Humans are accelerating global change, and the effects are especially affecting northern environments, which are warming at an alarming rate. This theme issue explores the changes and challenges northern environments face during this age of change. It presents three research articles and four discussion pieces. Maliniemi et al. highlight a multidecadal ecological shift in northern boreal forests: the decline of lichens and the expansion of dwarf shrubs. Kasprzak explore extreme events in Wedel-Jarlsberg Land in Svalbard and present two landforms that originated from them. Watson and Hubbard examine the causes and consequences of global sea level rise and project three scenarios to local flood projections in the Morecombe Bay area in the UK. In the discussion pieces, Varnajot and Lépy reflect on their experiences from a ship-based fieldwork on an expedition cruise ship to the geographic North Pole. Alahuhta *et al.* discuss about the importance of freshwater plants for ecosystem stability, water quality and carbon cycling, while their responses to environmental change are lacking research efforts. Tukiainen and Toivanen present an introduction to geodiversity through the example case of Rokua UNESCO Global Geopark in northern Finland. Finally, Kasprzak and Hubbard point out the possibility of the shift and intensification of spring floods in Ostrobothnia, Finland.

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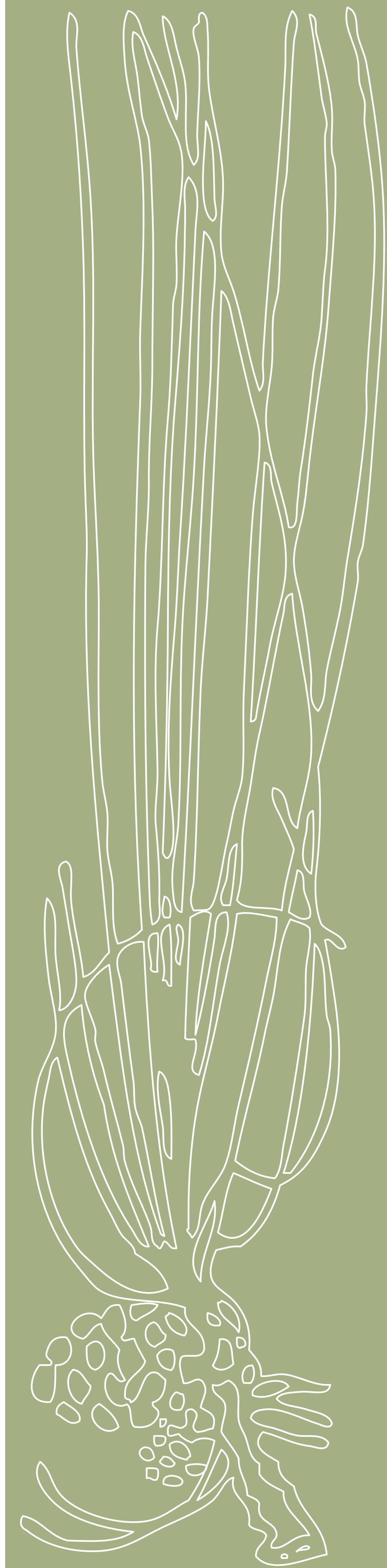

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Theme issue

Addressing global change in northern environments: insights from spatial data and analysis

edited by
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Contents

Editorial

Addressing global change in northern environments: insights from spatial data and analysis

Eirini Makopoulou[a], Henriikka Salminen[a] & Alun Hubbard[a,b]

While change is a fundamental characteristic of the natural world, it is now universally recognized that humans are also potent agents of accelerated change, altering ocean, atmospheric and terrestrial environments and associated ecosystems from the micro to the global scale. This is particularly true of northern environments, where climate warming over the last five decades is almost four times the global mean (IPCC 2021; Rantanen *et al.* 2022), and where infrastructure development (Hjort *et al.* 2022), natural resource extraction (Hovelsrud *et al.* 2011), socio-economic transformations (Hovelsrud *et al.* 2011; Serreze *et al.* 2021) and widespread pollution (Turetsky *et al.* 2020) have compounded ecological responses leading to acute biodiversity loss and ecosystem degradation (ACIA 2005; Bjerke *et al.* 2017).

These abrupt changes cut through the entire northern biosphere with knock-on impacts to its ecosystems, biodiversity, indigenous livelihoods and overall sustainability. They are evidenced across high latitudes into the Boreal regions (Westerveld *et al.* 2023), including marine (Sumata *et al.* 2023) and coastal environments (Irrgang *et al.* 2022), terrestrial space (Myers-Smith *et al.* 2011) and peatlands (Fewster *et al.* 2022; Könönen *et al.* 2022) as well as freshwaters (Koch *et al.* 2022; Lau *et al.* 2022) from specific species responses (Antão *et al.* 2022) to large scale biotic interactions (McKinney *et al.* 2022). Changes in northern environments also have far-reaching impacts on lower latitudes through, for example, regional moisture uptake and atmospheric circulation (Bailey *et al.* 2021), the global carbon cycle (Schuur *et al.* 2015) and committed sea-level rise due to deglaciation (e.g. Box *et al.* 2022).

Acknowledging the role of human-induced change in northern environments is key to shaping strategies for conservation, sustainable resource management and mitigating the detrimental impact of human activity on natural systems. To address these prescient challenges requires a unique set of analytical skills and a new toolbox capable of linking

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and interrogating diverse datasets from multiple interdisciplinary sources on a variety of spatial and temporal scales.

The aim of this theme issue in Nordia Geographical Publications is to bring together research and advancements that explore the challenges and opportunities posed by global change in northern environments, with a specific focus on spatial data and analysis. This theme issue presents three research articles and four essays that address the specific challenges that northern environments face in this new era of abrupt change.

In the research article, Tuija Maliniemi *et al.* highlight a major ecological shift in northern boreal forests: the decline of lichens and the expansion of dwarf shrubs over multiple decades. These shifts suggest a transition to moister conditions driven by succession and climate change while the long-term reindeer grazing is a key factor in lichen decline, a trend that may be exacerbated by shrub growth. Finally, Maliniemi *et al.* raise concerns about the potential local disappearance of lichens if the decline persists.

In his research article, Marek Kazprzak takes us to Wedel-Jarlsberg Land, Svalbard, where he explored extreme events and how their origins can be studied with limited temporal data, by adding field observations, measurements and GIS analysis. He presents two new landforms that originated from such extreme events - an alluvial fan and a potential landslide.

In their research article "The Causes and Consequences of 21st Century Global Sea Level Rise on Morecambe Bay, U.K." Holly Watson and Alun Hubbard investigate the contemporary causes and consequences of global sea level rise (SLR) via literature. They present three scenarios of SLR and relate them to local flood projections to show how floods are going to roam the shores of Morecambe Bay. The study highlights the need for land management strategies and action that is required to tackle imminent changes in sea levels.

In the first Discussions and interventions text, Alix Varnajot and Élise Lépy reflect on their experiences from a ship-time fieldwork on an expedition cruise ship to the geographic North Pole and through the Arctic Ocean. Their essay focuses on science-tourism nexus onboard cruise vessels. These vessels offer platforms of opportunities not only for natural scientists but human scientists as well but what sacrifices or strategies need to be considered before boarding?

A discussion text from Janne Alahuhta *et al.* that brings freshwater plant ecology to the surface. They reveal how freshwater plants are essential for ecosystem stability, water quality, and carbon cycling, yet their responses to environmental change remain poorly understood. Thus, there is a need for more extensive research to understand their biodiversity and ecological roles.

Helena Tukiainen and Maija Toivanen present a welcome introduction to and summary of the maturing sub-discipline of geodiversity. Focusing on the Rokua UNESCO Global Geopark in northern Finland as a case study, their paper reviews the early origins and development of geodiversity, and how it is embedded in the key concepts of geoheritage and conservation. Finally, they discuss the current debates and the future directions this research might take.

Finally, Marek Kazprzak and Alun Hubbard discuss the 2024 spring floods in Ostrobothnia and how climate change may not act to simply reduce snowmelt-driven flood risk with warmer winters but could also shift and intensify them. As Arctic temperatures rise, unpredictable warm spells are driving more variable ice conditions that could yield more frequent and severe flooding, even outside of spring. While Finland's civil response was effective, future resilience will depend on improved forecasting, adaptive planning, and continual real-time learning from events like this.

The theme issue unites multiple viewpoints about global change effects on northern environments through spatial data and analysis studies. The articles in this theme issue illustrate the complex environmental transformations occurring throughout Arctic regions. By exploring Arctic cruise-based fieldwork, ecological transitions in boreal forests, freshwater plant responses, geodiversity, sea-level rise, and extreme flooding in Finland and extreme events in High Arctic, the articles highlight both the complexity and urgency of understanding environmental shifts in high-latitude regions. Although these discussion and research articles cover very broad ground and specific topics, there are also significant commonalities that can be drawn between them that provide pointers to a new generation of scientists who are set to tackle the challenges of rapid natural and social change head on. Despite them all being concerned with environmental change – focusing on the north - the message from some have more optimistic in outlook than others with well documented examples of good practice and effective, pragmatic management. Despite this, there is an overall key message highlighting the future challenges in preserving and adapting to change. Whether it will happen through the implementation of new strategies for the mitigation of flooding under changing temperature and precipitation patterns or through the measures required to preserve the natural geodiversity and unique ecosystems services they support.

