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Arctic roads and railways: social and environmental consequences of transport infrastructure in the circumpolar North

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Abstract

Land-based transport corridors and related infrastructure are increasingly extending into and across the Arctic in support of resource development and population growth, causing large-scale cumulative changes to northern socio-ecological systems. These changes include the increased mobility of people, goods and resources, and environmental impacts on landscapes and ecosystems as the human footprint reaches remote, unindustrialized regions. Arctic climate change is also generating new challenges for the construction and maintenance of these transport systems, requiring adaptive engineering solutions as well as community resilience. In this review article, we consider the complex entanglements between humans, the environment, and land transportation infrastructure in the North and illustrate these interrelations by way of seven case studies: the Baikal–Amur Mainline, Bovanenkovo Railway, Alaska–Canada Highway, Inuvik–Tuktoyatuk Highway, Alaska Railroad, Hudson Bay Railway, and proposed railways on Baffin Island, Canada. As new infrastructure is built and anticipated across the circumpolar North, there is an urgent need for an integrated socio-ecological approach to impact assessment. This would include full consideration of Indigenous knowledge and concerns, collaboration with local communities and user groups in assessment, planning and monitoring, and evaluation of alternative engineering designs to contend with the impacts of climate change in the decades ahead.

Key words: roads, railways, climate change, development, permafrost landscapes, Indigenous communities, environmental and social impact assessment, circumpolar North

1. Introduction

Arctic and subarctic regions are characterized by their remoteness, low population densities, and limited availability of modern transport infrastructure. Roads and railways have long been major types of infrastructure facilitating human mobility, and land transport routes constitute the backbone of supply systems and development in many parts of the Circumpolar North. Throughout the 20th century, road and railway construction opened up new northern areas for development, and this process continues today with transportation projects of a larger global scale being conceived and implemented. These include highways, secondary and private roads, haul roads to mines and other industrial sites, temporary or seasonal ice roads, seismic and other survey lines, private and public railways, airports, seaports, and shipping routes.

While roads and railways can bring significant benefits to remote northern communities such as increased connectivity, access to jobs, and greater access to land and associated resources, they may also affect the natural environment by disrupting water flow and other landscape processes and by altering ecological processes such as vegetation growth and animal migration. The proliferation of transport infrastructure is also expanding the human footprint into areas inhabited and used by Indigenous peoples for thousands of years, to connect these locations to industrial and municipal centers via long-distance transport routes, with associated networks of secondary roads and off-road vehicle trails. At the same time, current and potential effects of climate change such as permafrost thaw, flooding, and extreme weather events are jeopardizing infrastructure built on ice and frozen ground, especially roads and railroads. This is catalyzing a search for more enduring solutions such as new year-round transportation corridors (Instanes et al. 2016; Vincent et al. 2017; Hjort et al. 2018; Walker et al. 2022).

There is now a large body of literature that addresses the social and environmental consequences of road and railway expansion in many parts of the world (Dalakoglou and Harvey 2012; Swanson 2015; Van der Ree et al. 2015; Borda-de-Água et al. 2017; Barrientos et al. 2019). Less attention has been paid to the complex interactions between humans, transport infrastructure, and the environment in northern high-latitude regions, which encompass a diverse set of cultures, landscapes, and ecozones, along with particularities that require special consideration such as ice-rich permafrost, accelerated climate change, and traditional land use practices (Orians et al. 2003; Raynolds et al. 2014; Vincent et al. 2017; Evseev et al. 2019; Ashpiz 2020; Walker et al. 2022). A notable early example of a detailed assessment of the socio-ecological consequences of linear infrastructure in the Arctic, as well as consideration of economic and engineering issues, is the Berger Inquiry of the proposed Mackenzie Valley gas pipeline in Canada. Conducted in the 1970s, the inquiry underscored that for any resource development in the region, "the goals, aspirations and preferences of the northern peoples should be fully explored before any decision is taken" (Berger 1977: 1). The Berger Inquiry also illustrated an integrated approach that is of direct relevance to northern road and railway assessments today.

In this review, we begin by introducing some general themes of road and rail literature from around the world, including the Arctic. We separate these into social and environmental subthemes while recognizing that most of these are intertwined, especially—and importantly—in the context of Indigenous rights and values. We then examine, by way of a structured template, seven case studies across the Circumpolar North (Fig. 1) that illustrate specific social and environmental issues confronted by Arctic and subarctic transport projects. We conclude this review by considering the key elements that would be required for a more integrated socio-ecological perspective to assess road and railway developments. This synthesis article contributes to the project "Rapid Arctic Transitions due to Infrastructure and Climate" (RATIC), which aims to promote sustainable Arctic infrastructure (Walker and Peirce 2015), and the "Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections" (T-MOSAiC) project, which applies system-level themes such as connectivity, thresholds, and regime shifts to understand the effects of climate change on northern high-latitude landscapes, ecosystems, and human systems (Vincent et al. 2019). The map below (Fig. 1) shows the location of the roads and railways presented in our case studies.

2. Social dimensions and consequences

Mobility is both a promise and social consequence of roads and railways (Dalakoglou and Harvey 2012). Opportunities to be mobile are seen as a condition of late modernity (Urry 1999), with benefits contributing to individual and collective well-being in the era of globalization. An expanding body of scholarship on railways and especially roads in the social sciences (Schweitzer and Povoroznyuk 2020) has led to the concept of the "mobility turn" (Sheller and Urry 2006), embodying a new focus on the spatial and social dimensions of transport infrastructure.

One important social aspect of mobility and connectivity brought about by transport infrastructure is speed. It compresses distances through the "annihilation of space by time" (Dalakoglou 2017: 9), and facilitates long-distance connections between people and places (Virilio 2006). In the post-war era, highways exemplified the acceleration of long-distance travel culture. In the 21st century, the similar effects of high-speed railway lines are now receiving attention from social scientists. For example, high-speed rail projects reduce travel time between major European cities and alpine areas but also affect spatial relationships and development (Ravazzoli et al. 2017). The associated social impacts on local communities, such as dust and noise pollution, have resulted in local protests, which in Italy's Susa Valley, for example, grew into the resistance movement "No TAV" against high-speed rail (Laszczkowski 2020). In the sparsely populated regions of the Circumpolar North, where railways primarily transport cargo, mostly of resources extracted in the region, high-speed railways have not been built, but they have been proposed. One such project, dubbed the "Arctic Railway", was planned to link Rovaniemi in Finland to Arctic shipping routes via the port city of Kirkenes in Norway. Among the ecological and economic considerations, a Saami protest movement was an important factor culminating in the suspension of the project in 2021 (Cepinskyte 2018; Nilsen 2021).

Mobility is thus both a politically charged concept and a relational quality of transport infrastructure. Different types of mobility can be seen by certain actors as hierarchical in relation to each other (Adey 2006). For example, in the modernization development-oriented paradigm, "modern" high-speed transport may be presented as more progressive and superior in comparison to older, traditional forms of mobility such as nomadism (Fig. 2). Thus, the politics and ideologies behind the large-scale road and railway projects may structure different forms of mobilities by supporting desirable ones and suppressing those that are seen as obstacles to development. In this way, one person's mobility becomes another's immobility (Diener 2011).

Accessibility of a place or a community is another social characteristic resulting from the construction of transport infrastructures, including roads and railways. Just like mobility, it can have both positive and negative consequences depending on the group, purpose, and perspective. Accessibility might mean the opening of new transportation routes through northern landscapes, which are often characterized by the absence of roads or limited transport access

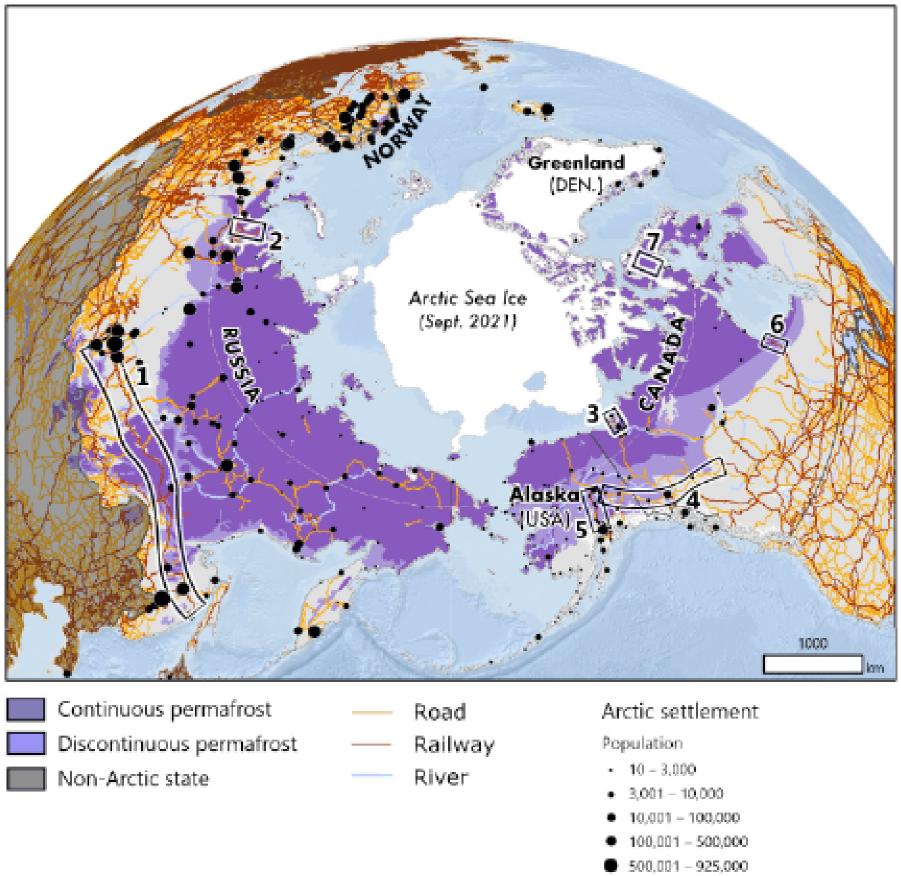

Fig. 1. Land transport infrastructure in the Circumpolar North, showing the extent of permafrost, rivers, and major settlements. The black rectangles demarcate the locations of the seven case studies: (1) Baikal–Amur Mainline (BAM); (2) Bovanenkovo Railway; (3) Inuvik–Tuktoyatuk Highway (ITH); (4) Alaska–Canada Highway (ALCAN); (5) Alaska Railroad; (6) Hudson Bay Railway (HBR); (7) proposed railways on Baffin Island. Source data for this map: Base layers: ESRI, Garmin, GEBCO, and NOAA/NGDC. Credit: Mia Bennett.

(Argounova-Low 2012b; Kuklina and Holland 2017). When present, accessibility and connectivity can facilitate access to other essential services such as banks, healthcare, education, and jobs, which are often located in neighboring communities.

The development of trade and tourism, under certain conditions, can also benefit local communities (Markovich and Lucas 2011: 19–20). Conversely, accessibility brings strangers and intruders to remote communities (Ardener 2012), while also facilitating the proliferation of harmful substances such as alcohol and drugs and toxic or industrial waste and accelerating the destruction of local wildlife and landscapes. Moreover, transport infrastructures often tend to encroach on communal lands, endangering the physical and cultural integrity of communities, even causing some residents to leave or relocate (Markovich and Lucas 2011; Argounova-Low 2012a: 29; Windle 2002). Thus, in certain cases, such as for the Indigenous Evenki community in East Siberia, remoteness may be a desirable condition that helps to protect cultures from rapid assimilation, the exploitation of renewable subsistence resources of the taiga by outsiders, and visits to the community by unwelcome guests (Schweitzer and Povoroznyuk 2019).

One other social consequence of roads and railways is their ability to facilitate existing social networks and engender new socialities. There are many links between transport, positive social interaction, co-presence, well-being, and quality of life (Markovich and Lucas 2011: 37–38). Increased mobility and access to transport services in most cases lead to more frequent travel and interactions with others, as illustrated by the regular air services among Inuit villages in northern Canada that are separated by vast distances. Unfortunately, these social linkages are a conduit for the transmission of human diseases, for example, the recent transmission of COVID-19 to northern Canada by airline passengers (e.g., Ritchot 2021)

An absence of and unequal access to roads and railways are seen as factors contributing to the social exclusion of already disadvantaged or vulnerable population groups (Markovich and Lucas 2011: 40). Travel does not only support and facilitate social networks between people living in different locations, but also new social relations and identities that are shaped while people are "on the move". The experiences of different types of travel, from hitchhiking and everyday commuting (Butcher 2011) to long-distance train rides (Leggett 2019) and trucking along major haul roads (tote roads) for

Fig. 2. Railways, the promise of modernisation and implied hierarchical relationships between new and Indigenous modes of transport. The slogan on this billboard on a building from the Soviet era promoting the Yamal Peninsula railway development translates as "Let's build our way to the future!" Photo credit: Bruce C. Forbes, Obskaia, July 1993.

resource development (Brown and Berg 1980), engender different types of interactions between passengers, and between passengers and the means of transport (Fisch 2018).

2.1. Demographic consequences

Roads and railways are typically seen as vehicles for economic development, which requires also a certain degree of demographic stability or increase. Apart from some failed attempts such as Stalin's "road to nowhere" (Mote 2003), railways and roads have typically led to population increases (e.g., Baron 2015; Levkovich et al. 2020). The more complex question is whether such an increase applies to all areas along a new linear transport infrastructure. There is evidence that in many cases the effect is more properly described as a form of population redistribution rather than gain. A new road or railway from A to B might result in population increases for A and (or) B, but it might also lead to outmigration in intervening areas (typically to A or B). If economic development in the intervening areas takes off, outmigration may be halted or reversed, and the areas off the road or railway may serve as the new outmigration pool (Gellert and Lynch 2003).

