2023); 46 Pedersen et al. (2022); 47 Box et al. (2019); 48 Nitzbon et al. (2020); 49 Waits et al. (2018); 50 Borgå et al. (2022); 51 Larsen et al. (2021); 52 Instanes et al. (2016); 53 Falardeau & Bennett (2020); 54 Post et al. (2009); 55 Pearson et al. (2013); 56 Bouffard et al. (2021); 57 Lonsdale et al. (2017); 58 Porfiriev et al. (2019); 59 Langer et al. (2022); 60 Vincent (2020); 61 Revich et al. (2022); 62 Gädeke et al. (2021); 63 Hossain et al. (2017); 64 Crépin et al. (2017); 65 Papastavridis (2018); 66 Jonsson & Setzer (2015); 67 Vollset et al. (2021); 68 Callaghan et al. (2022); 69 Berner et al. (2020); 70 Laaksonen et al. (2010); 71 Lemieux et al. (2022); 72 Townhill et al. (2022); 73 Wauchope et al. (2017); 74 De La Hamaide (2023); 75 Lane et al. (2023); 76 Constable et al. (2022); 77 Mendenhall et al. (2020); 78 Spijkers et al. (2021); 79 Zou & Huntington (2018); 80 Fohringer et al. (2021); 81 Serreze & Francis (2006); 82 Sokolov et al. (2016); 83 Jeppesen et al. (2017); 84 Chuffart & Raspotnik (2019); 85 Clarke et al. (2023); 86 Kharuk et al. (2021); 87 Lowe & Garfin (2023); 88 Beach et al. (2019); 89 Bezner Kerr et al. (2022).

in Ukraine, has shifted the priority away from adaptation to climate change in the Arctic and towards measures aimed at boosting economic activity, greatly influenced by Europe's need for new sources of energy. Furthermore, it has greatly hindered scientific collaboration and cross-border knowledge sharing with Russia (López-Blanco et al., 2024; Moe et al., 2023). Other non-climatic drivers that can affect the severity of potential climate change impacts and the possibilities to implement adaptation are global economic and social trends, technological trends, trading arrangements and geopolitics (Ford et al., 2014; Karahalil et al., 2021; Moe et al., 2023).

5 | DISCUSSION

Understanding the interactions and feedbacks between local and global impacts of climate change is necessary for developing efficient adaptation (Baldos et al., 2023). The rapidly expanding literature on climate change impacts in the Arctic highlights potential cross-border consequences. By systematically examining the transmission systems through which impacts of climate change propagate across borders (Carter et al., 2021), it is possible to bring together a large body of literature to identify key risks for a recipient region such as Europe and for those actors involved in designing and implementing adaptation policy, such as the European Union. Future studies of climate change impacts and interactions may reveal additional relevant cross-border impacts, but our review has underlined the need to pay attention to the mechanisms of impact transmission and to the consequences of responding to such impacts. Although our literature review was extensive, it still covers only English language literature, and there are subjective decisions involved in the literature platform applied and search methods chosen (cf. Table A1).

Alternative terminology and classifications could have been used in this review, but we argue that the key conclusions would not have been greatly affected. For instance, the "global-to-local-to-global paradigm" for improving models of Baldos et al. (2023) and the eight different categories of "societal cascading impacts" identified by Moser and Hart (2015) also highlight the importance of transmissions between systems. In examining adaptation responses, the differentiation of Instanes et al. (2016) between "structural" adaptation measures focused on planning, design, construction, and maintenance of structural elements for infrastructure and industry, and "non-structural" adaptation measures, which relate to changes to policies, regulations, and management, might have provided a useful typology of response transmission. However, it would probably not have changed the conclusion that there are potential conflicts between effective adaptation to cross-border impacts from the point of view of a recipient region and the region of origin (for further discussion on cross-border policy coherence, see Kivimaa et al., 2024).