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Research article

Dwarf shrub expansion and loss of lichens distinctly dominate multi-decadal changes in northern boreal understory plant communities

Tuija Maliniemi[a*], Joonatan Lohi[a], Janne Alahuhta[a], Karoliina Huusko[b] Risto Virtanen[b]

Abstract

Northern boreal forests and treelines are particularly sensitive to current climate change that has already resulted in increased productivity, shrub expansion and up- and northward shifts of species. However, these changes are expected to be gradual or lagged due to slow process rates, and can be buffered to some extent by large herbivores. Multi-decadal observations of understory change in northern boreal forests remain scarce, particularly those involving bryophytes and lichens despite their importance for biodiversity and ecosystem functions. Here, we analyse temporal changes in understory plant communities of northern boreal forests in Saariselkä, Finland (68.46° N, 27.37° E) that were originally sampled in 1981. We resurveyed plant communities (vascular plants, bryophytes and lichens) at 22 sites (including 88 vegetation plots) in 2014 and at 80 sites (320 plots) in 2022 in different forest site types. Reindeer grazing was moderate throughout the study period (1.5–2.0 reindeer/km^2), while mean annual temperature rose over 1 ^{o}C. We found clear temporal shifts in plant communities towards increasing dwarf shrub dominance and decreasing lichen cover and diversity, which were consistent across the study area and within different site types. However, the increase in dwarf shrubs was species-specific: the cover of bilberry (*Vaccinium myrtillus*), crowberry (*Empetrum nigrum*) and lingonberry (*Vaccinium vitis-idaea*) had increased over time, while the originally most

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dominant species, heather (*Calluna vulgaris*), had decreased and become subordinate to all the above. The observed changes reflect a shift into moister conditions and are likely linked to both succession and climate change. Long-term reindeer grazing is most likely the key driver reducing lichen cover, which may be further affected by the dwarf shrub expansion. The consistency of the observed changes in different site types is indicative of corresponding changes occurring elsewhere in northern boreal forests with comparable environmental conditions and grazing pressure. Importantly, our results raise concerns about the local disappearance of lichens if the declining trend continues.

Keywords: *Calluna vulgaris, Empetrum nigrum, Cladonia spp., reindeer lichen, shrubification, vegetation resurvey*

Introduction

Northern boreal forests and treelines are particularly sensitive to the current climate change (Holtmeier & Broll 2005) that is particularly pronounced in the polar regions (Rantanen et al. 2022). Several studies have reported increases in productivity (Kauppi *et al.* 2014; Zhang *et al.* 2008), shrub expansion (Myers-Smith *et al.* 2011; Rundqvist *et al.* 2011) and upward and northward shifts of treelines (Aakala *et al.* 2014) that have occurred over decades, often in response to climate warming, in high-latitude environments. In contrast, studies of long-term changes and dynamics of understory vegetation in the northern boreal forests are still relatively scarce, even though understory vegetation is ecologically important and affects many ecosystem processes (Nilsson & Wardle 2005). Particularly rare are studies at the plant community level, including non-vascular cryptogams, i.e. bryophytes and lichens. These are important components of understory plant diversity and play a key role in many ecosystem functions in high-latitude environments (Kumpula 2001; Turetsky *et al.* 2012).

Importantly, changes in high-latitude plant communities are likely to be relatively gradual (Chapin *et al.* 2004) or lagged (Jonsson *et al.* 2021) due to slow process rates and dominance of long-lived perennial plant species, and therefore require longer-term data to observe (Vellend *et al.* 2017). Resurveys of historical vegetation data are an essential method for revealing long-term trends in vegetation (Hédl & Chudomelová 2020; Kapfer et al. 2017; Maliniemi et al. 2023) and often serve as the only source of temporal information for areas lacking long-term monitoring. Old documentations of plant communities that include detailed information on non-vascular cryptogams are rare, and most include only vascular plants. It has therefore been relatively uncommon to study simultaneous long-term changes in different plant groups.

Understory vegetation in northern boreal forests is dominated by dwarf shrubs, which are keystone species in these environments, with mosses and lichens being abundant and important attributes of plant communities (Nilsson & Wardle 2005). Wildfires are a key factor in controlling the species composition and successional stages of understory vegetation, especially in unmanaged forests (Nilsson & Wardle 2005). However, wildfires are being strongly controlled or suppressed in certain parts of the boreal zone and fire regimes have changed over time (Gauthier et al. 2015; Granström & Niklasson 2008). This is likely reflected in the understory composition over long time scales as fire has long been a regenerating force in the boreal biome. In the absence of fires, understory vegetation develops towards a late successional stage, characterized by the dominance of crowberry (*Empetrum nigrum*) and feather mosses, which eventually leads to ecosystem regression, where soil microbial activity, decomposition and N mineralization slow down and conditions become less suitable for tree establishment and growth (Nilsson & Wardle 2005).

Reindeer grazing is another fundamental driver that influences high-latitude vegetation. Several studies have shown that grazing can inhibit the expansion of taller shrubs and trees (Olofsson *et al.* 2009; Vowles *et al.* 2017) and, therefore, buffer against climate-driven vegetation changes. However, grazing has less influence on dwarf shrubs, especially on evergreen dwarf shrubs (Vowles *et al.* 2017). Another distinct effect of grazing is its negative influence on lichens (Bernes *et al.* 2015; Kumpula *et al.* 2014,) that reindeer trample and use for winter food (Kumpula 2001). Despite the generally recognized responses of tall shrubs and lichens on reindeer grazing, its effects on other plant groups can be highly context dependent and vary in different habitat types (Bernes *et al.* 2015). Furthermore, these effects are mixed with local and regional climate change effects. Therefore, studies addressing local conditions are needed to advise research and management (Bernes *et al.* 2015).

In 2022, we resurveyed understory plant community data (including vascular plants, bryophytes and lichens) from northern boreal forests in northern Finland that was originally surveyed in 1981. The studied forests have remained outside forest management and other direct human disturbances, like most of the northernmost boreal forests (Gauthier *et al.* 2015), but have been grazed by reindeer the whole study period. In this study we analyse how the composition and diversity of plant communities have changed across the study area and within five different forest site types over the past 40 years. We investigate changes both at the level of the whole community and separately for different plant groups (vascular plants, bryophytes and lichens) and species, as well as in terms of temporal beta diversity. Finally, we include a smaller subset of data, resampled from same sites already in 2014, to explore temporal dynamics of dwarf shrubs and different plant groups in more detail. Based on evidence elsewhere, we expect to observe increases in vascular plant abundance but decreases in lichen abundance over time.

Materials and methods

Study area and vegetation resurvey

Study area is located in Saariselkä region in Northern Finland (68.46° N, 27.37° E), and represents one of the northernmost distributions of boreal forests (Gauthier *et al.* 2015). Mean annual temperature (1990-2021) in the area is -0.7 °C, ranging between -12 °C (mean in January) and +13 °C (mean in July) (Jokinen *et al.* 2021). Mean annual precipitation (1990-2021) is 600 mm, while mean snow cover is 70 cm, snow cover period lasting on average from October to May (Jokinen *et al.* 2021). During the past 30 years, mean annual temperature has risen over 1 °C, mean annual precipitation has increased approximately 90 mm and mean snow cover thickness has slightly decreased in the region, when compared to the reference period of 1960-1991 (data from the nearest weather station at Ivalo airport: Finnish Meteorological Institute 1991).

The study area has remained outside direct human impact (e.g. forestry) that is represented by a few non-paved roadways and a power line crossing easternmost gradient (Fig. 1). None of the sampling sites overlap with these disturbances and we estimated them having only a minor effect on the adjacent sites. However, the area is a part of a year-round reindeer pasture in Ivalo herding district (Kumpula *et al.* 2014). The number of reindeer in the herding district increased sharply during 1970-80s, reached a peak of nearly three reindeer/km^2 in the late 1980s and since stabilized at around 1.5–2 reindeer/km^2 (Appendix S1). To our knowledge, there have been no recent forest fires in the area, and no evidence of forest fires was observed during the resurvey or mentioned in the original publication (Lyytikäinen 1983).