The opening up through transport infrastructures of previously inaccessible parts of a country leads to specific consequences. It is typically accompanied by large settler movements either ordered or encouraged by the state or based on the incentive of personal profit. Such migration often results in gender imbalances, as the settlers and construction workers are more often men than women (Povoroznyuk et al. 2010). Often it has been part of colonial movements, be they forms of internal (Marks 1991; Karuka 2019) or external (Aguiar 2011) colonization. Indigenous women and children are vulnerable to the negative effects of large "man camps" of workers, especially sexual violence, during the building of transport infrastructure (e.g., the Alaska Highway; Fox 2019). There have been clear calls to address this serious issue directly in environmental assessments "to ensure communities, and in particular women and children, do not shoulder the burden of impacts of industrial camps" (Gibson et al. 2017).

2.2. Economic consequences

Conventional wisdom on the economic effects of road and railway construction assumes a direct and positive relationship between transport infrastructure investments and economic growth (Rostow 1960). Although there is a long lineage of scholars critical of this supposed relationship, railways and other large transport systems obviously bring about significant economic benefits as a result of their construction and ongoing transportation of goods and passengers, as well as through their employment of many people, who in turn support many other segments of the economy.

In many cases, an interdisciplinary analysis of the longer-term impacts of roads and railroads is needed to assess the effects on national and regional economies. For example, a team of Swedish and Spanish economists and geographers examined the role of railways in economic development in the Nordic countries of Denmark, Finland, Norway, and Sweden between 1860 and 1960 (Enflo et al. 2018). Their assessment was that the 20th-century transition of the Nordic countries from being among Europe's poorest countries to some of the world's most prosperous can be partly explained by improvements in the transport system, primarily railroad expansion (Enflo et al. 2018: 63–64).

While the impact of individual roads is rarely as significant as that of a railway line, integrated road systems of national or international significance can have large-scale impacts. Examples include the German Autobahn (Vahrenkamp 2010) and the Interstate Highway system in the USA (Lewis 2013). Such extensive road systems cannot be simply reduced to specific economic, ecological, social, or other consequences because they were part of dramatic transformations that vastly affected ecosystems, such as the widespread destruction of wetlands, and all parts of society, from new patterns of mobility and sociality to new forms and locations of consumption.

The economic impacts of industrial infrastructure on traditional subsistence activities of local and Indigenous populations have been often interpreted within the prevailing developmentalist paradigm (Blaser et al. 2004) and deserve special attention. Pollution and abandonment of pastures, hunting grounds, and fisheries are among the most common but often neglected negative impacts of transport infrastructure. Increased access to previously remote resource-rich regions and associated infrastructure development can undermine

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Indigenous peoples' traditional ways of life, including subsistence practices (Parlee et al. 2018).

2.3. Cultural dimensions and consequences

The construction of roads and railways reshapes the cultural and social fabric of local communities by assimilating Indigenous and minority groups. To date, research on transportation infrastructure includes a number of ethnographic studies examining roads as conduits of change and transformation of Indigenous cultures. Argounova-Low (2012a) shows how a semi-abandoned road in Siberia, which once fragmented the Indigenous community of Essey Yakuts, later came to symbolize webs of social relations of kinship and exchange. The road has become part of local memory narratives about cultural change and transformed Indigenous identities (Argounova-Low 2012a). Even to a larger degree than roads, railways have become projects of technological and social engineering (Beaumont and Freeman 2007; Schweitzer and Povoroznyuk 2020). Their construction brings about significant numbers of migrants and the assimilation of local Indigenous communities, often within the context of colonization and nation-building programs (e.g., Payne 2001; White 2011; Povoroznyuk 2017).

Historical and social science research demonstrates how roads and railways have shaped new social identities. Road construction in Peru, which requires not only scientific expertise but also detailed vernacular knowledge of local landscapes, has given rise to a professional culture of local engineering expertise (Harvey and Knox 2015). Even individual railroad yards can give rise to their own cultures, as Edelman (1997)'s ethnography of shunters, or assemblers of train cars, in Sweden reveals.

Finally, while this review focuses on historical and contemporary dynamics of actually existing infrastructure, the "promise of infrastructure" (Anand et al. 2018), including future plans for roads and railways, can be a powerful social agent as well. The absence of transport infrastructure or "roadlessness" has been a driver of development plans in different contexts (e.g., Siegelbaum 2008; Argounova-Law 2012b) but is now tempered with a growing awareness and concern about environmental issues.

3. Environmental consequences of road and rail developments

The construction of transport infrastructure across remote regions has a broad range of system-level consequences for the environment, most notably in terms of threshold effects and connectivity. The construction of a road or railway in a pristine landscape represents an abrupt step-change in the ecosystem. It marks a threshold shift to a completely new biophysical regime, with a set of emergent properties involving more than simply the combination of engineered structure plus landscape. Roads and railroads connect remote areas to industrialized and populated centers, thereby producing a conduit for the transfer of people, plants, animals, pathogens, contaminants, and off-road activities. At the same time, road and rail infrastructure can serve as a barrier, reducing landscape, and habitat continuity for natural processes such as water flow and animal migration.

With transport networks expanding rapidly in previously roadless areas, there is growing recognition of the need to maintain road-free zones as a way to protect global ecosystems (Laurance and Balmford 2013; Ibisch et al. 2016). Increasing attention is also paid to the essential role played by Indigenous communities in environmental management and conservation; the Global Assessment of Biodiversity and Ecosystem Services estimates that "at least a quarter of the global land area is traditionally owned, managed, used or occupied by Indigenous peoples" (IPBES 2019: 14). International discussions about the conservation of undeveloped lands have largely focused on tropical and other warm regions of the world (e.g., Dean et al. 2019; Kleinschroth et al. 2019; Vilela et al. 2020). In contrast, the vast, largely unroaded permafrost terrains of the Circumpolar North have received much less consideration.

Three sets of environmental properties and processes affect all ecosystems: physical, chemical, and biological. These closely linked and interacting features provide an initial framework to assess the environmental consequences of roads and railways across northern lands. Analysis of these features also provides a systematic approach towards identifying mitigation measures to minimize the negative effects of infrastructure on high-latitude ecosystems and associated traditional cultures and practices, and towards the application of proactive adaptation strategies in the face of rapid climate change.

3.1. Physical impacts and mitigation

The physical implications of transport infrastructure are of special concern for lake and river ecosystems, which are major features of the northern landscape and vitally important to Indigenous and local communities. High densities of waterbodies and flowing waters are found throughout the Arctic, which has been referred to as "the world's largest wetland" (Kling 2009). Building a road bisects the landscape and alters the distribution of snow and the pattern of water flow. This alteration modifies the hydrological connectivity between land, wetlands, streams, rivers, and lakes, and the resultant ecological effects require particular attention in northern environmental impact assessments (EIAs). The strong hydrological effects of linear infrastructure include channeling, impeding and intercepting flows, interruption of ephemeral stream flow, and increased ponding and erosion, but many of these effects can be substantially mitigated by appropriate engineering designs (Raiter et al. 2018; Cochand et al. 2020).

The distribution of lakes and rivers has major implications for alignment of transport infrastructure and the decisions that go into the planning of safe, cost-effective routes, including the need for bridges and culverts. It also has implications for maintenance of that infrastructure, especially over permafrost watersheds (Vincent et al. 2017). The presence of liquid water can result in underground thermal erosion via water flow and heat transport, with resultant thawing, collapse, and gullying of ice-rich permafrost (Fortier et al. 2007; Shur et al. 2015). Embankments trap snow and water that amplify these thermokarst (permafrost thawing and erosion) effects, and the close proximity of lakes, ponds, and streams to roads (Walker et al. 2022) and railways (Ashpiz 2020) makes the stability of the transport infrastructure especially vulnerable. As it is often difficult to implement adaptive engineering strategies for these sections, recommendations include avoidance of the most problematical areas based on detailed mapping (Vincent et al. 2017; Walker et al. 2022), including sedge wetlands and drained lake basins (Meehan 1988); reduction of the embankment slope to reduce snow build-up (Ashpiz 2020); use of passive cooling systems (Doré et al. 2016); avoidance of heavy vehicle use on adjacent lands that may disturb the local hydrology (Shur et al. 2015); and careful attention to drainage designs to avoid or minimize ponding, thermokarst, and gullying (Meehan 1988; Doré et al. 2016; Ashpiz 2020; Cochand et al. 2020).

Extreme weather events are becoming more frequent and exhibiting greater intensity in the North (e.g., Landrum and Holland 2020; Bégin et al. 2021; Christensen et al. 2021). Climate change is set to exacerbate this trend, and the risk of extreme water-related events is of increasing concern for transport infrastructure in the Arctic. Hazards include extreme precipitation and flooding events (Instanes et al. 2016), as well as heating and thaw, and the production of meltwaters from ice-rich permafrost (Shur et al. 2015). An additional risk factor associated with warming is the bursting of snow dams in thermokarst basins that were previously drained but then filled with snow, which melts and breaches the dam, resulting in the abrupt release of flood waters (Arp et al. 2020). Northern engineers must increasingly design their present-day structures to contend with future averages and extremes in climates that are very different from today (Doré et al. 2016). This "designing for change" involves engineering designs that may be more expensive in the short term than conventional approaches, but that are economical and ensure safety in the longer term. Ashpiz (2020), for example, suggests that design decisions for northern railways should be based on forecasts of changes in permafrost conditions modeled at least 50 years out after construction.

Part of the need for careful consideration of design options is that linear infrastructure may disturb the thermal equilibrium of permafrost and in multiple ways. Permafrost landscapes can be envisaged as three-layer systems in which the permafrost and active layers are overlain by a surface buffer layer that may include organic detritus, vegetation, snow, and (or) infrastructure (Vincent et al. 2017). Snow can have beneficial effects because it constitutes a high albedo surface that reflects a large portion of the incident solar radiation, thereby preventing the transfer of this radiative energy to the ground. However, snow also acts as an insulating layer that inhibits the cooling of permafrost during winter. This insulating property increases with the thickness of the snow cover (Stieglitz et al. 2003) and is especially problematical at the base of road and rail embankments that accumulate snow (see fig. 3 in Malenfant-Lepage et al. 2012). Mechanical snow removal and compaction have been identified as management techniques to reduce these effects on permafrost degradation (O'Neill and Burn 2017). Gravel roads have low reflective properties (low albedo) because of the dark hue of their constituting material, and this effect is exacerbated on paved roads by the blackish bituminous surface; some attention has therefore been given to making Arctic road surfaces lighter and more reflective to reduce their solar absorption (Dumais and Doré 2016). Additional effects on the local radiation balance may result from dust deposited on adjacent snowbanks, which reduces albedo and enhances warming. Observations in Alaska showed that road dust caused early snowmelt and a snow-free zone up to 100 m away from the road, along with accelerated thermokarst activity (Walker and Everett 1987).

For terrestrial as well as aquatic wildlife, the presence of roads and railways may constitute a barrier to migration. On the other hand, they may also serve as unintended corridors for early migration of waterfowl and other wildlife in the spring because of early melting ponds and tundra next to the roads caused by effects of road dust (Walker and Everett 1987; Truett et al. 1997). Additional physical effects imposed by vehicular traffic include the possibility of collisions with animals (e.g., Clair et al. 2020) and the effects of noise on wildlife populations such as bird species (e.g., Lucas et al. 2017).

Roads and railways also increase the risk of fire on surrounding lands because of increasing human activity, including campfires, and the release of sparks from vehicles. A primary environmental effect of the Siberian Baikal–Amur Railroad, for example, has been more frequent fires caused by sparks from the diesel locomotives (Sergeev 2021). In a remote sensing analysis of fire distribution in Siberia, there was a strong correlation between burned forest and the presence of roads (Kovacs et al. 2004). In a similar Canadian study, the extent of fire activity in the Taiga Plains and Taiga Cordillera was correlated with the presence of roads, suggesting an effect of human activities (Gralewicz et al. 2012). In the Sakha Republic (Yakutia), one of the most fire-prone regions of Russia, forest clearing and agro-industrial development, including associated roads and road services, have resulted in human activities now exceeding lightning strikes as the primary cause of fires (Kirillina et al. 2020). In addition to fires set by humans, there may also be effects of vegetation change. A study in the Canadian boreal forest showed that wildfire frequency increased with increased road network density, which the authors attributed to the invasion of exotic grasses along the berm of forest roads, producing flammable litter that would readily catch fire by lightning strikes (Arienti et al. 2009).

3.2. Chemical impacts and mitigation

Chemical effects have long been identified as among the most serious impacts of transport infrastructure on terrestrial and aquatic ecosystems (Trombulak and Frissell 2000). These include the toxic effects of road dust (Fig. 3), inorganic and organic contaminants, and major spills associated with collisions and other accidents.

The impacts of road dust on Arctic tundra vegetation involve a mixture of chemical, physical, and ecological effects

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Fig. 3. Road dust and ponding at the edge of the Dalton Highway, near Toolik Lake, Alaska. Photo credit: Christopher Arp.

