A growing anthropogenic impact on the Arctic environment affects the ecology of polar vegetation

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Abstract

Recent climatic changes, anthropogenic impacts and new infrastructure development across the Arctic may increase risks for terrestrial ecosystems. A wide range of anthropogenic impact factors are reported for the Arctic, such as air and marine pollution including plastic, black carbon deposition on snow, remnants from oil, gas, and mining operations, increased land use due to expanding industrial activities leading to habitat loss, and, last but not least, waste and pollution from tourism. Recently, satellite data has revealed the expansion of infrastructure and growing anthropogenic impacts throughout the Arctic. Regarding the effect of warming on plant biodiversity, both responses are reported, *i.e.* decreases and increases in the number of plant species forming communities. Air pollution may affect tundra environments and its vegetation in different ways. Black carbon from diesel engines, fires, and other combustion processes can settle on snow, decreasing its ability to reflect sunlight which causes faster melting and changes in water availability for plants. In areas close to settlements, the direct effects of anthropogenic pollutants on vegetation may play a role. In Svalbard, local anthropogenic sources of emission, such as burning fossil fuels in local coal power plants, vehicle exhaust and mining activities contribute to the pollution of the environment and interact with plants. Moreover, wastewater discharged by Longyearbyen into the fjords delivers heavy metals and other pollutants that represent a potential risk to marine algae.

Key words: Arctic, POPs, pollutants, heavy metals, *in-situ* burning, oil spills

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Introduction

The anthropogenic impacts on terrestrial, fresh water and marine arctic ecosystems on Svalbard have been studied, especially over the last few decades. Local, regional and global anthropogenic impacts on the ecosystem were identified, both historical issues (the effects of mining) and more recent issues related to global warming. Regarding terrestrial vegetation, historical anthropogenic effects were investigated by Kruse et al. (2021) who focused on changes in vegetation caused by mining-related environmental change in the neighbourhood of Advent city (Svalbard). The study reports a reduction in the patchiness of vegetation, beneficial growth of some vascular species on newly formed areas of bare soil caused by construction work, and, last but not least, a limitation in the microenvironments needed for the successful growth of liverworts and lichens.

Recent changes in vegetation cover, caused by anthropogenic impacts, are studied using a wide variety of methods. Among them, the analysis of satellite data vegetation indices, in particular normalized difference vegetation index (NDVI), is a promising and effective approach to evaluate changes. Bartsch et al. (2021) provided a panarctic satellite-based record of the expansion of infrastructure and anthropogenic impacts and reported that the area of detectable human-impacts in the Arctic coastal region has increased by 15% since 2000. The same approach (NDVI changes in Arctic) provides basic information about ecosystem responses to climatic trends, variability, ecological disturbance, and successional processes, in particular the phenomenon of Arctic greening. A recent study by Frost et al. (2025) published data on greening dynamics and attribute it to high spatial-temporal variability caused by complex interactions with climate warming, ecological disturbance, and other factors. Arctic greening is apparent across large regions and is connected to long-term shifts in the structure of the vegetation.

Anthropogenic impact on the Arctic

Recently, the Arctic has been heavily impacted by global human activities, mainly through: (1) increased greenhouse gas emissions that drives accelerated warming of Arctic ecosystems, (2) melting sea ice, and the destabilization of permafrost, which in turn may affect local terrestrial ecosystems. Long-range pollution is also considered to be among global environmental issues. On a local scale, a significant role is played by the construction of infrastructure and its operation (pollution caused by plants and industries), the development of transportation, and deposits of waste. The local anthropogenic impact on Arctic vegetation mainly includes the physical disturbances that come from human infrastructure (roads, mines, residences), which create persistent patches of altered vegetation due the to slow recovery rate toward its original composition and structure. Moreover, an increase in vehicle traffic on local roads brings road dust generated by moving vehicles that dries out the area and covers the vegetation with dust which has a negative effect on local ecosystems (Walker et al. 2015). Apart from roads, vehicle tracks over open Arctic tundra is a factor that affects vegetation. On tracks which area were used repeatedly over multiple times the vegetation cover is significantly reduced (Kevan et al 1995). Natural regeneration after such anthropogenic disturbances to tundra vegetation cover is slow, however, assisted regeneration treatments have recently been tested in Svalbard with promising results (Neby et al. 2022).