According to Ahti *et al.* (1968), the study area belongs to the northern boreal vegetation zone. Forests in the study area are mostly *Pinus sylvestris* -dominated, relatively open xeric (dry) and sub-xeric (semi-dry) forests (Fig. 1) with *Betula pubescens* ssp. *czerepanovii* forming the altitudinal treeline. Understory vegetation is typical to northern boreal forests; relatively species-poor and dominated by a few dwarf shrubs (*Calluna vulgaris*, *Empetrum nigrum*, *Vaccinium myrtillus*, *Vaccinium vitis-idaea*), with bryophytes and lichens, of which the most dominant are feather mosses (*Hylocomium splendens*, *Pleurozium schreberi)* and reindeer lichens (*Cladonia* spp), respectively. According to Lyytikäinen (1983) plant communities can be classified into *Calluna-Cladonia* type, *Empetrum-Calluna-Cladonia* type (that is the most common and include infertile and fertile variants, and *Betula* variant at

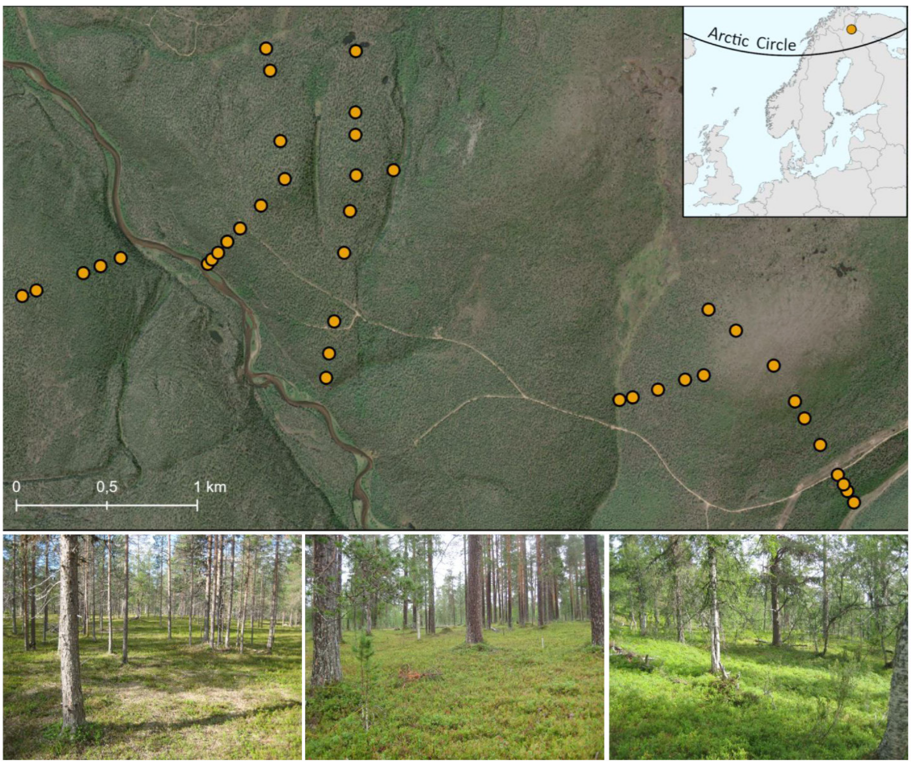

Figure 1. Location of the study plots. Vegetation in the study area is mostly old, open pine dominated xeric (dry) (photo lower left) and sub-xeric heath forests (semi-dry) (lower middle) with patches of old mixed mesic (fresh) heath forests (lower right).

the treeline) and *Calluna-Uliginosa* type, representing a continuum from dry to semi-dry types to more fresh types, respectively.

The original vegetation survey was carried out in 1981 by Lyytikäinen (1983) who mapped vegetation from a total of 100 sites along elevational gradients on four forested hills (Fig. 1). Together, elevational gradients extend from 190 to 400 m asl. and cover different aspects. Treeline is reached only in the easternmost hill, where there is a small area of treeless heathland. Study sites were established in pairs, i.e., two sites are next to each other, separated by 15 meters. At each site, vegetation was mapped from four 1 x 1 m plots. Plots were placed five meters away from the centre of the site and at an angle of 45 degrees in each direction, in relation to the elevational gradient. In the case of a tree or a large rock, the plot was systematically moved clockwise. Each vascular plant, bryophyte (excluding small liverworts) and lichen species (excluding a few crustaceous species growing on one plot) were identified from the plot and were given a percentage cover value using the following scale: + (< 1 %), 1, 2, 3, 4, 5, 7, 10, 15, 20, 30, 40, … 90, 95, 100 %. Non-vascular cryptogams growing on rocks and tree trunks were not included. For each site, the percentages for each species were averaged across the four 1 x 1 m plots. Basal area was measured from 31 sites.

In the summer 2022, we resurveyed 80 sites (Fig. 1), consisting of total of 320 vegetation plots of 1 x 1 m, using the same methodology as in the original survey, described above. These include 12 sites of *Calluna-Cladonia* type, 31 infertile variant of *Empetrum-Calluna-Cladonia* type, 17 fertile variant of *Empetrum-Calluna-Cladonia* type, 10 *Betula* variant of *Empetrum-Calluna-Cladonia* type and 10 *Calluna-Uliginosum* type. Of the 80 resurveyed sites, 22 sites were resampled already in 2014 for another study (Maliniemi, Happonen & Virtanen 2019). This data also represents different site types and is used in the final analysis of this study to complement interpretation on temporal dynamics of dominant species and plant groups. For all of the analysis, certain bryophyte and lichen species were identified or combined at the level of genus (e.g. *Dicranum* spp., Appendix S2) due to highly similar appearance and to reduce the identification error. Old and new data were harmonized in terms of species taxonomy before the analyses.

The old sites did not have coordinates, so their relocation was based on the original map in Lyytikäinen (1983) where gradients were drawn and the information on elevation, slope and aspect that was given for each site. Thus, sites are quasi-permanent, which is often the case with old vegetation data (Kapfer *et al.* 2017). This inevitably causes some relocation error between the old and the new site locations. However, this error was estimated relatively small in this study because the gradients could be relocated relatively precisely. Moreover, the species-poor and homogeneous vegetation in the study area and the averaging from four vegetation plots reduces the error. In general, comparable resurveys to our study have been shown to be robust to the relocation error (Kopecký & Macek 2015).

Data analyses

We used non-metric multidimensional scaling (NMDS) to explore temporal shifts in plant communities, both across all study sites and within different habitat types. NMDS was calculated with absolute cover values (%) and Bray-Curtis dissimilarity. Covers of dominant species (*C. vulgaris*, *E. nigrum*, *V. myrtillus*, *V. vitis-idaea*) and plant groups (vascular plants, bryophytes and lichens) were fitted into the ordination as correlation vectors. The effect of time on compositional shift across all study sites was tested with permutational manova (PERMANOVA; Anderson 2001). Permutations (n = 999) were not allowed within the paired sites due to repeated measures design. In addition, possible increases in compositional similarity over time, indicating biotic homogenisation, were tested using the homogeneity of multivariate dispersions (PERMDISP; Anderson *et al.* 2006). This was done by comparing site-wise distances to the spatial median of all sites in a multivariate space between the surveys. Analyses above were implemented in R version 4.3.0 (R Core Team 2024) using a 'vegan' package (Oksanen *et al.* 2024).

We used temporal beta diversity index (TBI; Legendre 2019) to estimate the magnitude of temporal turnover in plant communities. TBI was calculated for each pair of sites (original survey in 1981-resurvey in 2022) using species absolute cover values and percentage difference (i.e., Bray-Curtis) as a dissimilarity metric. TBI values range from 0 to 1, indicating completely similar (at 0) or dissimilar (at 1) community composition between surveys, and were further decomposed into species losses and gains. The shares of losses and gains were plotted and tested with permutation tests with 9999 permutations to find out whether gains or losses dominate temporal turnover. TBI was calculated for the whole species composition but also separately for vascular plant, bryophyte and lichen compositions to explore temporal dynamics in different plant groups. To estimate species-level changes over time, we used paired t-tests. P-values were permuted (n = 9999) and corrected for multiple testing using the Holm correction. TBI, the related analyses and t-tests were calculated using R package 'adespatial' (Dray *et al.* 2023).

The effect of site type on the observed changes in the cover of dominant dwarf shrubs and plant groups was tested with linear mixed effects model (LMM), using the package 'nlme' (Pinheiro *et al.* 2023). The time of the survey and the interaction of time and site type were assigned as fixed effects in the models. Hierarchical and temporal structure of the data was taken into account by assigning plot ID, nested within the site (i.e. pair of sites along the gradient), as a random effect in each model. Residual diagnostics were checked for each model and if necessary, response variable was square root -transformed to meet assumptions of normal distribution.

Finally, using the data resampled also in 2014, we explored cover change dynamics in dominant dwarf shrubs and different plant groups, using the three time periods. Of the data from 1981 and 2022 we included only those sites (n = 22, consisting of 88 vegetation plots) sampled in 2014. We ran LMMs for each response variable, using year as a fixed effect and plot ID as a random effect (in this dataset there were no pairs of sites along the gradient but only one site). To analyse if there were significant difference between the pairs of group (year) means, Tukey's post hoc test was run using the package 'multcomp' (Hothorn *et al.* 2023).