(Everett 1980; Barnes and Connor 2014; Walker et al. 2022). Early studies along roads in northern Alaska drew attention to the colonization of dust-impacted areas by minerotrophic vegetation, including many moss species, accompanied by a decrease in *Sphagnum* and other acid preferring mosses (Walker and Everett 1987; Auerbach et al. 1997). There was a decrease in lichen colonization, including complete elimination of some species in areas of highest dust fall. Subsequent studies along the Dalton Highway showed that road dust effects had expanded, with an increase in soil pH from 4 in moist, acidic, tussock-sedge tundra to around pH 6 after 25 years of road operation. This was accompanied by a shift in vegetation, including a large increase in graminoids (grass-like plants) and a substantial decline in mosses (Myers-Smith et al. 2006). The calcium carbonate dust from this highway was also shown to coat the leaves of roadside vegetation, leading to a change in their spectral reflectivity (Ackerman and Finlay 2019).

The chemical effects of dust on northern aquatic ecosystems have received little attention but are a source of concern at some sites, as the Baffin Island case study below indicates. The chemical composition of dust and its effects on receiving waters are likely to vary greatly depending on the source of the rock material and the intensity of traffic. In a paleolimnological study of a set of subarctic lakes along a gradient up to 46 km away from a dust-prone highway, lakes within 1 km of the highway had higher ion contents, but no dust effect could be discerned on the biological indicators in the lake sediment cores (Zhu et al. 2019). In a study of dust by Ackerman and Finlay (2019) on the Dalton Highway, the deposition of particulate phosphorus, dissolved inorganic carbon, and dissolved calcium decreased exponentially with distance from the road, consistent with the pattern of dust distribution and indicating the potential for localized chemical perturbation of the soil environment as well as adjacent waterbodies. For a set of lakes in the vicinity of the Dempster Highway, 11 chemical variables decreased with increasing distance from the road, including alkalinity, conductivity, pH, Ca^{2+}, sulfate, and nitrate (Gunter 2017). Road and rail transport was also identified as a contributing factor to chemical pollution of lakes in the Murmansk port region in Russia (Slukovskii et al. 2020).

There is rising concern in northern countries about the routine use of de-icing salts in winter to maintain road safety. Many lakes over the last few decades have experienced a rise in salinity, by as much as a factor of three, in parallel with the development of highways and the use of road salts (Dugan et al. 2017). Monitoring observations have shown that these salts move rapidly into waterways during snowmelt, and that roadside snow contains a cocktail of inorganic and organic pollutants, in addition to the road salt. This requires the targeted removal of roadside snowmelt, including during warm periods in winter, to protect specific waterways (Fournier et al. 2022). In Canada, de-icing protocols based on road salts are mostly restricted to southern roads but may move northwards with the expansion of high-speed roadways into the subarctic. Alaska uses salt and brines for dust control in the subarctic and Arctic (Barnes and Connor 2014), and deicing salts are used in the Murmansk region (Slukovskii et al. 2020). Additional contaminants have been identified on roadways in the south, for example, compounds derived from automobile tires that are highly toxic to certain fish species (Tian et al. 2022) and microplastics derived from the vehicle-pavement interactions. All of these pollutants may accumulate in roadside snow and wash into rivers and lakes during rainfall and melting events (Fournier et al. 2022). Heavy metal pollution of adjacent soils is also associated with railway operations (e.g., Jiasheng et al. 2020).

The third type of chemical impact involves road accidents or derailments and the resultant spill of fuels and other chemicals. This requires systematic attention in any EIA to evaluate the risk of occurrence of a spill along sensitive areas of the road or railway track, the identification of potential flow pathways of the pollutant through surface and ground waters, and assessment of the hazardous impacts of the pollutant on the environment (Lacey and Cole 2003), along with emergency clean-up and mitigation protocols. This concern was addressed, for example, in the EIA for the Inuvik–Tuktoyaktuk Highway, Canada's first road to the Arctic Ocean, which opened in 2017 (see below), and has been flagged as one of several important issues to consider in EIAs for mining transport infrastructure across salmon fishery watersheds in Alaska (Kravitz and Blair 2019).

3.3. Biological impacts and mitigation—habitat integrity

The biological effects of road and railway constructions and their subsequent operations are especially related to ecological connectivity (linkages within and among ecosystems) but in two contrasting ways. Transport infrastructure lessens connectivity by acting as a barrier to the free movement of organisms across the landscape and their associated terrestrial and freshwater habitats. Conversely, roads and railways increase the mobility and range expansion of certain plants and animals, including invasive species, by providing a conduit for dispersal along the linear infrastructure, often over long distances.

The disruptive effects of roads and railways on habitat integrity have been documented for many terrestrial animal groups throughout the world (e.g., birds, Kocioleket al. 2011; bears, Proctor et al. 2020; carnivores, Ceia-Hasseet et al. 2017; vertebrates, Pinto et al. 2020). However, this ecological perturbation and its interactions with other stressors are generally not well addressed in EIAs for transport infrastructure (Jaeger 2015). These effects are especially relevant to northern ecosystems and their migratory land animals such as caribou, and the extensive hydrological networks over Arctic lands that support fish and other mobile aquatic species, with impacts on the food security of remote northern communities who rely on country foods.

The first issue in assessing habitat disruption is the spatial scale of potential impacts, which can extend well away from the infrastructure. For example, for many bird populations, these impacts extend over distances up to 1 km, and for many mammal populations over several km, with large variations according to species and habitat type (Benitez-López et al. 2010). The second issue is the timescale of impacts, which again vary among species. There are likely to be delayed responses to habitat loss, deterioration of habitat quality, and impaired migration, which may extend over decades and ultimately lead to a state where the population is at risk of massive decline or even extinction (Jaeger 2015). A third factor is the interaction between these infrastructure effects and other stressors in the environment. For example, migratory animal populations are likely to be under increasing habitat stress as the Arctic region continues to warm (Davidson and Ruhs 2021), and climate change will likely amplify the negative consequences of road and railway infrastructure.

The influence of Arctic infrastructure on caribou and reindeer (*Rangifer tarandus* (Linnaeus, 1758)) has been of special concern for road and railway developments throughout the North. This is not only because the large populations of these migratory herbivores are such a major component of Arctic terrestrial ecosystems but also because of the subsistence, economic, and spiritual significance of these herds to northern Indigenous peoples, for example, Nenets reindeer herders (see below), Saami reindeer herders (Tyler et al. 2021), and subsistence hunters of caribou (e.g., Tanner 2007; Ettinger 2020; Borish et al. 2021). The negative effects of roads on caribou have been documented in many areas. In a petroleum development area west of Prudhoe Bay, Alaska, the abundance of calving caribou was reduced within 4 km of roads and decreased exponentially with increasing road density, with a shift in high-density calving from the development area to inland habitats that had lower forage biomass (Cameron et al. 2005). Despite 40 years of oil development activity in the North Slope area, caribou did not show evidence of habituation and continued to avoid infrastructure during all seasons (Johnson et al. 2020). Mothers with calves are especially sensitive to vehicle traffic (e.g., Prichard et al. 2022).

Modeling of reindeer habitats in southern Norway shows that roads are major barriers to reindeer movement, with fragmentation of the effective area of reindeer habitat into smaller areas delineated by roads that are infrequently crossed (Beyer et al. 2016). In a study on the barrier effect of roads on caribou movement in northern Québec and Labrador, Plante et al. (2018) observed large year-to-year differences in road avoidance behavior that may reflect variations in snow cover and habitat availability. There were very few crossings of the Trans-Labrador Highway, indicating that it acted as a migration barrier, but a herd crossed the Trans-Taiga Highway during winter despite avoiding it in the past. The effects may be more complex than simply avoidance. In a migration study across an industrial road with relatively low levels of traffic in northwestern Alaska, Wilson et al. (2016) found that for 30% of the tracked animals (equivalent to 70 000 caribou in the full population), there was a delay of on average 33 days between first encounter and the crossing of the road. This long delay for a subset of the herd may have effects on individual survival and reproduction.

Among other risks, caribou on and near roads are more exposed to sports hunters, although avoidance of roads by these animals would reduce their vulnerability (Plante et al. 2017). Sports hunting may compete with subsistence hunting, with major economic consequences for families who rely on this food source (Guettabi, et al. 2016). Increased pressure by subsistence hunting from roads represented a concern for caribou management along the Dempster Highway in the western Canadian Arctic and compelled the enactment of a regulation based on Indigenous knowledge to restrict hunting and "let the caribou leaders pass" during the first week of migration. Many residents took issue with this regulation, including some Indigenous groups who saw it as inter-

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fering with their subsistence hunting culture and infringing upon Indigenous political autonomy. After a period of conflict, this regulation was subsequently overturned by legal action (Padilla and Kofinas 2014).

Very little is known about the effects of transport corridors on Arctic freshwater ecology, but studies in road and rail ecology from other latitudes show how disruptions of water flow across the landscape affect different trophic levels in the aquatic food web. Research in central Europe has shown that road crossings negatively affect the richness and abundance of benthic macro-invertebrates (animals living on stream beds that are a food supply to birds and fish), including protected species (Gál et al. 2020). In a study of Alaskan hydrological networks, the observations suggested an effect of hydrological connectivity on food web composition, with large-bodied zooplankton more prevalent in poorly connected lakes with low fish diversity (Beaver et al. 2019). Fish are especially sensitive to transport infrastructure as barriers to migration, but also because of effects on habitat quality including temperature, suspended sediments, food supply, and the timing and magnitude of water flow (Trombulak and Frissell 2000). Roads and railways may also disrupt the transport and distribution of woody materials, which play a major ecological role in river ecosystems by producing diverse habitats for aquatic life (Wohl et al. 2019).

The connectivity literature in applied aquatic ecology draws attention especially to the key influence of culvert design and also of inspection and maintenance strategies to ensure the culverts remain fully operational in their ecological as well as engineering function. This will be especially important for adapting to extreme weather and flood events as the climate continues to warm. In Alaska, for example, culverts have been inventoried with a set of standardized techniques and protocols and graded on a color scale from adequate to inadequate for fish passage (Eisenman and O'Doherty 2014). Following concerns expressed by the Labrador Métis Nation, a survey of the newly constructed Trans-Labrador Highway, Canada, showed that 53% of culverts would interrupt fish passage, due to design and installation problems, and an apparent lack of environmental oversight. This study led to government plans for culvert redesign and restoration in cooperation with the Indigenous communities of the area (Gibson et al. 2005).

Another example of ecological progress in transport design is the environmental management of the River Teno system (Tana in Norwegian; Deatnu, meaning "great river" in Saami) at the border between northern Norway and Finland (70°N, 28°E). This is a prime site for wild Atlantic salmon fishing, as the species can be found across more than 1100 km of the river and its tributaries through which it migrates between the sea and inland waters. The Saami people living in this region call themselves *čáhcegátte olbmot* in Northern Saami, which means "people living by the shore", and traditional salmon fishing is central to their traditional culture and well-being (Hiedanpää et al. 2020). Road construction and stream crossings have threatened this resource. Restoration measures have focused on the downstream outlet area of road culverts, specifically by reducing the drop and expanding the associated outlet pool. This management has greatly improved connectivity and has expanded the production area accessible to juvenile salmon (Erkinaro et al. 2017).

Studies on fish ecology in Alaska have drawn attention to the importance of ecological connectivity, and the need to implement adaptive management plans at a watershed scale. For the fish species Arctic grayling (*Thymallus arcticus* (Pallas, 1776)), some populations occupy stream reaches as summer feeding habitats, while others use them as migration pathways to access seasonally frozen lakes (Heim et al. 2019). These observations underscore the need to recognize the important spatial relationships between lakes and rivers on the landscape, along with the need to consider scenarios of watershed responses to climate change and extreme events (Arp et al. 2019).

3.4. Biological impacts and mitigation—habitat and range expansion

Roads and railways increase the mobility and range expansion of species by providing a conduit for dispersal, often over enormous distances. For the most part, this is through direct transfer of organisms or propagules between destinations. Newly constructed infrastructure may also unintentionally create disturbed habitats that favor certain species. Gravel embankments and associated ponded water provide habitats for aquatic bird species (Meehan 1988) and promote the growth of certain plant species. Tall shrubs have proliferated along the edge of the Dempster Highway in Northwest Territories, Canada, as a result of greater soil moisture and feedback effects that promote shrub recruitment and growth (Gill et al. 2014; Cameron and Lantz 2016).

Indigenous knowledge is an important source of information to track changes in biodiversity associated with invasive species. For example, in the Republic of Sakha (Yakutia) in Russia, local communities have observed the arrival of many new plant species, which they attribute in part to vehicle traffic, initial colonization of road shoulders by the plants before spreading elsewhere, and species brought in with gravel used in construction. In view of their traditional ecological knowledge, Indigenous peoples are well-placed to monitor, manage, and maintain Arctic biodiversity (Ksenofontov et al. 2019).

Transport infrastructure can facilitate the spread of invasive species into Arctic ecosystems in a number of ways, which runs the risk of causing large-scale economic, cultural, and ecological damage. The establishment of invasive species involves five steps (Lockwood et al. 2005): (1) uptake from the native range; (2) transport by vectors; (3) release after transport; (4) establishment; and (5) population development. A critical factor is "propagule pressure" or the number of individuals invading an area in a specified time. Road and rail transport amplifies this pressure over long distances, including via the dispersion of propagules across previous ecological barriers such as mountain ranges and rivers (Ascensão and Capinha 2017). After newly colonizing species establish themselves, transport networks can serve to expand their range. Land disturbances associated with road and railway development provide opportunities for colonization and spread of invasive plant species at the expense of native communities.