Numerous studies have focused on the potential effects of oil pollution (crude oil and refined products) on wildlife (invertebrates, fish, birds, and marine mammals) and coastal communities within the Arctic and Subarctic regions (for review, *see* Bi et al. 2025). For terrestrial ecosystems, it is mainly pipeline ruptures caused by corrosion that represents a major risk (Law et al. 2010[3]). The leaking oil enters the snow and soil subsurface and may affect tundra ecosystems (Arnold 2006[1]). For marine and coastal ecosystems, the risk of an oil leak from a ship that results in a massive oil spill on the sea and/or the coast line has major negative effects on sea and coastal biota as was seen after the Exxon Valdez accident in 1989 (Piatt et al. 1990). A secondary negative effect on coastal vegetation may be caused by the *in-situ* burning (ISB) of oil along the coast line. This is rarely used in the remediation of oil spills but brings the risk of smoke and soot deposition to terrestrial ecosystems (Wang et al. 2022). It was observed by Wegeberg et al. (2021) that ISB had long-term effects at a high littoral level, probably due to the high degree of heat generated by the burning processes. For remediation of oil spills along the shore, surface washing agents (SWAs) are commonly applied to enhance oil removal by altering the oil and interfacial properties at the oil/water interface. Since SWA substances are toxic (Fingas 2013[2]) negative effects on sea algae and costal line vegetation have been reported.

Risks related to contaminants from local industry and mining sites

The natural resources found in the Arctic have led to industrialization oriented towards mining of copper, nickel, titanium, diamonds, coal, and numerous rare earth minerals. As a consequence of extensive mining, waste bearing environmental contaminants have been produced and disposed of near to mine sites. The contaminants are not only in stores and disposal tanks but are also located close to the sites. They are drilling muds and fluids, mine tailings that contain toxic metals, radioactive material that has been dug up and then dumped and spilled fuel. Such contaminants are located in the substrate, tailing deposits, or frozen in the permafrost. Recent warming thus leads to the risk that the warming and thaw of formerly stable permafrost near the surface may unlock frozen disposal sites, and destabilize foundations and containment structures. As a consequence of this, contaminants may be released into the surrounding environment (Langer et al. 2023). The aging of fuel tanks also leads to the risk of an accidental release of contaminants as demonstrated by the diesel fuel that poured into the Ambarnaya and Daldykan rivers near Norilsk after a tank collapse in 2021. This huge diesel fuel spill negatively affected the vegetation of the floodplains (Telyatnikov 2022).

Tailing deposits are also a source of serious contaminants. Holm et al. (2003) reported high concentrations of heavy metals and sulphate in acid mine drainage that caused damage to the local tundra vegetation close to a coal mining site in Svalbard. Heavy metals accumulate in soils and vegetation near mine sites, as shown by Wojtuń et al. (2019) for the *Sanionia uncinata* moss and the *Salix polaris* dwarf shrubs in the Longyearbyen area. A recent study by Samecka-Cymerman et al. (2025) revealed harmful levels of Cr, Mn, Ni and Zn in *Sanionia uncinata* in samples from Longyearbyen but not Hornsund (Polish Arctic station, SW Svalbard) and Iceland. Mosses are frequently used as bioindicators for heavy metal contamination in particular environments. In Svalbard, they have been successfully used by Wei et al. (2022) as bioaccumulators to allow the evaluation of heavy metal transport by airborne dust carried by the wind and by surface runoff from snow meltwater (study of *Dicranum angustum*, London Island, Svalbard). Bioaccumulation of heavy metals by mosses and vascular plants could be used for the phytoremediation of polluted Arctic terrestrial ecosystems, as suggested by Karnaeva et al. (2021), to remediate historical petroleum pollution at a site on the Yamal Peninsula (plant in scope: *Eriophorum scheuchzeri*). Heavy metals represent a risk for freshwater habitats (Rajaram et al. 2023).

Black carbon deposits

Local emission, long-range transport, and combustion generated aerosols such as black carbon (BC) can influence the radiative ability of the Arctic atmosphere and. In particular, the impact of atmospheric aging on the mixing state of BC particles (Zanatta et al. 2023). When deposited on snow, numerous types of aerosols cause an increase in the amount of solar radiation absorbed by the snowpack, thus accelerating snow-aging processes and a decrease in the snow albedo(Skiles et al. 2018, Mori et al. 2019, Kang et al. 2020).

At Svalbard, the effects of BC have recently been reviewed by Bertó et al. (2021). The study provides an overview of BC interaction with Arctic ecosystem compartments. BC particles are aerosols and are most effective in absorbing visible and near-infrared solar radiation. These primary insoluble, refractory and carbonaceous particles are emitted by both natural and anthropogenic sources, such as open fires or diesel engine exhausts.

POPs in Arctic Ecosystems

Persistent organic pollutants (POPs) are an emerging problem in Arctic ecosystems (Li et al. 2023). It is well established that POPs mainly enter the Arctic through long-range transport, *i.e.* through atmospheric and ocean/river currents. Local sources of POPs also exist. They are related to local contaminants from industrial, municipal, or infrastructure-related environmental releases (*see* e.g. Gabov et al. 2024 for the Vorkuta power plant). POPs have a negative impact on the health of the indigenous populations and represent an environmental risk for Arctic ecosystems (Li et al. 2023).