Results

A total of 68 species were identified on the study plots during the surveys (Appendix S3). Of the species (or genera considering non-vascular cryptogams), 53 were found in the original survey (33 vascular plant, 8 bryophyte and 12 lichen species or genera) and 63 were found in the resurvey (40 vascular plant, 13 bryophyte and 10 lichen species or genera). There were no considerable gains or losses over time, i.e., species gained or lost were typically recorded once or twice (Appendix S3).

The composition of plant communities changed significantly over time across the study sites (PERMANOVA: F = 11.75, p = 0.001, Fig. 2a), but showed no significant temporal decrease in compositional dissimilarity, i.e. biotic homogenisation (PERMDISP: average distance to spatial median 0.356 in 1981 and 0.328 in 2022, F = 1.83, p = 0.193). Plant communities shifted towards *E. nigrum* and *Vaccinium* spp. dominance and away from *C. vulgaris* and lichens, and these shifts were consistent across all site types (Fig. 2b). NMDS1 axis generally represents site type gradient from mesic to dry types, according to the classification in the original survey (dashed ellipses in Fig. 2). The driest site type, *Calluna-Cladonia*, no longer exists as it was in 1981 but resembles more *Empetrum-Calluna-Cladonia* types.

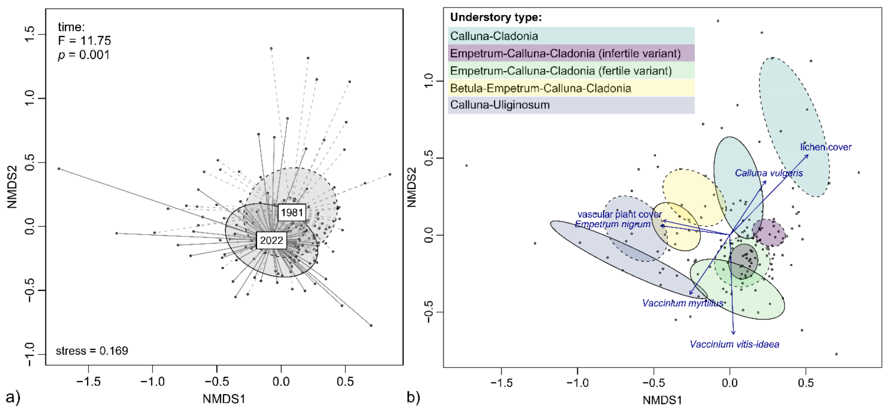

Figure 2. Non-metric multidimensional scaling (NMDS) illustrating temporal shifts in plant community composition, based on Bray-Curtis dissimilarity and species absolute cover values (%). a) Ellipses (1 standard deviation) are drawn across all study sites during both surveys. b) Ellipses are drawn across different habitat types during the original survey in 1981 (dashed lines) and the resurvey in 2021 (solid lines). Arrows represent significant correlation vectors for the cover of *C. vulgaris* (r^2 = 0.166, p = 0.001), *E. nigrum* (r^2 = 0.194, p = 0.003), *V. myrtillus* (r^2 = 0.200, p = 0.001), *V. vitis-idaea* (r^2 = 0.384, p = 0.001), all lichens (r^2 = 0.494, p = 0.001) and all vascular plants (r^2 = 0.185, p = 0.002).

Table 1. Mean temporal beta diversity index (TBI) and its components (losses and gains) calculated across pairs of sites (original survey and resurvey) for all species and different plant groups. Mean change (gains-losses) indicates the direction of change, i.e. whether losses (negative) or gains (positive) dominate. Its associated p-value is tested with 9999 permutations.

Variable	Losses	Gains	TBI	Mean change	Stat	*p.perm*
All species	0.235	0.186	0.421	-0.049	-3.230	0.002
Vascular plants	0.159	0.259	0.418	0.010	3.732	0.001
Bryophytes	0.197	0.198	0.396	0.001	0.037	0.967
Lichens	0.678	0.026	0.703	-0.652	-22.652	0.001

Temporal beta diversity index (TBI) was 0.42 across all sites with all species included and the compositional change of plant communities was dominated by species losses (Table 1; Fig. 3a). Of the different plant groups, species gains dominated only in vascular plants, while lichens had the highest TBI value (0.70) that was almost entirely due to species losses (Table 1; Fig. 3b-d).

Species-level investigations further confirmed temporal changes in the cover of dominant dwarf shrubs (Table 2). Originally the most dominant species *C. vulgaris* has become subordinate to *E. nigrum*, *V. myrtillus* and *V. vitis-idaea*, of which the former was the most dominant species across the study sites in the resurvey. Evergreen dwarf shrub with more northern distribution, *Arctous alpina*, had also significantly declined, although having small coverage during both surveys. Of bryophytes, the cover of *Pohlia* spp. had increased (although this can be due to more precise observer in 2022, as small *Pohlia* individuals are often found among other bryophyte samples) while that of *Polytrichum* spp. had declined. Reindeer lichens (*Cladonia arbuscula*, *C. rangiferina*, *C. stellaris*) had decreased the most in cover, but the decline was also clear with *Cetraria ericetorum*, minute *Cladonia* spp. and *Stereocaulon* spp. (Table 2). There was no significant difference in the basal area between the surveys (Appendix S4).

Despite the observed general trends above, there were site type-specific responses in the cover changes of dominant dwarf shrubs and different plant groups (Fig. 4). *C. vulgaris* tended to decrease in all but the driest site type (*Calluna-Cladina*), whereas *E. nigrum* tended to increase especially on those types where it was least abundant in 1981. *V. myrtillus* and *V. vitis-idaea* increased particularly in the *Calluna-Uliginosa* type. Vascular plant cover tended to increase in all but the site type typical to treelines (*Betula-Empetrum-Calluna-Cladonia*), where it was influenced by the strong decline in the cover of *C. vulgaris*. Bryophyte cover tended to slightly decrease in all but the driest *Calluna-Cladina* type where it had replaced previously abundant lichens (Fig. 4).

Temporal comparisons including data from 2014 indicate nonparallel temporal dynamics regarding dominant dwarf shrubs and different plant groups (Fig. 5). Whereas the decrease in the cover of *C. vulgaris* seems to have generally taken place before 2014, the strong increase in *E. nigrum* is a more recent event. Decrease in lichen cover have also mostly taken place before 2014. Bryophyte cover shows a decreasing trend until 2014, after which it has recovered, resembling the cover in 1981 by 2022. The cover of vascular plants remained stable throughout the whole study period (Fig. 5).

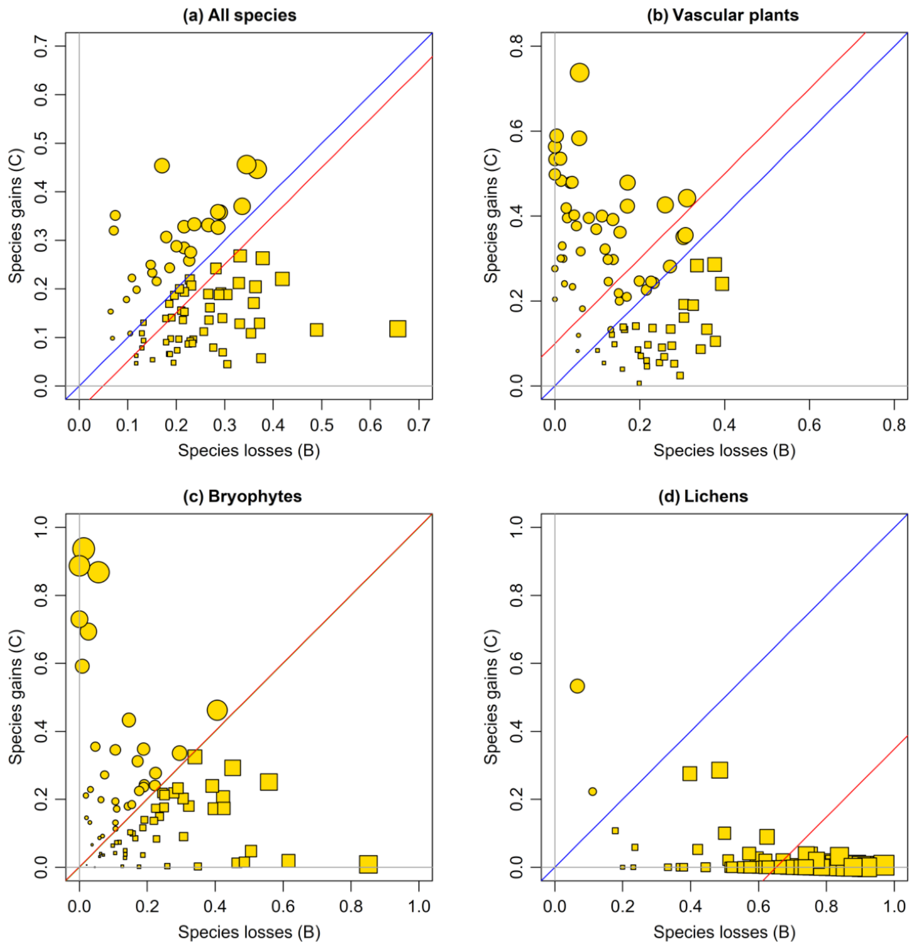

Figure 3. BC-plots illustrate the output of TBI analyses by displaying if temporal changes in plant communities are dominated by gains (circles) or losses (squares). Each symbol represents one site, and its size is proportional to the TBI values. BC-plots are drawn for a) all species and separately for b) vascular plants, c) bryophytes and (d) lichens. The diagonal blue line indicates where there is a balance between gains and losses, while the red line passes the centroids of all the symbols and is placed on the side that dominates temporal changes.