Mitigating the risk of invasive species requires close attention during both the construction and maintenance stages, especially along road and railway berms (Hansen and Clevenger 2005). Alien grasses can be especially efficient in colonizing such disturbed lands, with their dispersal then potentially amplified by waterborne seeds in transport networks that intersect rivers (Rahlao et al. 2010). Even the range of slow-growing Arctic plant species may be extended northwards by transport activities. For example, a white spruce tree seedling was found growing on the gravel berm of the Dalton Highway, Alaska, 50 km further north than the treeline and on the northern side of the Brooks Range, which would normally pose a dispersal barrier to this species (Elsner and Jorgenson 2009).

Primary transport routes open up opportunities for secondary routes, including informal tracks used by off-road recreational vehicles as well as mobile industrial and survey machinery (e.g., seismic survey track vehicles; Raynolds et al. 2020). These create further landscape damage that may enhance invasions. Primary and secondary roads are also conduits for aquatic invasive species, which are often carried on recreational boats moved by trailers (Cole et al. 2019). Many invasive water plants (non-native aquatic macrophytes) can be dispersed by small amounts of plant tissue, and these persist as viable propagules for long periods of time, even in the absence of liquid water (Bruckerhoff et al. 2015). There is concern, for example, about the recent invasion of the water weed *Elodea canadensis* Michx. into Alaskan lakes, and its potential effects on water quality and salmon habitat (Larsen et al. 2020), with dispersal among waterbodies likely facilitated by float planes and recreational boats. These effects require monitoring and early warning, as well as an information campaign, as in Alaska, to alert boat owners and apply boat decontamination protocols.

Invasions of alien species are now taking place at unprecedented rates throughout the world (IPBES 2019), largely due to human activities. For example, 116 alien plant species have been reported in eastern Russia, likely associated with increased trade and transport connectivity (Vinogradova et al. 2020). It should be noted that there are few reports of invasive plant species along Arctic roads in general (with some examples noted above), despite the many decades since their construction, or even from road-associated areas subject to disturbance by forest and tundra fires. This implies that the ecological barriers to plant invasion remain significant at high northern latitudes. Climate change, however, is amplifying the risk of new species introductions, potentially placing native species under stress and reducing such barriers for potential invaders. Continuous investment in public education is crucial to reduce this risk (Cole et al. 2019), as is attention to the issue of alien species invasions in transport EIAs.

4. Case studies of northern roads and railways

In this section, we examine a set of road and railway developments in different parts of the Circumpolar North. Most developments are well-established, while one is newly established and another is in an advanced planning stage. Each site illustrates specific facets of the complex nature of northern transport infrastructure, and although we apply a common template throughout (background, economic, social and cultural, environmental, and engineering aspects) to facilitate comparisons, comprehensive information is rarely available for all of these topics.

The Baikal–Amur Mainline in Russia highlights a variety of demographic, socio-economic, and cultural transformations as well as environmental changes that the large-scale infrastructure project has induced. This example illustrates how the historical and political context is important to understand the long-term consequences of railway infrastructure for local communities. The far northern Bovanenkovo Railroad on Russia's Yamal Peninsula shows how transport infrastructure can rapidly transform the Arctic landscape and pose both challenges and opportunities to the Indigenous population as well as present engineering challenges for construction and maintenance on permafrost.

In North America, the Alaska–Canada Highway was promoted as a heroic project of man fighting against the wilderness during the period of its construction, but it has had dramatic impacts on subsistence activities while leading to the marginalization of the Indigenous population. This case study also illustrates the challenges of road building and maintenance on permafrost and the nature of engineering solutions to address these challenges in a warming climate. The Inuvik–Tuktoyatuk Highway in Canada is an example of a road transport project receiving broad Indigenous support based on projected economic and social benefits, despite construction near lakes of cultural and ecological importance, risks to a subsistence fishery, and other environmental issues.

While it could be argued that the construction of transcontinental railways was instrumental in forging the USA and Canada (Charland 1986), very few railroads cross the landscapes of the Arctic and subarctic areas of North America. Only one Canadian railway line terminates north of 60 degrees northern latitude. This is the Mackenzie Northern Railway, now owned by the Canadian National Railway and renamed the Meander River subdivision. This railway line ends in Hay River, a rail, river, and road transport hub in Northwest Territories that expanded rapidly in the 1970s with the (unrealized) prospect of Arctic oil and gas development (Bell and Jackson 2020). Thus, Hay River is considered the northernmost point of the contiguous North American railway network. While there are no railway lines in northeastern Canada north of 60, one line ending at about 55 degrees North is relevant in our context. It is the Tshiuetin line connecting the city of Sept-Îles, Quebec, in the south with the small northern settlement of Schefferville, Quebec—a former mining town—via the province of Newfoundland and Labrador. What is noteworthy about the Tshiuetin Railway (Ellingson 2020) and more recently the Hudson Bay Railway in Manitoba is that they are both owned or co-owned by Indigenous consortiums.

Our case studies below include three North American railroads. The Alaska Railroad is now a key link within Alaska's transportation network, and there is interest in extending it to Canada to service the mining and oil industries. The socio-ecological consequences of this infrastructure have been little explored, and Indigenous concerns were given little consideration during its planning and construction, despite acknowledgment that major cultural and ecological transformations were likely to take place. The Hudson Bay Railway serves Canada's "Arctic port" of Churchill, Manitoba, and this case study illustrates the vital importance of rail supply of goods to a northern community as well as the vulnerability of that infrastructure to climate change and extreme events. Our final example is a proposed new railway development on Baffin Island, Nunavut. This project has been subject to an exceptionally detailed assessment across a broad set of socio-ecological topics, including the application of Indigenous knowledge, but it has come under close public scrutiny due to a conflict between large economic interests and outspoken Indigenous concerns about potential environmental impacts.

4.1. Baikal–Amur Mainline, Russia

4.1.1. Background

The Baikal-Amur Mainline (BAM) is a 4324-km-long northern railway that crosses six administrative regions in Siberia and the Russian Far East (Figs. 1 and 4). The history of the BAM starts with the first plans dating back to the 19th century and continues with the first sections of railroad built under the Stalinist regime in the 1930s, while the majority of the mainline was built between 1974 and 1984 during the Brezhnev era. The railroad was designed to stimulate regional development through the exploitation of largely untapped natural resources and to strengthen collective faith in the administrative command system (Ward 2009). The late Soviet-period BAM became a large-scale project of transformation of natural landscapes and internal colonization, similar to other Soviet industrial projects (Kotkin 1997). The construction and operation of the railroad had a number of unprecedented environmental, economic, demographic, and socio-cultural impacts, which have been assessed sporadically. While the Soviet economic assessments and development plans highlighted the gains from the BAM project, one sociological survey conducted on the eve of the construction project revealed both expectations and concerns among local and Indigenous residents in a number of villages that would be affected by the railroad (Boiko 1979). Since then, no large-scale social impact assessments have been undertaken to monitor the consequences of the railroad infrastructure on the local and Indigenous populations, their subsistence activities, and their ways of life.

4.1.2. Economic factors

The BAM project of the late Soviet period was conceptualized within the framework of the regional development program "Mastering of the North" (Slavin 1982). The program sought to form so-called "territorial industrial complexes," with the BAM expected to provide access and enable extraction and transportation of non-renewable resources such as coal, oil, timber, and metals from the region to Asian markets. Yet, once the BAM began operating in the 1990s, the amount of cargo transported and the railway's overall economic performance was far below expectations (North 1990: 213). As a result, the BAM construction boom eventually resulted in an economic and infrastructural decline (Mote 1990), which was aggravated by dramatic socioeconomic transformations following the dissolution of the Soviet Union. However, the state investment in BAM ultimately paid off: by 2015, the railroad transported 75.5 billion ton-km of cargo and 7 million passengers annually (Informatsiia 2016). At present, the state-owned Russian Railways Company (RZhD) operates the BAM, which forms the backbone of the regional transportation system. The railway supplies local communities with produce and goods and also provides jobs, especially in the mono-industrial settlements en route. The launch of the state-sponsored railway reconstruction program BAM-2 in 2014 has also been associated with plans for a new wave of socio-economic development of the region (Povoroznyuk 2019; Povoroznyuk 2020).

4.1.3. Social and cultural issues

The BAM was a population magnet from the 1970s through the 1990s. Brezhnev's prestige project did not just include the construction of a railway line: it also brought to life a number of railway towns, such as Tynda, Severobaikal'sk, Novaia Chara, and smaller settlements. In the 1970s and 1980s, the state recruited labor migrants from across the USSR with a combination of ideological propaganda and material benefits. According to some estimates, over 500 000 labor migrants in their 20s and 30s arrived at the BAM construction sites (Ward 2009). The general tendency of population growth between 1970 and 1989, however, transformed into a dramatic population outflow after the collapse of the Soviet Union in 1991. As a result, some cities along the railway, such as Tynda, "the capital of the BAM," lost almost half of their populations.

The pre-BAM population of the region included Indigenous Evenki and Buryiat, as well as earlier Soviet (primarily Russian) migrants to the North. The sociocultural changes triggered by the BAM especially affected the Evenki. The railway impacted their traditional nomadic way of life based on reindeer herding and hunting. Environmental pollution, forest fires, and destruction of pastures and hunting grounds caused by the construction and exploitation of the mainline pushed and continue to push, Evenki out of their traditional lands. The resource extraction projects associated with the BAM led to further alienation of traditional lands and reduced opportunities for continuing ways of life based on subsistence activities (Fondahl 1998; Povoroznyuk 2011).

The BAM did not only bring new migrants: it also became an important social and cultural icon of the 1970s and 1980s (Ward 2001). While *bamovtsy*, or BAM builders, primarily settled in railway towns and cities, they often visited Evenki villages and taiga camps to exchange products and attend cultural events. Their interactions with Indigenous residents ranged from conflicts to friendships and mixed marriages. The phenomenon of "the children of the BAM" (*deti BAMa*), the next generation of local residents with mixed biological and cultural backgrounds and multiple or shifting linguistic

Fig. 4. The Baikal–Amur Mainline (BAM), Russia. The main function of the railroad is cargo, including oil transport (above, July 2017), but passenger services (below, Yuktali station, July 2017) are also important throughout its more than 4000 km extent. Photo credit: Olga Povoroznyuk.

and cultural competences and identities (Turaev 2004), became one of the results of the encounters between local and migrant populations during the BAM project.

The proliferation of Soviet ideology, popular culture, and the Russian language along with the changes to the sociodemographic structure, traditional land use, and nomadic practices described above led to the overall cultural assimilation and Russification of Evenki people during and after the BAM construction. While Evenki communities residing well away from the railroad, such as, for example, Ust'-Niukzha, continued to leverage their relative remoteness to strengthen local ways of life as well as their language and culture (Schweitzer and Povoroznyuk 2019), the changes brought by the BAM greatly affected Indigenous villages that are in close proximity and connected to the railway.

4.1.4. Environmental issues

While any large transportation project obviously has many ecological impacts, no thorough environmental studies or expert assessments were conducted prior to the start of the BAM construction in 1974 (Pryde and Mote 1990: 53). Yet building a railway line extending several thousand kilometers did severely impact the environment. It transformed and polluted the northern taiga landscapes and disturbed the habitats of endangered species. Destruction of hunting grounds and reindeer pastures affected the land use and subsistence activities, which are of vital significance for the local and Indigenous populations (Zadorozhnyi et al. 1995). Indigenous reindeer herders and hunters continue to suffer the environmental costs of the BAM, which in most cases remain officially unrecognized. Garbage thrown out in the taiga by passengers that attracts wolves, collisions of domestic animals crossing the rails with trains, and forest fires negatively impact reindeer herding and other subsistence activities practiced by Evenki and other Indigenous groups in the BAM region (Povoroznyuk 2021).

4.1.5. Engineering issues

Environmental change impacts the condition of permafrost and geotechnical processes, which have an effect on infrastructure throughout its life cycle. Two contrasting adaptive strategies can be used to maintain the stability of infrastructure: an engineering protection foreseen in the construction project (see above) or annual repairs that support the functioning and the original qualities of infrastructure. In the first case, research data and forecasts of the climate and permafrost dynamics are required (e.g., Doré et al. 2016; Ashpiz 2020). This results in a considerably increased cost of construction and responsibility of the investor for the successful construction and operation of infrastructure. In the second case, engineering and construction are implemented according to the existing norms and regulations. Climatic change is assessed through the quotient of the margin of safety and responsibility for infrastructure maintenance is delegated to repair contractors. Interestingly, in the European part of northern Russia, regular repair of subsidence and heaves of railroad tracks has had lower costs than geotechnical protection measures (Voitenko et al. 2017). This may not apply to the regions of East Siberia.

In 2014–2015, the Institute of Environmental Geoscience and the Water Problems of the Russian Academy of Science surveyed the total impact of permafrost processes on the 72-km-long side track Novaia Chara-Cheena of the BAM in the Zabaikal'skii Region. Until then, this railway section had not seen any repair or protective and compensatory measures. It was constructed in 1998–2001 as a railroad leading from Novaia Chara to the polymetallic ore deposit Cheena (Chesnokova et al. 2016). Generally, geocryological processes activated by technogenic impacts and disruptions of the terrain are estimated to decrease within a few years after the end of construction. However, in some cases, this does not happen for many years, and, moreover, new sites of land disturbance can emerge. These changes are connected with the gradual change of background permafrost conditions, as well as with slowly developing processes such as the expansion of *taliks* (a layer of unthawed ground, for example, beneath lakes). Warming climates activate one kind of unfavorable process (thermokarst), while seasonal cooling leads to heaving and *aufeis* (sheets of ice formed from groundwater outflows) that may continue to occur in winter despite warmer temperatures. The BAM and its side tracks were traditionally designed with advanced proactive protective measures, but after 40 years of operation, it became obvious that the cumulative changes in geocryological conditions were too large and may exceed the capacity for annual repairs (Afanasenko et al. 1995a; Afanasenko et al. 1995b).