The literature that has considered the link between Arctic impacts and risks to Europe is still limited. Despite the apparent complexity of potential interactions that are evident in the many linkages shown (purposefully) in Figure 2, our review suggested that there is still limited information on the specific dynamics of the impacts and even less on the available responses. The many climate system feedbacks that are being triggered by changing climate in the Arctic were outside the scope of this review, as they are processes that can only realistically be managed through mitigation of the anthropogenic causes. However, many of these feedbacks are inextricably linked both to the cross-border impacts we have addressed as well as to the potential adaptation responses they may require. This suggests that there is scope for additional research at this interface, both to untangle the mechanistic interactions, such as through earth system modeling, as well as to consider possible responses, for example by analyses of EU and Arctic States' policies, including interviews of key actors. Such studies would be important for the EU which strives to become a world leader in climate change mitigation and adaptation (Dobson & Trevisanut, 2018).

Responses to many of the cross-border impacts of climate change require compromises and trade-offs because adaptation cannot be developed in isolation from other societal objectives. For example, although local resilience could be enhanced by minimizing impacts from resource extraction and transport in the Arctic, EU climate policies that aim at curtailing carbon emissions implicitly build on expanding the extraction of raw materials in the Arctic and elsewhere for the green transition, indirectly also supporting the expansion of shipping routes in the Arctic.

To address such trade-offs effectively, noting that they are embedded within a growing list of adaptation measures (cf. Table 1), it is important to identify compromises that will strengthen overall resilience. For this purpose, the likelihood of the risks, the magnitude and level of threat of the impacts, and the time horizon of both the impacts and the responses should be considered (Larsen et al., 2021; Rannow, 2013). The time horizon is particularly relevant since some impacts are already felt while others, like shipping with its global reach and profit, will only be relevant after the 2030s (Boylan, 2021).

6 | CONCLUSION

Climate change is progressing fast in the Arctic, emphasizing the need to understand not only how impacts affect the Arctic, but also other regions. By systematically reviewing literature using an impact transmission framework, we examined how warming, extreme weather events and increased rainfall trigger initial impacts that may propagate and eventually become risks or opportunities in regions outside the Arctic. The framework connects impacts that are often analyzed separately, highlighting how they may interact leading to cross-border risks for trade, critical infrastructure, finance, biophysical effects, geopolitical relationships, or human security and social justice. It demonstrates that melting of glaciers and the Greenland ice sheet, sea ice retreat, permafrost thaw, altered species distribution and abundance, changes in surface water and snow conditions, and increased risk of wildfires are systemic changes that are transmitted and transformed into other impacts that eventually cross the boundaries that represent the Arctic.

A systemic perspective can guide planning of adaptation within the Arctic and in regions affected by the propagation of impacts to achieve coherent responses to the risks. It changes the view of what is at stake. For example, there are numerous imminent risks to indigenous livelihoods, but if they are seen only as local issues, potential adaptation measures may not be implemented for want of resources. Seen in a wider context of cultural heritage and risks to human security and social justice, they become global issues of adaptation for which different regions should share responsibility. Other impacts, such as sea level rise and changes in the yield of important fisheries, are already recognized as large-scale and far-reaching risks, but analyses of the transmission of impacts across borders can offer new angles on processes at work that can guide the prioritization of adaptation action. For example, it can help target much needed further investigation that directs a critical lens towards perceived investment opportunities in the Arctic, and to understand both the physical and economic risks involved.

A systemic approach also highlights the need to recognize non-climatic trends and unexpected wildcard events. The war in Ukraine has demonstrated that a non-climatic geopolitical crisis outside the Arctic can have repercussions on the implementation of adaptation to climate change within the region. In developing sustainable activities, including economic opportunities, the links between the Arctic and other regions need to be recognized. The impact transmission framework can be used to bring together knowledge to ensure that both emerging activities and adaptation to climate change support pathways that are consistent with the sustainable development goals.

AUTHOR CONTRIBUTIONS

Claire Mosoni: Conceptualization (lead); data curation (lead); formal analysis (lead); investigation (lead); methodology (lead); visualization (lead); writing – original draft (lead); writing – review and editing (lead). **Mikael Hildén:** Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Stefan Fronzek:** Conceptualization (supporting); formal analysis (supporting); investigation (supporting); project administration (lead); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Christopher P. O. Reyer:** Conceptualization (supporting); formal analysis (supporting); investigation (supporting); project administration (equal); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Timothy R. Carter:** Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (supporting); visualization (equal); writing – original draft (supporting); writing – review and editing (supporting).