Table 2. Changes in species' frequencies, absolute mean cover (with 95 % confidence intervals) and relative cover across all study plots over time. Only species with significant changes are listed. P-values are based on paired t-tests made for species absolute covers with 9999 permutations (p.perm) and are corrected for multiple testing (p.adjust). *Seedlings only. List of all species in Appendix S3.

species	frequency 1981 / 2022	cover (%) 1981 / 2022	absolute cover change (CI's) (%)	relative cover change (%)	p.perm	p.adjust
Arctous alpina	14 / 6	0.22 / 0.02	-0.20 (-0.38, 0)	-90.9	< 0.001	0.032
Calluna vulgaris	69 / 65	12.78 / 7.68	-5.10 (-7.83, -2.36)	-39.9	< 0.001	0.017
Empetrum nigrum	80 / 80	9.94 / 15.05	+5.11 (2.94, 7.28)	+51.4	< 0.001	0.007
Festuca ovina	6 / 1	0.04 / <0.01	-0.04 (-0.08, 0)	-92.9	0.016	0.799
*Pinus sylvestris**	30 / 41	0.13 / 0.34	+0.21 (0.05, 0.37)	+161.5	0.003	0.135
Vaccinium myrtillus	78 / 78	6.02 / 9.19	+3.17 (1.32, 5.03)	+52.7	< 0.001	0.037
Vaccinium uliginosum	22 / 22	0.33 / 0.85	+0.52 (0.02, 1.02)	+157.6	0.012	0.627
Vaccinium vitis-idaea	80 / 80	4.99 / 8.11	+3.12 (2.07, 4.18)	+62.5	< 0.001	0.007
Pohlia sp.	13 / 33	0.04 / 0.20	+0.16 (0, 0.35)	+400.0	< 0.001	0.017
Polytrichum sp.	35 / 22	0.78/ 0.15	-0.63 (-1.43, 0.16)	-80.8	< 0.001	0.007
Ptilidium sp.	31 / 38	0.91 / 0.31	-0.60 (-1.15, -0.04)	-65.9	0.015	0.770

Cetraria ericetorum	14 / 2	0.15 / 0.01	-0.14 (-0.25, -0.04)	-93.3	< 0.001	0.011
Cladonia arbuscula	79 / 73	6.86 / 0.38	-6.48 (-7.92, -5.04)	-94.4	< 0.001	0.007
Cladonia rangiferina	78 / 77	4.00 / 0.45	-3.55 (-4.47, -2.64)	-88.8	< 0.001	0.007
Cladonia stellaris	68 / 43	2.36 / 0.15	-2.21 (-3.11, -1.31)	-93.6	< 0.001	0.007
Cladonia sp.	80 / 80	3.03 / 1.41	-1.62 (-2.27, -0.97)	-53.5	< 0.001	0.007
Stereocaulon sp.	20 / 3	0.09 / 0.01	-0.08 (-0.12, -0.04)	-88.9	< 0.001	0.007

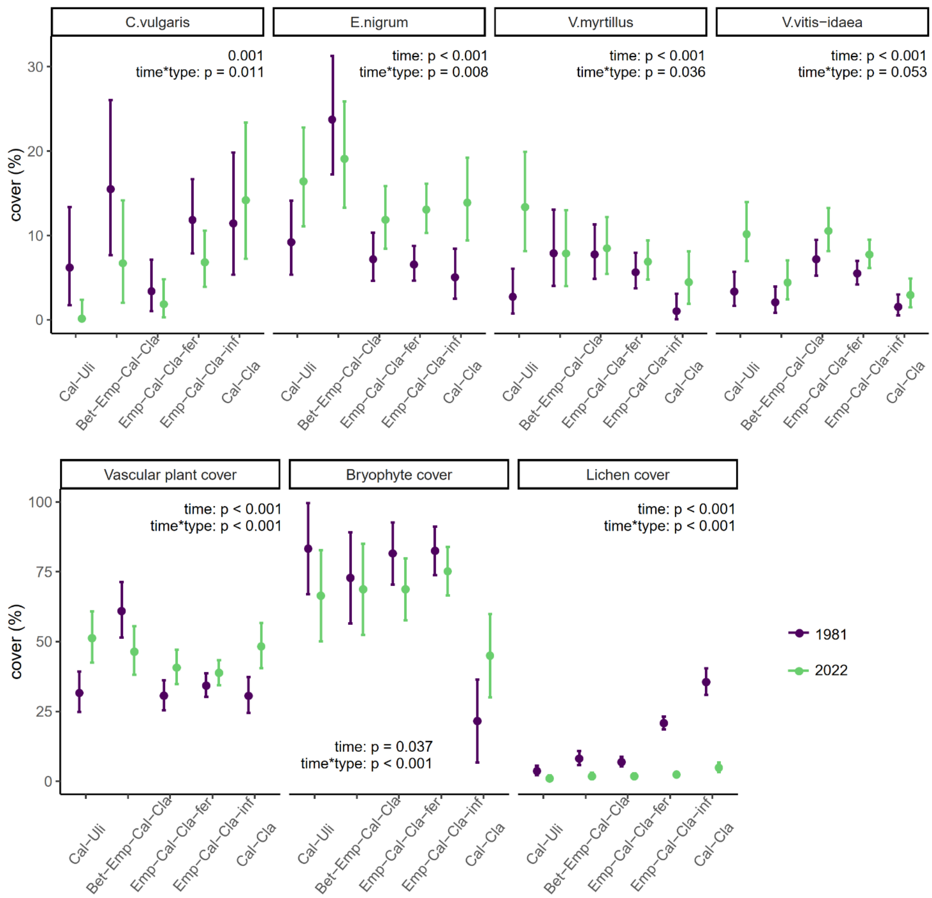

Figure 4. Temporal changes in the mean cover of dominant dwarf shrubs (upper panel) and in the cover of different plant groups (lower panel) in different vegetation types. Means are linear mixed model effects with 95 % confidence intervals. For each variable, the significance of time and the interaction between time and vegetation type are shown (detailed model statistics in Appendix S5).