4.2. Bovanenkovo Railroad, Russia

4.2.1. Background

The Bovanenkovo Railroad is the northernmost railway in the world, connecting the railway station Obskaia, 12 km from the nearest city of Labytnangi, to the Bovanenkovo gas field on the Yamal Peninsula at 70.37°N (Fig. 1). The railway was designed and constructed by the Russian state-owned corporation Gazprom, which continues to operate the line. The 525-km long railroad was officially opened in 2010 and extended by an additional 47 km in 2011. There are plans to extend this railway another 170 km to the LNG terminal in Sabetta, which would thereby become the easternmost port with a railway link on the Northern Sea Route (Chernov 2021).

4.2.2. Economic factors

The Bovanenkovo Railroad was constructed by Gazprom to deliver materials and equipment for the development of their Bovanenkovo site, one of the world's largest gas fields, and to allow year-round access to the industrial site. The proposed extension to Sabetta has been projected to cost approximately US $3 billion (Staalesen 2018). This link would ultimately connect with another proposed railway, the 707-km Northern Latitudinal Railway (NLR), thereby connecting Russia's Ural and West Siberian regions to the Northern Sea Route. The NLR would link two existing Arctic railway lines, the Northern Line from Arkhangelsk and the line between Nadym and Tyumen, with an estimated cost of US $1.7 billion. This would include a 40-km long bridge across the Ob River and would rely on private investment (Staalesen 2018).

The Bovanenkovo Railroad has had a number of positive economic consequences for the Nenets, the Indigenous people of this region, but also negative impacts on the environment and cultural activities detailed below. In the early 1990s, there was widespread unemployment throughout the Russian Federation. Conditions were especially hard for people living on the tundra, far from settlements and access to goods and services, including child support services and medical help. Still, most of the Nenets people continued to survive in the tundra by practicing traditional reindeer herding and fishing.

With the arrival of the extractive industry workers, the reindeer herders and other tundra people tried to establish contact and build relations (Forbes et al. 2014). The Indigenous tundra dwellers acknowledged many benefits from the industrial and transport development, such as mobile telephone connections and the opportunity to buy fuel (Forbes et al. 2009). In addition, the free use of railroads provided to Indigenous residents by Gazprom stimulated mobility among the least mobile groups of Nenets people, including women, children, and elderly people. Indigenous reindeer herders now regularly use the railroad to commute between their tundra camps and towns for buying supplies and other errands (Terekhina and Volkovitskii 2020).

4.2.3. Social and cultural issues

From the earliest stages of this project, the social consequences of the railway for the Indigenous residents have been a major issue. The railway traverses migration routes of the Nenets families, and important reindeer pastures, creating impediments to the seasonal migration of reindeer herders across the tundra (Fig. 5). Some Nenets groups changed their migration routes, but others continued to follow their old ways of traveling in the tundra, experiencing many difficulties and limitations as a result (Forbes et al. 2009; Degteva and Nellemann 2013; Forbes 2013). Nenets people did not isolate themselves from these changes, but rather developed new networks of communication with railway workers, and built businesses to obtain revenue and buy goods, including fuel and basic food supplies at the tundra railway stations (Forbes 2013; Forbes et al. 2014).

The railway construction resulted in many cases of conflicts (Stammler and Forbes 2006; Stammler 2011) and continues

Fig. 5. Nomadic Nenets reindeer herders crossing the Obskaia–Bovanenkovo railway tracks near the Yuribei River, Russia, July 2010. Photo credit: Bruce C. Forbes.

to have wide-ranging effects on Indigenous culture, mobility, economy, and social activities. For many Nenets families, their sacred places play an important religious role and their loss is viewed as a tragedy (Khariuchi 2013: 46; Laptander 2020). At the end of the 1990s, the Nenets Sacred Mountain Enzor Pe, part of the Polar Ural Mountains, was destroyed to extract stones for the construction of the railway embankment. Not surprisingly, this has become a sensitive topic. In an interview in 2006, the leader of a reindeer herding brigade belonging to the Yarsalinskii farm, confirmed that the railway workers had destroyed important sacred places in the tundra for the needs of the railway construction work (Kumpula et al. 2010; Forbes et al. 2014). In the summer of 2009, local reindeer herders and semi-nomadic reindeer herders complained about illegal fishing by Bovanenkovo gas field workers in the Nenets subsistence fishing lakes. They wrote a letter to the director of Gazprom stating their concerns and requests. Although the company did not respond directly to this letter, rules were later established for extractive industry and railway workers prohibiting them from illegal fishing in the lakes and rivers of the tundra (Laptander 2020: 87).

4.2.4. Environmental issues

Transformation of the tundra landscape due to the Bovanenkovo Railroad took place very rapidly (Kumpula et al. 2012), with implications for the freshwater fishery resources of the area and their role in the local economy. A researcher visiting the Yuribey River in 2008 noted that construction was already underway, including a 3.9 km bridge over the floodplain. A year later, the railway was already operational for the transport of fuel, goods, and people to the Bovanenkovo gas field (Kumpula et al. 2010). There were complaints about how these intensive construction activities had led to a lack of the fish in the river. In compensation, Gazprom gave new outboard motors to some of the Nenets families for their boats (Laptander 2020). Today, there is sale of fish by reindeer herders to the industry workers at a fixed price, which provides a summer income for the family budget, allowing purchase of food, gasoline, and other supplies at the stations along the railway.

While the Bovanenkovo railway has become an integral part of the present tundra landscape, with people learning how to live within an altered environment, the new infrastructure still presents many difficulties (Forbes et al. 2014). Field research in the area has shown that the initial construction phase of the railway caused many problems for reindeer herders and their traditional way of life, destroying their pastures to make sand pits (Forbes 1995), and causing garbage and pollution (Forbes et al. 2009; Kumpula et al. 2010). There have, however, been efforts at land restoration and clean-up near the railway (Forbes et al. 2014), and the landscape is beginning to recover. However, there is ongoing concern about reindeer wounding or deaths due to collision with trains when they cross the railway. One reindeer herder commented that before they had only tundra predators, but now there is a new "iron predator": the railway (Laptander 2020). Additionally, the railway line has now permanently altered the traditional migration routes, with attendant difficulties for herders and their reindeer.

4.2.5. Engineering issues

The construction of the railway over permafrost lands and waterways posed a number of major engineering challenges, and its design required attention to thermokarst, subsidence, and the dissipation of heat, snow, and water (Ashpiz 2020). Lakes, rivers, and wetlands are a feature of this landscape, as throughout the Arctic, and the crossing of the Yuribey River floodplain was the most difficult part of the construction. This involved an unusual engineering design with a 3893 m-long overpass constructed on an elevated roadbed above the water, supported by 110 pillars with a diameter of up to 3 m that were sunk 30–60 m into the ground. The section of track included 88 bridges, with two that are 110 m in length. The construction involved specialized equipment, including drilling units that could operate on permafrost at subzero temperatures (Railway Technology 2009).

4.3. Inuvik–Tuktoyaktuk Highway, Canada

4.3.1. Background

The Inuvik–Tuktoyaktuk Highway (ITH) in Canada's Northwest Territories opened in 2017, becoming the first public highway in North America to the Arctic Ocean. The ITH extends the Dempster Highway, which opened in 1979 and previously terminated in Inuvik (population 3370; 2019 census), by 138 km. This two-lane gravel road stretching across lands traditionally occupied by the Inuvialuit (the Inuit of the western Canadian Arctic) and the Gwich'in now reaches all the way to the hamlet of Tuktoyaktuk (population 995; 2019 census) on the continent's edge, where the biodiverse Mackenzie Delta slopes into the hydrocarbon-rich Beaufort Sea. This all-weather highway replaces the seasonal ice road that had been maintained each winter on the frozen Mackenzie River. The ITH proposal was initiated by Tuktoyaktuk residents as a way to improve the supply of goods and services to the local community, and it received support and funding from the Canadian Government given its alignment with the Federal goals of northern economic development, natural resource extraction (especially of natural gas and oil reserves), and reinforcement of Canadian sovereignty by providing road access to the Arctic Ocean (De Guzman et al. 2021).

4.3.2. Economic factors

A distinct feature of the ITH is that it falls entirely within the Inuvialuit Settlement Region, which was established in 1984 following the signing of the Inuvialuit Final Agreement with the Canadian Government. Inuvialuit land title, along with the establishment of the Inuvialuit Regional Corporation and the emergence of Inuvialuit businesses and entrepreneurs, was central to the road's realization, from its conceptualization to its assessment, construction, and now operation (Bennett 2018). Inuvialuit politicians successfully lobbied the territorial and federal governments to contribute the majority of funding (CAD $200 million of CAD $300 million total) to build the road. The ITH thus exemplifies the rise of both Inuit corporate governance (Wilson and Alcantara 2012) and Indigenous-driven projects across the Western Arctic, from Canada to Alaska, where aboriginal corporations also advocate for development (Ganapathy 2011). Such infrastructure projects differ from Arctic megaprojects in previous eras, which were largely envisioned and spearheaded by national governments (e.g., the Alaska Railroad, described in the next section). While territorial and federal financing was still key to financing the ITH's construction, Inuvialuit people helped realize it through their own volition, labor, and, importantly, political capital.

Although the budget was considerable, there was a need to reduce costs substantially during construction, and the minimum embankment thicknesses had to be revised. This involved additional field surveys, mapping, and redesign to identify sections where a thinner embankment and therefore less fill could be employed, within the limits of acceptable risk to protection of the underlying permafrost (Grozic et al. 2018). The project envisaged an annual maintenance cost of $1.9 million (Bird 2017) and a lifetime of 75 years. It remains to be seen whether these estimates are realistic given the rapid warming taking place in this part of the Arctic.

In a landmark study, Mathieu (2021) examined the effects of the ITH on food costs in Tuktoyaktuk. This is the first economic analysis of how new transport infrastructure in an isolated Indigenous community may affect food security and is especially relevant given that the highway was projected to result in $1.5 million in cost savings to residents for food, fuel, and services (Bird 2017). This study found that the cost of a basket of standard grocery items in 2019 was extremely high, as elsewhere in the Canadian North, and was around twice the cost of the same selection in southern Canada. Contrary to expectation, however, the costs were higher than before the highway opened. This was primarily because the community no longer qualified for a Canadian Government food subsidy for isolated northern communities, given that Tuktoyaktuk now has road access.

The economic development consequences of the road are likely to be wide-ranging. For example, the road was projected to stimulate tourism and bring in an estimated $2.7 million in revenues to the region (Bird 2017). Within the first and second years after the ITH opened, there was already a large influx of tourists to Tuktoyaktuk as a result of its promotion as a unique destination reachable by road (Lamontagne-Cumiford 2020). On the theme of "just transitions" across the Arctic (McCauley et al. 2022), the implementation of green energy alternatives is often constrained in the North by a lack of qualified technicians to install, maintain, and repair specialized equipment, and the road link to Inuvik now makes that technical support more feasible. One interviewed Elder in a study on renewable energy solutions in the region noted how "now that there's a road [between Inuvik and Tuktoyaktuk] it's a bit easier. There's no electricity people in [Tuktoyaktuk] so they have to wait for someone from Inuvik to come up and fix problems" (MacKay et al. 2021; p. 1137). The ITH is a functional component of the Mackenzie Valley Highway project to extend an all-weather road throughout the region, and economic assessments of the huge costs of this overall plan are now incorporating the uncertainties of climate change impacts (Li et al. 2022).

4.3.3. Social and cultural consequences

The unpaved ITH winds its way across the permafrost-laden tundra (Fig. 6), curving around lakes that the Inuvialuit have inhabited and used since at least 1250 AD, and their predecessors for even longer (Lyons 2009). Although the road construction received broad public support in the two communi-

Fig. 6. The Inuvik–Tuktoyaktuk Highway (ITH) in Canada's Northwest Territories. This illustrative section of the highway shows the engineering challenges for routing across the landscape while protecting the abundant freshwater resources, including the Inuit subsistence fishery in Husky Lakes. Source data: CanVec, NRCan (Open Government Licence—Canada), and ESRI High-Resolution Imagery (ESRI, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community). Rendered with QGIS v3.14 (GNU General Public License).

ties it connects and now facilitates travel between them, residents have also expressed concerns regarding its negative social and environmental impacts (Bennett 2018). As is the case with roads to places that previously had sporadic or no overland connections to the rest of the world, new roads can suddenly make it easier for residents to out-migrate and for drugs, alcohol, and outsiders to enter; an indicative example here was an illegal consignment of alcohol intercepted on the ITH barely 2 years after it opened (CBC 2019).

The ability of Indigenous corporations and businesses to benefit financially from the construction of infrastructure like roads and other forms of industrial development indicates shifting relationships between Indigenous peoples and their lands. As pressures from the outside and increasingly from within to develop the land increase, they may both undermine and strengthen subsistence practices while imbricating Indigenous peoples into circuits of global capitalism (Bodley 2008). Examining road projects on Indigenous lands such as the ITH can produce insights into the wider interaction of internal and external pressures and traditional and contemporary practices while also problematizing such binary categorizations. In this, roads may be thought of as "interfaces" that negotiate, create, consolidate, and transcend "the limitations of prior relations in their promise of newfound connectivity" (Dalakoglou and Harvey 2012: 461).