POPs in Arctic environments are linked to human activity. However, the origin of POPs and other chemical pollutants in the atmosphere of the Arctic is still considered to be ambiguous, with new sources occurring due to the ongoing industrialization and urbanization of the Arctic (Weber et al. 2017), global warming-induced shifts in shipping routes, and increased car and snowmobile use (Reimann et al. 2009).

Recent research activities have mainly focused on clarifying the sources and pathways of POPs to the Arctic, as well as assessments of individual contaminants. Several studies evaluated two hexachlorocyclohexane (HCH) isomers, that enter the Arctic through long-range atmospheric transport (α-HCH, *e.g.* Becker et al 2008), and long-range ocean transport (β-HCH). The atmospheric transport and deposition in Arctic terrestrial ecosystems play a major role with HCH accumulation found in the snowpack (Hansen et al. 2008), however, α-HCH concentrations in the snowpack were found to be highly dynamic with large and rapid fluctuations throughout the winter months. A recent study

(Pawlak et al. 2024) showed that the atmospheric transport of HCH might be combined with remobilization from the ocean or snowpack resulting in high peak HCH concentrations in Arctic ecosystem (study performed at Hornsund, Svalbard). Atmospherically transported POPs deposited in ice, moreover, may undergo photochemical transformation that changes the toxicity of photoproducts found in ice and meltwater (Klán et al. 2003).

Svalbard terrestrial ecosystems are recipients of POPs and a lot of research has been done into the interaction between POPs and ecosystem components, especially over the last two decades. Recently, a long-term study by Gebru et al. (2023) that analysed eight years of monitoring data from Svalbard, described the temporal trend of levels of polychlorinated naphthalene (PCN) in the Arctic atmosphere. PNCs are an increasing concern not only for the biota forming polar terrestrial ecosystems but also for human health (for review *see* Domingo 2004), and the environment (Fernandes et al. 2020).

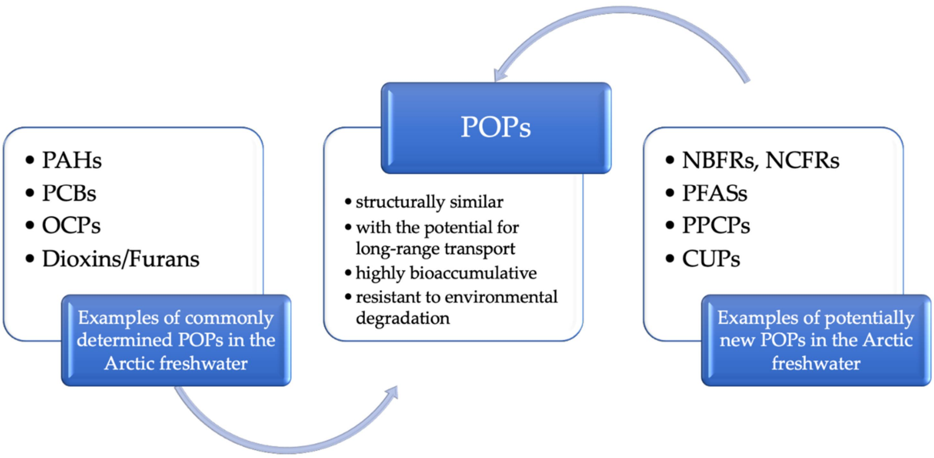

Fig. 1. Pollutants in the Arctic that may be considered to be POPs (adopted from Kosek and Ruman 2021, with permission from Water MDPI).

Effects of POPs on vegetation

POPs and PCNs in particular, were found in snow (Herbert et al. 2005), soils and plants from Svalbard (Dong et al. 2022). The latter study focused on a variety of species, ranging from Arctic willow to several species of herb, fern and moss. The study confirmed the presence of PNCs in samples from Ny-Ålesund, London Island, and Longyearbyen. However, the concentration of PNCs in the samples were found to be rather low and the toxicity risks were much lower when compared to PCN contamination worldwide. In general, POPs accumulate in plants in relatively high quantities, as shown by Franzaring and van der Eerden (2000) for subarctic vegetation. The capacity for POPs accumulation is, however, species specific. Within Arctic ecosystems, several studies focused on the accumulation of POPs in soils (Zou et al. 2024), however, the actual content of POPs in terrestrial plants and their ecophysiological effects has barely been studied (Dong et al. 2022).