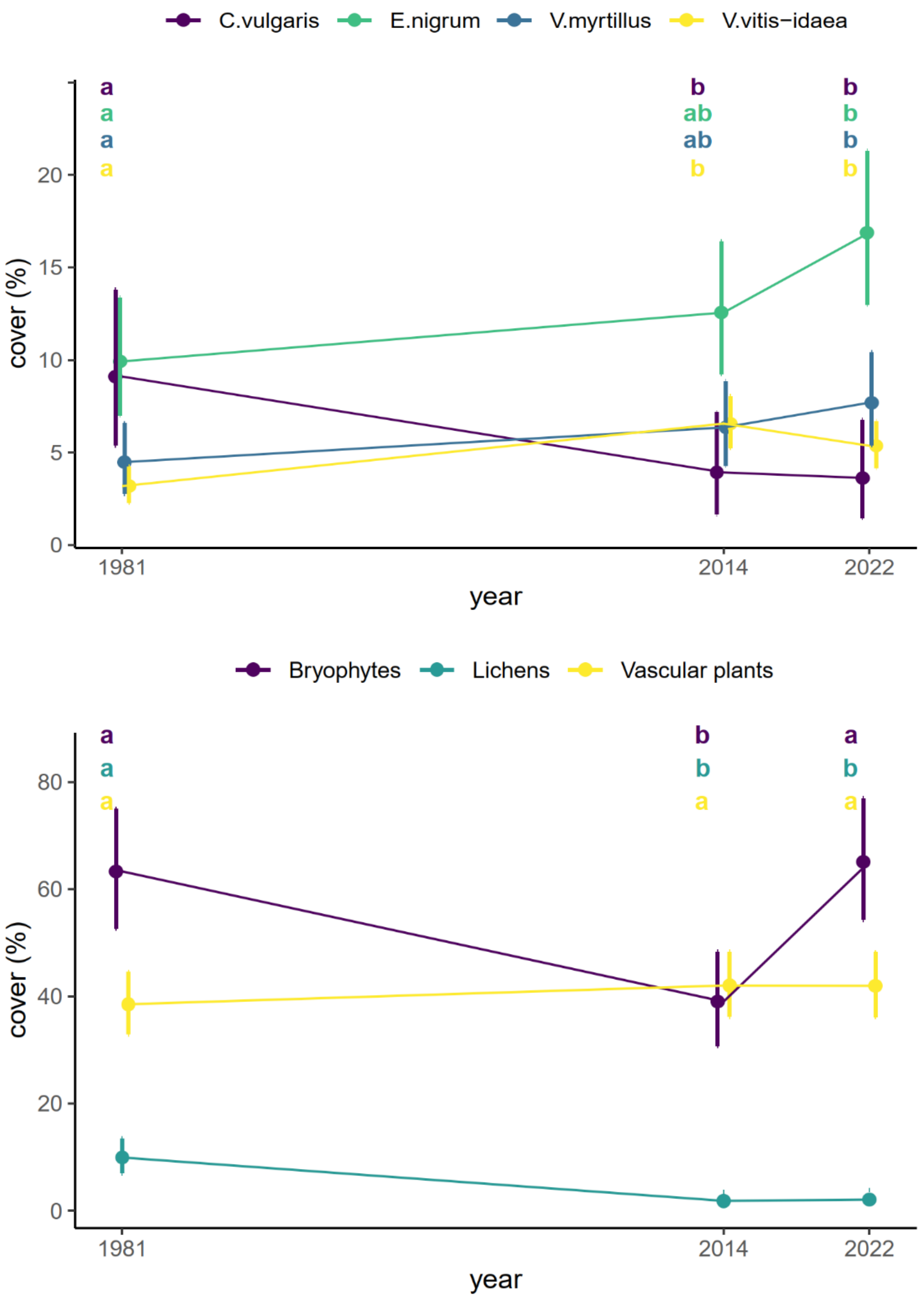

Figure 5. Temporal dynamics in the cover of dominant dwarf shrub species (upper panel) and different plant groups (lower panel) in three time points. Same sample sites (n = 22) were included from each year. Means are linear mixed model effects with 95 % confidence intervals. Letters indicate significant ($p < 0.05$) difference between years and are based on Tukey's post hoc tests (statistics in Appendix S6).

Discussion

We found that the studied northern boreal plant communities have shifted towards more dwarf shrub dominance and have experienced profound losses in lichen cover and diversity during the past 40 years. While these changes were expected based on earlier studies (e.g. Väre *et al.* 1996), the decline in lichens was particularly pronounced, indicating that certain species are close to disappear locally. Recently, the expansion of evergreen dwarf shrub *E. nigrum* have been reported from mountain birch forests, treeless heaths, and tundra (Bråthen *et al.* 2024; Maliniemi *et al.* 2018; Vowles *et al.* 2017; Wilson & Nilsson 2009,), but less from boreal forests, where its strong expansion is indicative of late successional stages and potential ecosystem retrogression (Nilsson & Wardle 2005). However, its relatively rapid increase during the past decade in the study area (Fig. 5) suggests that it can be increasing more broadly also in northern boreal forests. Our study showed that understorey vegetation change is evident over several decades in northern boreal forests with generally slow process rates and that it is important to consider also non-vascular cryptogams (bryophytes and lichens) to gain a comprehensive understanding of the vegetation dynamics and their potential outcomes over the long-term.

The studied plant communities were already characterised by dwarf shrubs 40 years ago. However, their cover had increased over decades, but with species-specific changes. Increased cover of dwarf shrubs is in line with long-term observations of increasing shrub abundance made across the northern hemisphere that have been linked to warmer climate (e.g. in Bråthen *et al.* 2018; Maliniemi & Virtanen 2021; Myers-Smith *et al.* 2011; Tuomi et al. 2024), but also to natural succession in the absence of forest fires (Maliniemi *et al.* 2023). The latter also explains, at least partly, the changes in species dominance patterns from *C. vulgaris* dominated system towards *Vaccinium* spp. and *E. nigrum* dominance, which is indicative of late successional stages in boreal forest understories (Nilsson & Wardle 2005; Tybirk *et al.* 2000). This stage is characterized by moister conditions due to faster accumulation of organic material (Wardle *et al.* 2003). However, tree canopies in the study area have remained rather unchanged (Appendix S4), comparable to findings in Franke *et al.* (2015) from the same area in 1983-2009. Thus, not only succession due to closing canopy, but also changing moisture conditions driven by long-term changes in snow cover duration and thickness most likely co-drive the observed trends (Luomaranta, Aalto & Jylhä 2019). Especially evergreen dwarf shrub *E. nigrum* show a strong response to earlier snowmelt (Wipf & Rixen 2010) that has been observed in the study area during the past decades (Callaghan *et al.* 2011).

Our results clearly show that *E. nigrum* expansion is occurring also in northern(most) boreal forests in Fennoscandia and suggest that this is a rather recent phenomenon (Fig. 5). Similar to what has been reported from treeless heathlands (Bråthen *et al.* 2024), *E. nigrum* expansion has been strongest on sites with originally low *E. nigrum* cover (Fig. 4). As a clonally growing allelopathic species that is a strong nutrient competitor, *E. nigrum* has the advantage of being able to colonize effectively compared to most other accompanying species (Nilsson & Wardle 2005; Tybirk *et al.* 2000). Strong increase in dwarf shrubs and especially *E. nigrum*, has high potential to start slowing down regeneration of *P. sylvestris* (Nilsson *et al.* 1993) and can eventually lead to ecosystem retrogression (Nilsson & Wardle 2005). However, *E. nigrum* is sensitive to disturbance, especially fires, that can prevent its expansion and revert its effects on the ecosystem (Nilsson & Wardle 2005). Evidence from high-latitude environments has shown that *E. nigrum* has a negative impact on many aspects of biodiversity (Bråthen *et al.* 2024;

Salminen *et al.* 2023; Tuomi et al. 2024). Therefore, further expansion of *E. nigrum* could be detrimental particularly to lichens, which were severely declined in the study area compared to 1980s, and these dynamics should be closely monitored.

Reindeer grazing is a key factor driving long-term lichen decline in northern Fennoscandia (Akujärvi *et al.* 2014; Bernes et al. 2015; den Herder *et al.* 2003; Kumpula *et al.* 2014; Stark *et al.* 2023) and the observed lichen decline in this study is in line with this firm evidence. Our results strongly suggest that when considering both frequency and cover, lichen species *Cetraria ericetorum* and *Stereocaulon* spp. have declined close to a level of local disappearance. Although our data do not allow testing the effect of different drivers on the observed lichen decline, it is likely that in addition to grazing, dwarf shrub encroachment further suppresses lichens, as also found by Tonteri *et al.* (2022), and this may be the case especially with pioneer lichens such as *Stereocaulon* species. Taller shrub expansion or increased tree saplings was not observed in this study, similar to other grazed areas in northern Europe, where reindeer inhibit expansion of taller shrubs and tree saplings (Maliniemi *et al.* 2018; Vowles *et al.* 2017; Vuorinen *et al.* 2017). Reindeer grazing has also been shown to have a negative impact on *C. vulgaris* biomass (Väre, Ohtonen & Mikkola 1996) and cover (Kumpula *et al.* 2011), yet some other studies have not observed such effects (Vowles *et al.* 2017). Also, as a by-product of digging for food, reindeer remove the protective snow cover in winter, which can harm *C. vulgaris* (and lichens) but perhaps to a lesser extent some other species, such as *E. nigrum*, that are more adaptable to changing snow conditions (Bienau *et al.* 2014). *C. vulgaris* is particularly sensitive to reduced wintertime snow cover that, when extreme, has been documented to cause *C. vulgaris* diebacks (Bjerke *et al.* 2017; Hancock 2008). However, it is likely that grazing alone does not explain decreased *C. vulgaris* cover, but it is also negatively affected by the long-term succession and changing climatic conditions.

Although temporal changes in dwarf shrub dominance patterns showed a general increase in *E. nigrum* and *Vaccinium* spp. and decrease in *C. vulgaris*, there were some site type specific differences. One of the most distinct compositional changes had occurred in the driest *Calluna-Cladina* site type where the expansion of *E. nigrum* was strongest (Fig. 5) and where bryophyte cover had replaced lichens. Such shift in the cover of non-vascular cryptogams may have occurred in response to grazing (also in Tonteri *et al.* 2022), as shown by Väre *et al.* (1995) in a comparable site type in northern Finland, whereas strong *E. nigrum* expansion is comparable to that occurring in the oligotrophic treeless heathlands of northern Finland (Maliniemi *et al.* 2018). In general, differences between site types seem to have become smaller, as also indicated in the NMDS (Fig. 2), even though biotic homogenisation across the sites was not statistically confirmed. However, our results indicate that if the current trend continues, biotic homogenisation will likely be evident in the future.