Given the involvement of the Indigenous community of Tuktoyaktuk from the conception of the project onwards, there were many opportunities for conveying Indigenous knowledge and influencing decision-making, even though some local hunters and trappers still feel that more could have been done (Bennett 2018). The EIA responded to several Indigenous concerns, for example, the importance of traditional fishing in the Husky Lakes. This resulted in a modified routing of the ITH to reduce the risks to these waters posed by vehicle accidents and fuel spills (Kiggiak-EBA 2011).

4.3.4. Environmental consequences

Environmental risks arising from the ITH parallel those concerning roads traversing other ice-rich permafrost regions of the Arctic, as discussed above. The ITH runs directly across many streams and rivers where fish spawn and migrate, and potential effects on these aquatic ecosystems were considered in the EIA by way of extensive fish surveys and recommendations (Kiggiak-EBA 2011). While culverts were built to mitigate disturbances to aquatic species, construction irreversibly altered their habitat, just as it did for terrestrial species like caribou and fox. There is some evidence following the ITH construction of phosphorus enrichment occurring in nearby adjacent lakes, and a potential reduction in fish habitat quality that is also being influenced by climate change impacts on water chemistry (Murdoch et al. 2021). Every passing vehicle also presents a risk by generating dust that is dispersed onto the tundra, altering the substrate, and reducing vegetation cover (see above for examples elsewhere). The possibility of catastrophic accidents is also of concern. In a worst-case scenario outlined in the EIA (Kiggiak-EBA 2011), an accident involving a fuel supply truck during the spring melt season when water levels are highest could devastate the annual fish harvest on which many locals depend. These worries led to a rerouting of the road, although not to the more expensive "highland" route that would have been farther from the lakes, which community consultations initially recommended.

4.3.5. Engineering issues

The ITH posed many engineering challenges given the abundance of lakes and rivers, severe weather and cold winter darkness, and the difficulties of building a durable road on ice-rich permafrost in a region that is subject to rapid Arctic climate change. The latter required establishing thick gravel embankments to insulate and protect the underlying permafrost, with fill thicknesses ranging from 1.5 to 12 m depending on topography (De Guzman et al. 2021) and budgetary constraints (see above). Fill thicknesses were based on extensive field measurements and geophysical modeling, validation, and projections. Routing decisions were carefully made to try to avoid sensitive terrains such as ice-rich polygonal ground, organic-rich deposits, existing retrogressive thaw slides, and steeper slopes that were vulnerable to failure (Grozic et al. 2018). Some 300 culverts were installed to allow water flow and habitat connectivity, and eight bridges were constructed using adfreeze steel pilings. This latter engineering approach is more suited to light loads and stable permafrost conditions, neither of which is the case for the ITH, and an adaptive management plan was formulated involving regular monitoring and the potential use of thermosyphons (Hoeve and Fortin 2019). Studies on the stability of the road have shown snow accumulation at the toe of embankments, flooding at some sites, and warming of toe-soil temperatures and embankment cracking (De Guzman et al. 2021), indicating the need for careful monitoring and vigilance.

4.4. Alaska–Canada Highway, USA and Canada

4.4.1. Background

When the USA purchased Alaska from Russia in 1867, the only way to reach the new territories from the contiguous United States was via maritime links along the Pacific coast. This situation persisted over the following decades, but the early 20th century saw the first ideas of a road connection via Canada, which had initially shown little interest in such a mega-project. This changed with the Japanese attack on Pearl Harbor in late 1941, which demonstrated the military vulnerability of the North American west coast. U.S. President Franklin D. Roosevelt authorized the construction of the Alaska–Canada Highway (ALCAN) in early 1942, which was built in record time between March and October 1942. Constructed by the U.S. Army of Engineers, it contained 2400 km of mostly gravel road for military purposes running from Dawson Creek, BC, to Delta Junction, Alaska (and on to Fairbanks, Alaska). An associated pipeline was also built to assure wartime supplies of oil (the Canol Project) at an estimated cost of US$300 million and was shut down and abandoned in 1945 (Gage 1990).

The Alaska–Canada Highway route aligned more or less with the so-called Northwest Staging Route, a string of airfields from Montana to Alaska via Canada as part of the Lend-Lease Program (Nelson 2011: 646; Peyton 2017: 65). While the construction in Alaska and Canada was a purely U.S. endeavor initially, the Canadian part of ALCAN was turned over to Canada after the end of World War II. From the beginning, the construction was presented in heroic terms of the battle of men against wilderness, while at the same time highlighting the awe-inspiring aspects of the journey (Godsell 1944). This was also a watershed moment in permafrost science, through the seminal work of geologist Simeon Muller, who was recruited to advise on the engineering challenges across frozen landscapes. Muller coined the term "permafrost" and his report (Muller 1947) is considered the first English language treatise on the subject.

4.4.2. Economic factors

Economic development and tourism were the initial motivations for early discussions in the 1920s about a highway between Canada and Alaska, but it was the military imperative in the 1940s that led to a massive investment of resources. This included 10 607 soldiers (including a major contingent of African American soldiers; Witcher 2020); and around 16 000 Canadian and American civilians, with an investment by the United States of US$147.8 million for the road construction, and US$108 million by Canada for associated airfields, buildings, and other assets. These investments in dollar amounts at the time, along with the ancillary costs of the servicemen involved and the Canol Project, have been estimated as totaling more than $4 billion dollars in today's currency (Baird 2021). The highway was subsequently paved throughout and has had wide-ranging economic benefits including to the forestry, oil, mining, tourism, and trucking industries (Gilchrist 2016). From its completion onwards, it provided a stable supply route that ensured that no air or sea blockade would prevent the delivery of food and supplies to Alaska (Stevenson et al. 2014). A major economic factor at present is the maintenance and remediation costs required to repair sections of the road across permafrost terrain that are subject to ongoing degradation (see below).

4.4.3. Social and cultural issues

The initial impacts of road construction, usage, and maintenance are difficult to assess almost 80 years after the fact. While we are not aware of any impact assessments at the time of construction or shortly thereafter, the occasion of the 40th anniversary led to a symposium and a subsequent publication (Coates 1985) addressing various dimensions of the highway including its impacts. This volume contains an account of the social impacts of the highway on the First Nations of the Yukon (Cruikshank 1985). Based on her fieldwork data since 1974 and on archival sources, Cruikshank lists a number of direct and indirect impacts of the highway on subsistence practices, ranging from hunting pressure by construction workers and urban hunters to shifts in employment and residence patterns by villagers. Conservation measures were applied that focused on protecting the environment without its links to the associated Indigenous culture, with closure of hunting to all on the Kluane Park side of the highway. This led to food insecurity, hunger, cases of imprisonment, and loss of traditional knowledge associated with loss of access to the land. Cruikshank (1985: 185) concludes that "the highway was a decisive factor bringing Yukon Indians to the marginal position they have in the present Yukon economy and society" and that "the Alaska Highway might serve as a case study of how seemingly short-term projects can have long range, far-reaching effects" (Cruikshank 1985: 186).

While there have been no subsequent dedicated assessments, we have documentation of health impacts that are at least indirectly tied to the construction of the Alaska–Canada Highway, namely through toxic waste at a military site and staging area for the road construction (Godduhn et al. 2013). The associated Canol Project also left behind a legacy of environmental hazards, including an estimated 46 000 barrels of oil spilled along the route (Gage 1990). From the time of construction onwards, there has been a continuous string of protests by rural, mostly Indigenous, residents against plans to build roads in the western, "roadless" part of Alaska. In recent years, the so-called Ambler mining road has been the object of protests against the plan (e.g., Buxton 2014), controversial approval of the road by the Trump administration as a "Road to Resources" (Rosen 2020), and counteraction by rural villages (DeMarban 2020). Thus, while few people doubt the potential social benefits of roads, from increased mobility to lower grocery prices, some communities opt for their "right to remoteness" (Schweitzer and Povoroznyuk 2019), as they see the potential negative impacts of road construction on subsistence activities and traditional lifestyles.

4.4.4. Environmental issues

The massive Alaska–Canada Highway project took place before consideration was given to land and water protection. Given the wartime circumstances, priority was given to clearing land and installing the road in the minimum amount of time, with the routes based on aerial photographs and ground surveys sometimes led by Indigenous guides, and a brute force approach to road clearing: "Ten Caterpillar D8 bulldozers, four or five abreast, advanced along the trail, knocking down and uprooting all trees and other vegetation in a swath 100 feet wide" (Witcher 2020). The road crosses many waterways, with 133 bridges 6 m or longer and several thousand culverts (Gilchrest 2016). Aquatic pollution from road activities may therefore be an ongoing issue, for example, from road tire pollutants (Challis et al. 2021).

4.4.5. Engineering issues

From the beginning, environmental and climatic conditions in the North hampered the construction and maintenance of the Alaska–Canada Highway, and permafrost thaw was especially problematical (Remley 1976; Nelson 2011: 65–66, 163–164; Twichell 1992: 209–210). Despite major upgrades and reconstructions since 1940s, some of these problems persist and are likely to worsen with ongoing climate change. The northern 200 km of the highway from Burwash Landing to the Yukon/Alaska border, has received particular attention for analysis and remediation. Since its construction, this section of the road has been seriously affected by permafrost thaw (Fig. 7), and a three-step approach was adopted to address these issues: vulnerability assessment, adaptation strategies tailored to specific sites, and implementation of the adaptation design.

The first step was to characterize the permafrost and identify possible engineering solutions. Mapping of ground ice types and amounts has proven to be essential for infrastructure design as well as repair and maintenance (Calmels et al. 2015, 2018*a*). This is especially important for choosing engineering solutions to keep the permafrost frozen and to stabilize the infrastructure for as long as possible (Calmels et al. 2016, 2018*b*). The project team used multiple techniques, including permafrost coring, geocryological analyses, ground temperature and climate monitoring, electrical resistivity tomography, and remote sensing. The results showed that the regional glacial history has influenced permafrost distribution and characteristics and that this section of the highway was almost completely built on permafrost (Calmels et al. 2016).

The second step consisted of designing permafrost thaw remediation strategies in critical areas. Using the vulnerability assessment, six candidate sites that required and were potentially responsive to thaw mitigation or remediation techniques were identified and assessed for their suitability for adaptation measures to preserve permafrost. The selection of techniques was based on results from test sites, including at the Beaver Creek test site (described in Stephani et al. 2014). In a third step, the first remediation was undertaken at a road site that was highly vulnerable to thaw settlement due to the presence of massive ice observed 10 m below the ground surface (the Dry Creek site). Three options were considered: an air convection embankment, thermosyphons, and a heat drain coupled with a high-albedo surface. Finally, the site was fitted with thermosyphons (Fig. 7, bottom), which have stabilized this section of the highway. This 8-year project underscored the importance of considering the distribution of permafrost and how it will react to environmental changes before designing adaptation strategies, and the need for ongoing monitoring to closely track the performance of these strategies once they are implemented.

4.5. The Alaska Railroad, USA

4.5.1. Background

The precursors to the Alaska Railroad were a multitude of short rail lines built for mining shortly after the Klondike and subsequent gold rushes beginning in 1896. At Seward, an ice-free harbor in the south of Alaska, railroad construction began in 1903, but the private companies involved in the construction process subsequently went bankrupt (Fitch 1967). In 1914, the U.S. government decided to step in and to extend the line to Fairbanks. A bill authorizing construction of the railroad was passed by Congress on March 12, 1914, and the president was directed to designate a route from the Pacific to the Interior of Alaska (Schneider 2018: 43). A year later, on April 30, 1915, President Wilson determined that the rail-

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Fig. 7. Adaptive engineering to protect the Alaska–Canada Highway in a warming climate. A section that was especially prone to permafrost thawing and collapse (top; photo credit: Daniel Fortier), was rebuilt and fitted with thermosyphons to maintain the frozen state of the permafrost (bottom; photo credit: Fabrice Calmels).

road would run 760 km from Seward to Fairbanks (Schneider 2018: 43–44), and the line was completed in 1923 (Fitch 1967; Hegener 2017; Fig. 8). A Northern Rail Extension (NRE) has been proposed and partially constructed (Alaskan Legislature 2019), and there is interest in connecting to a hypothetical megaproject in Canada, the Alaska Canada Rail Link (ACRL; also called the Alaska to Alberta Railway, A2A), which would connect to northern Alberta's oil sands (Watts et al. 2019).

4.5.2. Economic factors

The Alaska Railroad was supported by the U.S. Federal Government as an essential step towards opening up the interior of the state and thereby accessing resources that could be transported to the coast, to the benefit of the entire country. At a congressional hearing for continued funding of the project, one of the speakers noted: "The whole Nation is vitally interested in the rational development of Alaska for its rich and varied deposits of minerals and other natural resources required in our industries, as a great source of food supply, and as a most promising and prosperous market" (U.S. House of Representatives 1919). This infrastructure was purchased from the Federal Government by the State of Alaska in 1985 for $22.3 million to create the Alaska Railroad Corporation (ARRC), which now receives federal grants, but no direct Alaska State funding. The ARRC currently reports assets of $1.06 billion, with 2020 revenue of $150.67 million (including $53.3 million in grant revenue), and a net loss of $7.8 million. In the year prior to the COVID-19 pandemic (2019), it transported 522 101 passengers and 3.49 million tons of freight (ARRC 2021). The ARRC employs 550–700 people (depending on the season), is a sponsor of many civic organizations that promote economic growth and commerce, and makes annual in-kind donations of rail transportation services of around $1 million each year (ARRC 2021).