Even though POPs are toxic for marine phytoplankton (Echeveste et al. 2016), algae are important ecosystem compartment for the metabolization of POPs in polar regions. Their accumulation in phytoplankton brings the possibility of contaminant transfer to higher trophic levels (Kosek et al. 2016). Marine microalgae are especially sensitive to the phototoxic effects of pyrene (Petersen et al. 2008, Tomar et al. 2023). Similarly, freshwater algae, show high, but species-specific sensitivity to the toxic effects of PAHs (Ben Othman et al. 2023). Freshwater reservoirs within the Arctic are particularly vulnerable to the accumulation of POPs as shown for Hornsund, Longyearbyen, and Ny-Ålesund, Svalbard by Kosek and Ruman (2021). A recent study by Shaji et al. (2024) demonstrated the presence of POPs in freshwater lakes near Kongsfjorden. Hydro-terrestrial (wetlands, seepages *etc*.) and terrestrial (soils, permafrost) ecosystems are considered to be important sinks of POPs and recent warming could release significant POP amounts to the environment (Johansen et al. 2021). Particularly in nutrient-rich conditions, wetland cyanobacteria and microalgae could contribute significantly to their sequestration (Berríos-Rolón et al. 2025).

The effects of POPs on cyanobacteria and algae are dependent on the compound under consideration, its concentration, medium composition, the organisms used for testing and may range from stimulation to inhibition (*e.g.* Touliabah et al. 2022). Chlorophycean algae are capable of effective POP removal up to 100% (Yang et al. 2025). The ability to remove POPs was also observed in cyanobacteria (Cepoi et al. 2016) and diatoms (Paniagua-Michel and Banat 2024). Therefore, the local algal or cyanobacterial strains could be suitable in the remediation of polluted areas in the Polar Regions as part of a microbial consortia, as they are used in warmer regions (Touliabah et al. 2022). For Polar regions, the following soil remediation technologies have been proposed: bioremediation including biostimulation and bioaugmentation, landfarming, biopiles, phytoremediation and electrokinetic remediation (Camenzuli and Freidman 2015).

Besides POPS, heavy or trace metals are another important anthropogenic factor in the Arctic. The highest heavy metal concentrations in Svalbard are associated with former mining activities (Dallmann 2015), and they are strongly positively correlated with POPs (Marquès et al. 2017). Similar to POPs, the effects of heavy metals could be positive, especially at lower concentrations, or negative at higher concentrations (Danouche et al. 2022, Xiao et al. 2023). Since the heavy metal concentration in some localities could approach the known EC50 (*e.g.* Lukavský et al. 2003), they represent a serious environmental risk to microbial communities. Increasing temperatures could release deposits of heavy metals thus increasing their concentration in the environment (Perryman et al. 2020).

Due to increased weathering caused by temperature rise in the Arctic, the rise of pollutant concentrations (Perryman et al. 2020, Johansen et al. 2021) as well as nutrients (nitrogen and phosphorus) lead to eutrophication (Ayala-Borda et al. 2021). Nutrient surpluses could cause cyanobacterial water bloom development (Sivarajah et al. 2021). Moreover, a warmer and prolonged vegetation season and milder winters could support the survival of non-native species that potentially could be invasive, for instance *Vaucheria* cf. *compacta,* which might affect local species composition and endanger the local microbial communities (Elster et al. 2023).

Apart from soils and plants, PNCs were also found in Arctic cod (Sinkkonen and Paasivirta 2000), polar bears (Corsolini et al. 2002) and marine mammals (Rotander et al. 2012, Vorkamp and Muir 2016). Other POP pollutants, such as *e.g.* organochlorine pesticides, PCBs, PBDEs, and PFASs, accumulate in the Arctic food chain and are transferred to humans through the consumption of marine mammals and fish. Inuit populations in the Arctic, due to their reliance on traditional marine-based diets, face higher exposure to persistent organic pollutants than non-native populations. The high levels of POPs found in Inuit communities may be linked to various health issues, including disruptions to the immune and endocrine systems and an increased risk of cardiovascular diseases. The level of POPs found in Inuit communities in Greenland who follow a traditional lifestyle, was positively correlated with inflammation markers (Schæbel et al. 2017).

Concluding remarks

Pollutants originating from distant, and recently even local, sources are an increasing threat to Arctic terrestrial ecosystems. The issue of the transport and fate of persistent pollutants has been the subject of increased attention over the last decade. Many studies have addressed anthropogenic pollution in Arctic ecosystems and suggested that further detailed studies be carried out into sources of emissions, their transport routes and fate in Arctic terrestrial environments. Special attention should be given to an evaluation of where they accumulate and whether they only accumulate in specific elements of the ecosystem, including non-vascular and vascular plants. In follow-up studies, special attention might be devoted to both pollutants that have traditionally been monitored and newly emerging risks such as *e.g.* microplastics (Pakhmonova et al. 2024).

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