Our results also hint at asynchronous temporal dynamics between dominant dwarf shrub species and different plant groups in the studied plant communities (Fig. 5). Lichen loss seems to have taken place earlier in the study period and may have resulted rather soon after the increase and peak in grazing pressure in late 1980s (Appendix S1). As lichens recover slowly (Klein & Shulski 2009), their cover has not restored under grazing pressure that stabilized at the level of circa 1.5-2 reindeer per square kilometer since the peak. However, even though current grazing pressure would no longer substantially reduce lichen abundance, further increases in the number of reindeer might do so, as well as ongoing climate warming that has been shown to have a negative effect on lichen cover and diversity (Klein & Shulski 2009; Lang *et al.* 2012). The increase of *E. nigrum*, in turn, seems to be a more recent phenomenon and coincides with the rapid warming during the later part of the study period. At the same time with the strong *E. nigrum* increase, also bryophyte cover increased substantially, which is characteristic to the late successional stage proceeding to retrogressive phase (Nilsson & Wardle 2005).

Historical vegetation data provide essential baseline information, against which temporal changes can be observed using a resurvey study approach. This approach complements long-term monitoring that is lacking in several areas and habitat types. Whereas two time points can reveal longer-term temporal trends in vegetation, more sampling points are needed to reveal more specific and shorter-term temporal dynamics (see also Hédl & Chudomelová 2020). Also, it should be noted that old site type classifications may no longer be valid as such (see Fig. 2 for temporal shifts in site types from 1981 to 2022) and this should be considered in areas and habitats where classifications dating back decades are used to guide current management and conservation.

Conclusions

Studied northern boreal forest understory plant communities have undergone clear shift in their dwarf shrub and lichen abundance over the past 40 years and currently represent a successional stage that is linked to ecosystem retrogression. Our results indicate that the observed shift, and especially the expansion of *E. nigrum* has occurred recently and relatively rapidly. *E. nigrum* expansion should be further monitored as it has negative effects on many facets of biodiversity and several above- and belowground processes (Nilsson & Wardle 2005). Severely declining lichens appear to be particularly vulnerable, facing multiple threats including reindeer grazing, climate warming and expansion of *E. nigrum*. Although the effects of reindeer on vegetation (other than tall shrubs and lichens) are highly context-dependent (Bernes *et al.* 2015) and further mixed with climate change effects, the consistency of the observed changes suggests that similar changes are occurring elsewhere in northern boreal forests with comparable environmental conditions and long-term grazing pressure.

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Research article

Geomorphic evidence of extreme events in the High Arctic (Wedel Jarlsberg Land, Svalbard)

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Abstract

Among the geomorphological processes determined by meteorological conditions, topography and geological factors, floods and various mass movements have an extreme origin. In the High Arctic, which is the domain of cryogenic processes, extreme events can reach a scale and intensity never before observed, considering the exceptionally rapid environmental changes caused by global warming. It is widely believed that the frequency of extreme events will increase. However, knowledge about their past activity is limited due to the low population density in high-latitude areas and the deficit of adequate observations before the digital era. They are recorded in sediments and landforms, which require comparative analysis. This paper gives two examples of landforms resulting from extreme geomorphological events occurring in Wedel-Jarlsberg Land on the western coast of Svalbard (approx. 77°N). A basic description of an alluvial fan with an area of 0.067 km^2 was provided, resulting from mud-debris flows from the Steinvik Valley, likely due to water being pushed out of a shallow lake with an area of 0.022 km^2. The possibility of a landslide occurring in the postglacial period on the slopes of the Jens Erikfjellet massif was also indicated. The timing of the events is discussed based on the existing dating of raised marine terraces. The presented data come from preliminary studies, such as field observations, simple measurements, and GIS analysis of available digital materials. The outcomes can introduce a better understanding of the scale of extreme processes and the search for similar landforms. Such inventory has not yet been comprehensively conducted on Svalbard, even though extreme events commonly occur during the Holocene climate fluctuations in this area. Their frequency and scale remain unknown.

Keywords: *extreme events, alluvial fan, landslide, Wedel Jarlsberg Land, Svalbard*

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Introduction

Svalbard is an area where climate change-driven landscape transformations are particularly noticeable. The increase in air temperatures, which is progressing 2–4 times faster than in other parts of the globe (Rantanen *et al.* 2022), affects the hydrosphere and cryosphere, causing a decrease in the extent and frequency of sea ice surrounding the archipelago (Urbański & Litwicka 2022), and on land, an apparent regression of glaciers (Farnsworth *et al.* 2020; Noël *et al.* 2020, Schuler *et al.* 2020) and thawing of permafrost (Biskaborn *et al.* 2019; Karjalainen *et al.* 2019). Changes in the hydrological regime include reducing snowfall in favour of rain and releasing loose sediment no longer bound by ice, intensifying geomorphological processes (Owczarek *et al.* 2014). Mass movements, including rockfalls, landslides, and debris flows, are noteworthy. In Arctic conditions, they can occur even on surfaces with a slight slope, using the slip surface, which is often the permafrost table (Kokejl *et al.* 2009; Lewkowicz & Way 2019). A particular category is also created by rapid glacial lake outburst floods (GLOFs) in the paraglacial zone (Taylor *et al.* 2023).

It can be argued that activating hydrological and geomorphological processes, which reflect climate change, is a normal reaction of the natural environment, striving to achieve equilibrium in new conditions. Nevertheless, their scale and dynamics often place them in the category of extreme events (Overland 2021; 2022). Among the many definitions of extreme events (Thywissen 2006), it is worth pointing out that their size, intensity or time of occurrence are usually surprising to humans.

The study of geomorphological effects of extreme events has entered a new phase with the digital revolution of recent decades, including the availability of data and the popularisation of remote sensing and GIS tools. In Svalbard, the turning point was undoubtedly the development of a high-resolution orthophotomap and other digital data of the entire archipelago by the Norwegian Polar Institute (geodata.npolar.no). Detailed studies began to appear, looking for landforms associated with GLOF events (Wieczorek *et al.* 2023) and the formation of gullies or landslides (Nicu *et al.* 2022; 2023; 2024), similar to other polar and mountain areas. Studies conducted on the scale of the entire Arctic are noteworthy (e.g. Lützow *et al.* 2023; Makopoulou *et al.* 2024). A feature of this type of work is the relatively easy creation of large-area databases using specific, uniform criteria, usually based on detailed field mapping instructions (e.g. Fell *et al.* 2008).

However, there is no appropriate material to which contemporary statistics could be related, primarily when the recognised landforms are not assigned an age. There are also visible differences resulting from the method of collecting information on the landforms, which in the traditional approach was not separated from geological observations and measurements, and their authors knew the research area perfectly well. However, the effects of conventional geomorphological mapping were often limited to certain areas or were performed by geologists/geomorphologists guided by different principles. As a result, there is a gap in knowledge about past extreme events before aerial photography, especially when considering uninhabited areas.

This paper aims to provide basic geomorphological information on the effects of two past extreme events in Wedel Jarlsberg Land, on the western coast of Spitsbergen – the outflow of mud-debris-flows from the neotectonically uplifted Steinvik Valley and a potential landslide that delivered rock material to the foot of the Jens Erikfjellet massif. Specific landforms have been identified, which have not been precisely characterised in the literature. The situation in the Steinvik Valley was observed by Jahn (1967), and his report was repeated by André (2017), although the given information was not precise in light of current knowledge. The connection of the debris from Jens Erikfjellet with extreme events has not been associated so far. Despite their considerable size, both landforms were not taken into account by the authors of detailed geological maps made in the study area (Birkenmajer 1990; Czerny *et al.* 1993), who were interested in the diversity of the occurrence of solid rocks, not the origin of Quaternary sediments. Also, the authors of the geomorphological map of this area (Karczewski *et al.* 1984) did not see the effect of extreme processes in them. The premise for taking up the subject is the fact that although an intensification of geomorphological processes is currently observed in the study area (Owczarek *et al.* 2014), none of them is comparable in scale to the documented events that took place before the period of contemporary, intensive climate change in Svalbard.

Methods

The presented material is based on field mapping conducted in the summer (July–August) of 2011 and 2012. The observations were supplemented by analysis of currently available digital data, including an orthophotomap generated in the Metashape program (Agisoft LLC) based on aerial photos purchased from the Norwegian Polar Institute and ArcticDEM v.4.1 (Porter *et al.* 2022) with a resolution of 2×2 m. The DEM was corrected based on elevation data from a topographic map to equalise the sea level to the zero height value and other elevations in proportion to the average height difference found for the highest peaks.