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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APPENDIX A

TABLE A1 Terms used in the systematic literature review.

General Search (*by keywords*)	**Terms used in systematic review (*Full text; terms within the same keyword were separated by "OR" but terms between keywords were separated by "AND"; truncation was used for some terms*)**
Climate change	Climate change, climate risk, climate variability, climate extreme, climate uncertainty, global warming, temperature rise, atmospheric change, environmental change
Impact	Impact, risk, effect, hazard, vulnerability, exposure
Arctic	Arctic, North Pole, polar region
Cross-border	Cross-border, transborder, cross-boundary, inter-region, cascading, transboundary, transnational, non-localized, cross-regional, international, spillover, external, indirect, teleconnected, telecoupled, across border
Adaptation	Adaptation, adaptive ability, adaptative strategy, adaptive capacity, adaptive capability, adaptive strength, adaptive potential, adaption ability, adaption capacity, adaption capability, resilience, response
Europe	EU, European Union, Europe, EEA, EEC, European economic area, European economic community
Topical Search (*by main impacts identified in scoping review*)	**Terms used in systematic review, identified as relevant in the scoping review (*Abstracts; all the terms were separated by "OR"; truncation was used for some terms*)**
Glacier and Ice Sheet	Melting of glacier, melt, glacier, melting of ice sheet, Greenland's ice sheet, Greenland ice sheet, sea level rise, human migration
Sea Ice	Sea ice, cryosphere, shipping, rescue, tourism, energy, mining, critical material, mineral, renewable, fossil, hydrocarbon, security, tension, threat
Permafrost	Permafrost, disease, infrastructure, transport, route, distribution system, investment, insurance, finance
Ecosystem	Ecosystem shifts, food web changes, species migration, ecosystem, biodiversity, fishing
Water and Snow	Hydrology, water, rain-on-snow, precipitation, indigenous people, indigenous communities, local communities, local population
Wildfire	Wildfire, extreme weather, storm
Adaptation Search (*by keywords*)	**Terms used in systematic review (*Abstracts: terms within the same keyword were separated by "OR" but terms between keywords were separated by "AND"; truncation was used for some terms*)**
Climate change	Climate change, global warming, environmental change
Cross-border impact	Compound risk, compound impact, compound effect, compound hazard, compound vulnerability, compound exposure, cascading risk, cascading impact, cascading effect, cascading hazard, cascading vulnerability, cascading exposure, cross-border risk, cross-border impact, cross-border effect, cross-border hazard, cross-border vulnerability, cross-border exposure, multiple risk, multiple impact, multiple effect, multiple hazard, multiple vulnerability, multiple exposure, transborder risk, transborder impact, transborder effect, transborder hazard, transborder vulnerability, transborder exposure, cross-boundary risk, cross-boundary impact, cross-boundary effect, cross-boundary hazard, cross-boundary vulnerability, cross-boundary exposure, transboundary risk, transboundary impact, transboundary effect, transboundary hazard, transboundary vulnerability, transboundary exposure, spillover risk, spillover impact, spillover effect, spillover hazard, spillover vulnerability, spillover exposure, teleconnected risk, teleconnected impact, teleconnected effect, teleconnected hazard, teleconnected vulnerability, teleconnected exposure, telecoupled risk, telecoupled impact, telecoupled effect, telecoupled hazard, telecoupled vulnerability, telecoupled exposure, risk severity, risk urgency, risk interactions, impact interaction, interaction between risks, interaction between impacts
Adaptation	Adaptation, adaptation ability, adaptation strategy, adaptation capacity, adaptation capability, adaptation strength, adaptation potential, resilience, response, prevention
Method	Method, framework, recommendation, priority, analysis, assessment, advice, measure, action, means, procedure, proceeding, initiative, protocol, step, program, system, rule, risk severity, risk urgency, non-climatic driver, policy awareness, policy readiness