The first phase of the NRE was by way of a bridge across the wide expanse of Tanana River, which cost around $190 million and was opened for military road traffic in 2014 (Ellis 2014). The full NRE passing over this bridge to Delta Junction, 130 km north of Fairbanks is estimated to cost $650–$850 million (CMSADMIN 2010) and would serve agriculture as well as increasing military needs at the Greely Missile Center (Alaskan Legislature 2019).

During the final months of the Trump presidency, the private railway project ACRL/A2A received US Federal Government approval, but the project has not as yet been fully considered by the Canadian Federal Government. The total ACRL/A2A project is estimated to cost US$14 billion to $15 billion and envisages 1740 km of railroad, of which 1400 km would be within Canada and 340 km in Alaska (Watts et al. 2019: 4). On the Canadian side, the project would generate an estimated 13 900 to 16 800 jobs over the construction period of 7 years, and the primary beneficiary of ACRL/A2A

Fig. 8. Steam engine in service of the Alaska Railroad in 1923. Photo credit: Alaska State Library—Historical Collections (by permission).

operations would be the mining industry, especially in the Yukon. Over a 30-year period, the net revenue derived from Yukon mining operation exports and imports is estimated to be \$22–23.5 billion (Watts et al. 2019: 22).

4.5.3. Social and cultural issues

While there has been no formal analysis of the social and cultural consequences of the Alaska Railroad, there is evidence of wide-reaching transformations. The city of Anchorage, currently the demographic and economic center of Alaska, began as a railroad construction camp in 1915 (Jones 2010). Up to the present day, the "railroad corridor" in Alaska refers to the area first made passable by the Alaska Railroad and later followed by the Parks Highway, which takes most of the traffic from Anchorage to Fairbanks today (together with air transport). Families and industries moved closer to the railway operations. For example, the settlement of Cantwell began as a construction camp for the Alaska Railroad and became a hub for the Valdez Creek goldmine. Families of the Ahtna, an Athabascan-speaking people who have lived in the region for about 5000 years, settled in Cantwell in the 1940s because of employment opportunities with the Alaska Railroad (Simeone et al. 2019). Unfortunately, the railroad construction also likely acted as a conveyor belt for the spread of the 1918 influenza pandemic (Hegener 2017: 197–199).

The best documented indirect result pertaining to Indigenous communities of the region is the Tanana Chiefs Meeting with Judge Wickersham in Fairbanks in July 1915 (described in Schneider 2018). This meeting was held between Athabascan leaders and government officials. For some of the Indigenous leaders, it was the first time to speak with government officials since the United States had purchased Alaska from Russia in 1867. While the Alaska Railroad, which was under construction at the time, was not an official agenda item, it was a major concern voiced by the leaders, namely that increasing numbers of settlers would push away the Indigenous inhabitants and their ways of life. Among those present at the meeting was Thomas Riggs of the Alaskan Engineering Commission, the agency, which oversaw construction of the railroad. He said, "After the railroad which we are building comes into this country, it will be overrun with white people … They will kill off your game, your moose, your caribou, and your sheep" (Schneider 2018: 43).

Much of the new NRE track would pass over military lands, and Indigenous concerns would likely be a less salient issue than in other areas. Nevertheless, the ACRL/A2A megaproject has already generated concerns by some First Nations people because of the potential environmental impacts on Indigenous lands, and a petition to halt the project has been started in Yukon, because it may support oil and coal production, contrary to Canada's mitigation objectives to reduce climate change (Connor 2020).

4.5.4. Environmental issues

There has been no analysis of the past environmental consequences of the railroad, but extensions are now subject to formal EIAs. The initial Environmental Impact Statement to seek environmental approval to pass across the Tanana River was turned down by the United States Environmental Protection Agency on the basis of "likely substantial effects on the natural ecology and hydrology of the Tanana River, both upstream and downstream of the project site," and in particular because of "potential impacts to water quality, open water habitats, wetlands, stream channels, and riparian areas" (Combes 2010).

Environmental effects on ecosystems were not assessed during the building of the Alaska Railroad, although logging impacts have been noted. Current operations include vegetation management to ensure safe passage of the trains operations, and this involves the use of herbicides (Alaska Railroad 2020).

4.6. Hudson Bay Railway, Canada

4.6.1. Background

The Hudson Bay Railway (HBR) extends 1011.7 km across Manitoba from The Pas to the western coast of Hudson Bay and was officially completed on September 10, 1929 (Bickle1995: 90), making it the first major transportation infrastructure to be built over permafrost in Canada. The northern endpoint of the line is the Port of Churchill (58°44′09″N), which opened in 1931 and saw the first grain arriving on August 26 of that year. The northern part of the railway line is characterized by permafrost and by Churchill's remote subarctic location.

The railway provides a transportation route for western Canadian resources but has primarily been used for western Canadian grain shipments to European and Northern African ports via Hudson Bay, a vast inland sea that is connected to the North Atlantic Ocean by Hudson Strait. The port has four loading berths and one tanker berth and is capable of handling large Panamax class vessels (up to 80 000 t). Hudson Bay is covered by sea ice for up to 9 months of the year, but ongoing climate change has resulted in Arctic warming and ice contraction, which may allow year-round navigation for even the lowest ice-class vessels at less than 4 °C global warming (Mudryk et al. 2021).

4.6.2. Economic factors

Plans to build a railroad from Manitoba to Hudson Bay were first discussed in the 1870s, but it took decades of political maneuvering before the necessary financial means and permits could be secured (Fleming 1957). During the early years of operation, the railway recovered its operating costs through traffic generated by military operations connected with World War II (Fleming 1957: 96). However, subsequent economic issues eventually led to its sale by the Canadian National Railway (CN) to the private U.S.-based holding OmniTRAX in 1997. In 2017, due to severe flooding and washout conditions, a reoccurring problem along the line, the company suspended service on the HBR (OmniTRAX 2017). The railroad provides a vital supply line for many remote communities, including Churchill, and this closure created severe problems for these communities, with an increased cost of goods and shortages of food and fuel. There was a public uproar and legal action against OmniTRAX, culminating in new ownership of the HBR in 2018, the beginning of repairs (Repairs 2018), and reinstatement of rail operations.

The new owner, the Arctic Gateway Group (AGG), was at first a consortium consisting of Manitoba communities, First Nations, and private companies (Brohman 2018). In March 2021, there was transfer of ownership of the Port of Churchill, the HBR, and associated assets, which are now entirely owned and operated by northern communities and Indigenous groups. This new AGG consortium received a US$40 million investment from the Federal Government for further repairs of the railroad track (DePatie 2021). Grain exports resumed in 2019, with 103 000 t of durum wheat and 35 000 t of lentils transported by the HBR and shipped through Churchill in the 2019–2020 crop season (Real Agriculture News Team 2021).

4.6.3. Social, cultural, and environmental issues

Like the Alaska Railroad and most of the older infrastructure elsewhere in the circumpolar North, the HBR was constructed at a time when there was little formal attention given to the social, cultural, or environmental impacts of infrastructure development. Indigenous knowledge was not formally sought and integrated through the means formalized by government today, but still played a key role in the early exploratory work associated with siting the railway corridor through the contribution of Indigenous guides. Major John Leslie Charles, chief engineer for the CN Western Region, was guided by Indigenous community members who knew the territory and could share knowledge on the characteristics of different terrain units. These contributions are not officially acknowledged nor compiled in the literature, but transpire through early reports in the form of quotes such as "a vast area of muskeg, with very little Timber, which the Indians call the "land of Little Sticks"; 'the Barren Lands' extend into this territory" (Charles 1959: 126).

Temporary closure of the HBR from May 2017 to November 2018 illustrated the precarious situation of the town of Churchill, in particular, in the absence of that transport connection to the South. Some families had to leave the town due to the massive rise in cost of living, with food arriving by air transport rather than by rail (The Canadian Press 2018). However, the new AGG ownership offers renewed opportunities to support the local economy, community interests, development plans, and Indigenous values, and 70% of the workforce is now Indigenous (Report Team 2021).

4.6.4. Engineering issues

There have been ongoing challenges for the HBR given that it runs across difficult terrain for transport infrastructure, especially sporadic discontinuous and continuous permafrost in ice-rich marine deposits that are vulnerable to thawing and erosion, extensive peatlands, and areas with high risks of flooding (Roghani 2021). In the discontinuous permafrost zone, the rail crosses elevated peat plateaus that are underlain by icy permafrost and separated by permafrost-free fens. Continued thaw settlement of the embankment has been occurring at the edge of the peat plateaus, which are degrading, requiring the addition of fill to keep the embankment to grade (Hayley 1989).

A test section over the permafrost terrain was surveyed in detail and equipped with 400 heat pipes in 1987, which provided positive results, and it was estimated that approximately 8000 heat pipes would be required to stabilize this portion of the rail. In 1989, Hayley reported that it had been difficult for CN, the owner of the rail until 1997, to keep pace with grade deterioration despite annual investments in maintenance that were three times the normal cost for other railways in the western division. More recent engineering studies have focused on applying a rating system for the severity of permafrost effects along the tracks, and to identify long-term solutions to stabilize the embankments including by control of heat conduction and convection (Addison et al. 2015*a*; Addison et al. 2016).

As thawing of discontinuous permafrost continues, climatic warming, wildfires, and flooding may exacerbate the difficulty of maintaining the track over permafrost sections. On the 15th of September 2018, a freight train on the line derailed at mile 99.59 near Ponton, Manitoba, caused by an undetected washout and collapse of an unsupported section of track (Fig. 9). This accident caused the death of the conductor and critically injured the locomotive engineer (Transportation Safety Board 2020). The washout was associated with summer rainfall that was 60% higher than the historical average (Transportation Safety Board 2020). Extreme events, such as the heavy rainfall in 2018 and the rain events that caused the washout and temporary closure in 2017, are likely to become more frequent with increased warming throughout the circumpolar North, resulting in the increased likelihood of heavy storms and floodwaters.

Wildfires have occurred along the railway over the years, and many of these fires resulted in moderate to high damage to the organic layer, which could accelerate permafrost degradation (Oommen et al. 2017). While exploring the use of remote sensing for the identification of problem areas, a relationship was identified between vegetation density and railway track quality, suggesting that remotely sensed vegetation indices could provide a means to identify areas of permafrost degradation and associated track deterioration (Addison et al. 2015*b*).

The HBR has now entered a promising new phase of ownership and science-based attention to its maintenance challenges. Recent work under the direction of the new AGG consortium includes advanced stabilization and support systems for the railway embankments in vulnerable sections of the track, and the development of collaborative projects with university-based groups of engineers and scientists to better understand, predict, and mitigate the effects of permafrost degradation and changing hydrological regimes along the infrastructure.

4.7. Baffin Island Railway projects, Canada

4.7.1. Background

Two railway projects to service a large-scale mine in the Canadian Arctic are currently receiving close attention and illustrate the entanglements of socio-economic, environmental, and Indigenous issues with northern infrastructure. The Mary River Mining project is an open pit iron ore mine operated by Baffinland Iron Mines Corporation and located on northern Baffin Island in Nunavut, 60 km south-southwest of the nearest community, Pond Inlet/Mittimatalik. At present, the ore extracted from the mine is transported north by truck along a 110-km tote road to the coast to a dedicated port in Milne Inlet for shipping of the ore to Europe and, occasionally, Asia. In a subsequent development phase, the company aims to build a railway 150 km south to a port site at Steensby Inlet on the southern coast, but in the shorter term, aims to replace the existing tote road with a northern rail line. Located at latitude 71°N, these two lines would be among the most northerly railways of the world, comparable to the Bovanenkovo Line on the Yamal Peninsula, Siberia, at 70°N.

4.7.2. Economic aspects

The overall mining project is in partnership with Inuit authorities, specifically the Qikqiktani Inuit Association (QIA), and is planned to bring substantial revenues into the Nunavut economy, estimated by the company to total CAD$2 billion in benefits and royalties for Inuit communities over the lifespan of the mine (Brown 2021a). Already the project has provided considerable benefits to northerners including employment opportunities, payments to Inuit companies for goods and services, and royalty payments to QIA. In 2019, these included $20.2 million in wages and salaries to Inuit employees, $288.8 million in contracts to Inuit firms, over 44 000 h of training to Inuit employees, $15.6 million in taxes to the Government of Nunavut, and $12 million in royalty payments and program spending (Clinton 2021).

The company has been operating at a loss during this initial phase of its operations (expenditures of $465 million vs. revenues of $454.5 million in 2019; Clinton 2021) and notes that to remain financially viable in the face of large fluctuations in ore prices (from $80/t to $220/t over the period 2020–2022), it needs to expand and shift the ore haulage from truck to rail. This would also substantially reduce the carbon footprint and dust emissions (see below). At a price of $100/t, revenues would rise from around $600 million in 2020 to $1.2 billion per year with the completion of the North Railway and $3 billion per year with the longer-term expansion and the South Railway (based on ore transported on the tote road in 2020 and estimates of future mining capacity; Baffinland 2021a).

4.7.3. Social and cultural issues

The Mary River mine has provided ongoing economic, employment, and training benefits to local communities. However, the newly proposed North Railway and the associated expansion of shipping activity has generated controversy because of concern about the potential effects of the railway on migratory caribou, the effects of dust on local ecosystems, and the impacts of increased shipping activity on the Milne Inlet and associated Eclipse Sound marine ecosystem, a major habitat for narwhals and other marine mammals (Marcoux et al. 2019; Watt et al. 2021). This controversy came to a head in early 2021 when a group of hunters traveled by snowmobile from the nearest village, Pond Inlet, to blockade the mine, preventing resupply of food and materials to the 700 workers at the mine (Brown 2021b). This blockade was voluntarily lifted prior to talks between the company and the hunters. Formal public hearings on the mine expansion continued, and in May 2022 the Nunavut Impact Review Board (NIRB) rejected the application for expansion, concluding that there would be "significant adverse ecosystemic effects" on marine mammals, fish, caribou, and other wildlife, including effects of mining dust (Murray 2022). A final decision by the Federal Government of Canada was expected later in the year.

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Fig. 9. Derailment on the Hudson Bay Railway line associated with flooding in 2018 Photo credit: Transport Safety Board of Canada, investigation R18W0237 (by permission).

4.7.4. Environmental issues

As throughout the Arctic, lakes and rivers are a major feature of the Baffin Island landscape, and, along with topography, these waters strongly affect the proposed railway alignments. In the environmental hearings, the Baffin Island hunters raised concerns about the effects of road dust on freshwaters of the area, and dust collectors have been mandated and installed along the tote road to monitor this source of contamination (NIRB 2020). One of the arguments for the installation of the North Railway is that it would eliminate the problem of road dust as well as reduce dust from the mine (Anselmi 2019). The importance of culverts for fish passes, and the need to clean and maintain the structures in a free-flowing state, has been underscored in annual inspections of the site (NIRB 2020).

The environmental impact study for the Phase 2 development has included hydrological fish and water quality surveys (Baffinland 2021b). It has paid special attention to effects on the freshwater ecosystems of the region, noting potential impacts through several pathways, including the need to divert the upstream portion of more than 20 streams into adjacent streams during the construction phase. In its environmental management plans, the company has proposed a range of mitigation measures and has stated its commitment to surface water and groundwater monitoring, including by Inuit monitors, and attention to *Inuit Qaujimajatuqangit* (IQ), the term for Inuit knowledge and societal values (Karetak et al. 2017).

The state of caribou populations is uncertain in this area, but the population density appears to be low, and hunters have expressed concern that the steep embankment supporting the railway would impede caribou migration. The company has taken this into account by designing embankments with materials and slopes that could be readily climbed by the animals and states that the train would slow or stop if caribou were seen approaching the tracks (Anselmi 2019). As noted above, the overall impact of such infrastructure on wildlife is a major uncertainty in transport EIAs in general, but the effects are likely to extend well beyond the tracks. In a study commissioned by the mining company on two bird species, the researchers concluded that impacts on birds should be considered at multiple scales, well beyond the nesting sites (Galipeau et al. 2019).

From the beginning, the mining company has made major efforts to engage with local communities and incorporate Indigenous knowledge of the area into their planning (Baffinland 2019). During the period 2015–2020, it undertook 218 consultations, comprising public meetings, hamlet meetings, working group meetings, site visits, and Inuit knowledge workshops. The latter focused on IQ, which consists of seven broad principles. In their impact assessment of Phase 2, the company systematically described how they are addressing each of these (Table 1 in Baffinland 2019); for example *Avatittinnik Kamatsiarniq* (environmental respect and stewardship) by way of environmental protection measures and establishment of wildlife and environmental management plans, and *Aajiiqatigiinniq* (decision-making through discussion and consensus) by full participation in numerous consultations, workshops and review processes. Attention to IQ has resulted in the modification of original plans including for shipping routes and timing to avoid critical time periods of Inuit harvesting activities, and IQ is being used to other planning decisions, for example, to identify wildlife crossings for the planned railways, and to select indicator species (such as berries and lichen) and locations for environmental monitoring. An Adaptive Management Plan for environmental stewardship includes combining Indigenous and scientific knowledge to set and review monitoring results against predetermined indicators and thresholds and feedback via Inuit committees (Baffinland 2021b).

4.7.5. Engineering issues

Geomorphological surveys along the proposed rail alignments have drawn attention to the ice-rich permafrost in the region (including large blocks of ground ice; Doré 2009), which challenges infrastructure construction and maintenance, particularly in the face of ongoing warming and the increased frequency of extreme climate events. A wide range of engineering solutions have been proposed to obviate thermal degradation and settlement problems, along with associated erosion, silt transport, and thermokarst activity. These include minimizing vegetation disturbance and excavation, especially in ice-rich permafrost areas; the construction of a 1.5 m thick thermal barrier of suitable fill to allow the permafrost table to aggrade upwards; the installation of convective cooling embankment, ducts, and thermosyphons at thermally sensitive sites; and control of water movement that would cause thermo-erosion, including avoidance of ditches near the toe of the embankments that would result in ponding of meltwater against the embankment (Roujanski et al. 2010). Permafrost degradation has resulted in ongoing maintenance problems for the existing tote road, with solutions tailored to specific types of erosion and safety hazards (photographed and catalogued in Jones 2019).

5. Conclusions and the way forward

The many examples from around the world, and the northern case studies that we have examined here, all point to the complexity of issues surrounding transport infrastructure and the far-reaching consequences that accompany the construction and operation of roads and railways. Many of the potential consequences are positive such as increased mobility, new or improved access to resources, industry, transport hubs and markets, and cost-savings to remote communities in terms of provisioning of goods and services. However, these must be gauged against the many potential negative consequences illustrated here, including the marginalization of local communities, disruption of Indigenous cultures and traditional ways of life, threats to the safety of Indigenous women and children, perturbation of water flows across the landscape, impacts on vegetation and wildlife, dispersal of invasive alien species, and increasing reliance on transport infrastructure that may be vulnerable to climate change.

Some of the consequences of transport infrastructure, be they positive or negative, may extend beyond those initially envisaged. On the one hand, such projects can provide new opportunities for local communities, including mobility and more accessible travel options (at least, for some groups), new technological opportunities (e.g., fiber optic cables along transport routes, which offer improved communications and internet access; improved technician access and support to remote communities), and new recreational and subsistence options (e.g., hunting and fishing over a wider area). On the other hand, longer-term cumulative ecological and social impacts of functioning roads and railways may contribute to cumulative environmental degradation and the cultural assimilation of Indigenous peoples.

Northern roads and railways are transport infrastructures that resemble one another in terms of their functions and affordances. Yet, they also have a number of typological differences that have to do with their materiality, the ways in which they transform the natural environment, their patterns of investments, and the purposes they serve. Roads are the oldest and the most common type of transport infrastructure, with a history reaching back in time to precedents such as paths, trails, and tracks across soil, tundra, and ice. Unpaved and often undocumented roads are still important for the small-scale transportation of goods and people as well as for community resupply in the North. They are usually maintained with the investments and efforts coming from local administrations or small and medium enterprises using them. Larger roads (e.g., the Lena Federal Highway in Russia or the Alaska–Canada Highway in North America) are associated with speed, modernity, independence, and individual mobility. Their construction usually requires greater public, private, or mixed investments, and their functioning leaves more visible environmental and social footprints than that of smaller scale or informal roads. Northern railways include large-scale infrastructures with high environmental and social impacts, that are funded by the state to serve transport of cargo and, to a certain degree, passengers, such as the BAM railway. At the same time, there are also cases of privately-owned railways of smaller scales and extents that serve primarily individual company interests, such as the Bovanenkovo railway and the proposed Baffin Island railways.

While the physical and environmental impacts of roads and railways can be compared and differentiated based on their landscapes and ecosystems, national and regional borders structure the social impacts of these infrastructures across the North. Today, the Arctic region is characterized by the shared concerns for reconciliation and respect of Indigenous human rights, environmental change, growing international trade, tourism, shipping, and safety issues, but also by rivalries arising from competition for natural resources, securitization, and militarization (Doel et al. 2014; Dodds 2018). The eight Arctic states have divergent colonial histories, political regimes, socio-economic systems, and governance structures, which affect the ways in which the planning, implementation, and maintenance of infrastructure projects of any sort—be they transport or otherwise—are carried out.

Our seven case studies examined here come from three different Arctic states—Russia, USA, and Canada—and demonstrate significant differences. They reveal variations in how local and Indigenous communities are positioning themselves vis-à-vis state and private companies, how they participate in road and railway projects, and how they can either exploit or be exploited by the development of infrastructures. The examples from the Canadian North show a considerable degree of empowerment of Indigenous peoples who build and (or) manage transport infrastructures, as with the ITH and the HBR, respectively, or who openly protest against infrastructure development as with the Baffin Island railways. Russian examples, in contrast, reveal historically defined patterns of political and economic marginalization of

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Indigenous and mixed local communities, who have limited capacity to resist state modernization and resource extraction driven by private companies, and who may experience considerable environmental costs relative to local economic benefits (e.g., BAM). Indigenous knowledge is critically important for collaborative research and co-production of knowledge in and about the Arctic (Degai et al. 2022). This powerful stream of experience-based knowledge that is tied to nature complements scientific knowledge (Wheeler et al. 2020) but has apparently had little influence on transport infrastructure decisions in many projects (e.g., Alaska Railroad, BAM). However, it played a prominent role in the Berger Inquiry process and in the routing of the ITH. Significant efforts to incorporate Indigenous knowledge have also been made during planning for the Baffin Island railways and figured prominently in the environmental hearings.

The seven case studies differ greatly in the extent to which environmental consequences have been assessed or considered, but there are a number of common features. All of these infrastructure projects extend across northern landscapes, where freshwater ecosystems are prevalent, and where the cumulative impacts on aquatic biota require particular attention. To varying degrees, these corridors traverse vast wildlife habitats and disrupt migration pathways. The infrastructures lie on permafrost ground that in the past offered a stable foundation, but that is now subject to the impacts of rapid climate warming, with permafrost degradation aggravated by the infrastructure itself. Extreme weather events have already had tragic consequences for the HBR and are likely to be more frequent and of greater magnitude in the future throughout the Arctic.

As our examples show, northern transport infrastructure projects are initiated and come to fruition via a wave of local or national political momentum, often with poor attention to long-term environmental, social, or even economic consequences. Most EIAs are inadequate for transport infrastructure in general (Jaeger 2015). Even more so, assessments of social benefits and risks from the construction of roads and railroads have been sporadic, if conducted at all. This situation has led to gaps in research on the social dimensions of resource extraction and infrastructure projects in the Arctic (Schweitzer et al. 2017, 2019). Despite historical examples of integrated assessments (such as the Berger Inquiry, noted above), recent attempts to evaluate environmental and social dimensions of (transport) infrastructures are rare (see, for example, Forbes et al. 2009). There is a pressing need for more regular assessments before and after the implementation of transportation projects, as well as for a comprehensive approach that focuses on local voices, integrates both social and ecological aspects, and considers the immediate as well as long-term consequences of such projects.

What longer term time frame would be appropriate? Ashpiz (2020) suggests that a 50-year horizon be adopted when building on ice-rich permafrost, with consideration of engineering designs and maintenance strategies that will cope with the impacts of climate change over this period. The development of social and environmental scenarios over this timeframe would also help to more fully assess proposed projects. A handful of transport infrastructures operational over a half-century period have been the focus of observation and research, offering insights into cumulative impacts. Among such examples are ecological studies on gravel roads in Prudhoe Bay, Alaska (Walker et al. 2022) and socio-ecological systems of the Yamal Nenets in Russia studied by a group of social and natural scientists (Forbes et al. 2009). While monitoring the impacts of industrial and transport infrastructures that have existed over the past 50 years will help predict and assess the longer-term consequences of new projects in the next half century, the increasing rapidity with which environmental changes are occurring must be taken into consideration.

Northern roads and railways cut across lands that have been occupied for thousands of years by Indigenous peoples. Their cultures are intimately linked to the natural resources of the Arctic wilderness. In keeping with the increasing role of Indigenous knowledge in northern development (e.g., Dawson et al. 2020), there is a need to protect Indigenous human rights and assure full Indigenous participation in transport infrastructure management, from consultation, planning, monitoring, and assessment, to decision-making, operations, maintenance, and benefit-sharing. An important part of that planning process is establishing optimal routes for road or railway construction in the multiple contexts of physical landscapes, cultural landscapes, and Arctic climate change. Such efforts require the detailed mapping of geohazards such as ground ice and flood-prone sites, in combination with ecological and sociocultural risk assessments. More holistic assessments require consultation with the local communities and the integration of Indigenous and academic knowledge systems to identify issues of concern and regions to avoid or otherwise protect for their ecosystem services. It also requires attention to the appropriate maintenance and alert systems to ensure the continued human and ecological safety of the infrastructure once it is in operation.

Vast regions of the Arctic are still largely free of roads and railways (Fig. 1), which now criss-cross many other areas of the world that until recently were protected by virtue of their remoteness (Ibisch et al. 2016). The installation of this infrastructure irreversibly changes the social, cultural, environmental, and ecological fabric of the landscape into something new and radically different, with the cumulative loss of non-fragmented tracts and the gradual attrition of roadlessness. Future project assessments for new transport options in the North need to carefully identify the distribution of costs and benefits from transportation projects between affected local communities, Arctic states, and transnational and national investors. This distribution should be balanced in ways that meet the long-term needs of local actors and the principles of sustainable development in the fast-changing Arctic.

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