In the field, additional oblique photos of the studied area were taken from the surrounding peaks. They allowed for the transformation of some images into orthophotomaps to illustrate the shape of selected landforms better. To register images in the UTM33N coordinate system, photo points were used – 5 bright sheets placed in the field, the position of which was measured by a GPS receiver (Trimble GeoXT) with a differential correction, giving a measurement accuracy of 10–30 cm. This work was carried out when aerial mapping techniques using UAVs were not widely available.

A Schmidt hammer type N (Proceq) was also used to check the relative age of the rock debris deposited below the Steinvik Valley mouth. Rock blocks with diameters greater than 1 m were selected for measurements, distinguishing their lithology. This activity aimed to check whether separate levels of the alluvial fan have the same or different ages. The values of the rebound of a metal pin from the rock surface, converted into force units, can be related to the resistance of the rock surface to damage (Goudie 2006; Niedzielski *et al.* 2009). The rock weathering level is assumed to increase with time, and the rebound values should decrease. Due to the geological settings, three lithologically different types of blocks were tested, 50–70 of each type at two levels of the alluvial fan.

Study area

The study area is located on the western coast of Spitsbergen, north of Horn Fjord and south of the eastern part of Torellbreen, the largest glacier of Wedel Jarslberg

Land (Figure 1). This is an area intensively explored since 1956 by Polish researchers (Zwoliński *et al.* 2013), who later established polar stations on Isbjørn Bay in Hornsund and at the moraine of the Werenskiold glacier – Baranowski Polar Station.

The Greenland Sea coast of this part of Spitsbergen is formed by the Hecla Hoek Succession rocks, predominantly greenstones, mica schists, amphibolites, and quartzites, assigned by the authors of the geological map (Czerny *et al.*, 1993) to four separate groups depending on age (middle and upper Proterozoic) and location. A complex of raised beaches (Birkenmajer 1960; Jahn 1968; Karczewski *et al.* 1981a) was formed along the coast, composed of marine gravels on a rocky base (Strzelecki *et al.* 2017). Inland, a mountain range rises to heights averaging 500–950 m a.s.l. It is cut by wide valleys, some of which remain glaciated (Błaszczyk *et al.* 2013). Smaller valleys with limited snow accumulation are not glaciated or consist of glaciers in the final recession phase (Wołoszyn & Kasprzak 2023). The terrain surface is covered with moraine deposits and weathering products in periglacial conditions: blockfields, debris, and finer -grain material, commonly subject to solifluction and frost sorting. Outside the zones of water impact in the taliks, the ground is perennially frozen (Kasprzak *et al.* 2017; Glazer *et al.* 2020; Kasprzak & Szymanowski 2023).

Local climate conditions are determined by measurements conducted continuously since 1979 at the Hornsund Polar Station (10 m a.s.l.). Since the beginning of measurements, mean annual air temperature (MAAT) has increased by more than 4 °C at an average rate of 1.14 °C per decade (Wawrzyniak and Osuch, 2020). Although in the measured multi-year period, MAAT has a value of −3.7 °C, in 2016, MAAT was recorded at a level of +0.3 °C (*Meteorological bulletins*… 2009–2023). The highest air temperature, 16.5 °C, was noticed on July 25, 2020. An increase in rainfall efficiency is also observed. On September 18, 2017, the highest daily rainfall was recorded, with an amount of 73.5 mm, higher than the previous record from September 2, 2012 by 13.7 mm. The average annual rainfall is 477 mm. In 1979–2023, it ranged from 230 mm in 1987 to 805.5 mm in 2016.

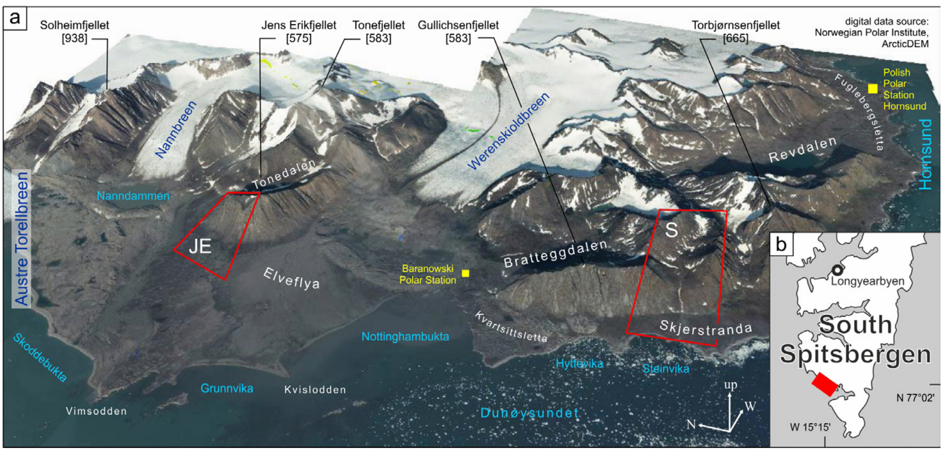

Figure 1. Study area (a) on the coast of South Spitsbergen (b): JE – Jens Erikfjellet area, S – Steinvikdalen (valley).

Results

Steinvik Valley

The Steinvik Valley has not been the subject of detailed geomorphological mapping, although it is included on the geomorphological map of the Horn Fjord area at a scale of 1:75,000 (Karczewski *et al.* 1984). It attracted the attention of geomorphologists after discovering marine gravels at its mount hang at a height of over 200 m a.s.l. (Jahn 1959). An alluvial fan was also identified below (Jahn 1967), but no more detailed research was conducted into the valley. In the summers of 2009–2011, hydrological and hydrogeological measurements were carried out here to identify the water's chemical and isotopic composition in the active layer above the permafrost table (Rysiukiewicz *et al.* 2023).

The Steinvik Valley is 2 km long, with a floor width of up to 250 m and a distance of up to 400 m between opposite mountain ridges. The valley bottom runs E–W and opens towards the sea coast (Figs 2 and 3). The bedrock is formed by Proterozoic metamorphic rocks classified by Czerny *et al.* (1993) as the Eimfjellet Group. The course of the upper part of the valley closely follows the lithological boundaries. The northern slopes of the valley are formed mainly by mica schists, its axis by varieties of amphibolites, and the southern slopes by quartzites.

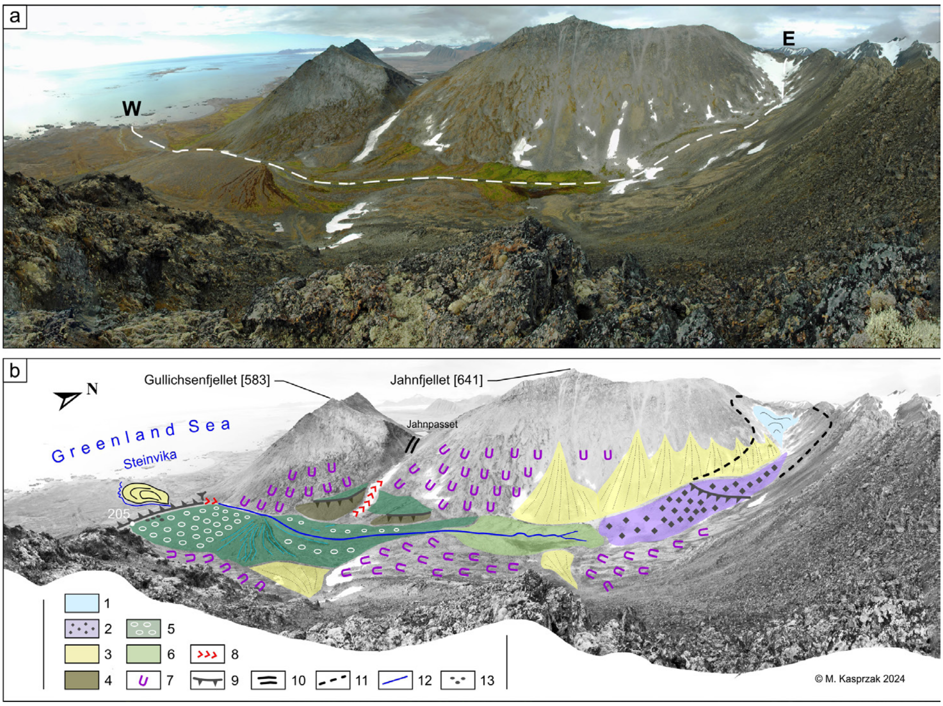

Figure 2. Steinvikdalen: (a) panoramic view based on a series of photos derived by M. Rysiukiewicz, section W–E in figure 3f; (b) geomorphological simplified sketch; 1 – glacier in deep recession phase or firn, 2 –coarse-grain glacial deposits (till and boulders) over bedrock, 3 – taluses and alluvial fans, 4 – bedrock, 5 – uplifted marine terraces, partially with pattern ground, 6 – wetland, 7 –solifluction-modelled slopes, 8 – ravines, 9 – main morphological edges, 10 – pass, 11 – LIA trimline, 12 – river channel, 13 – exposed marine cobbles.

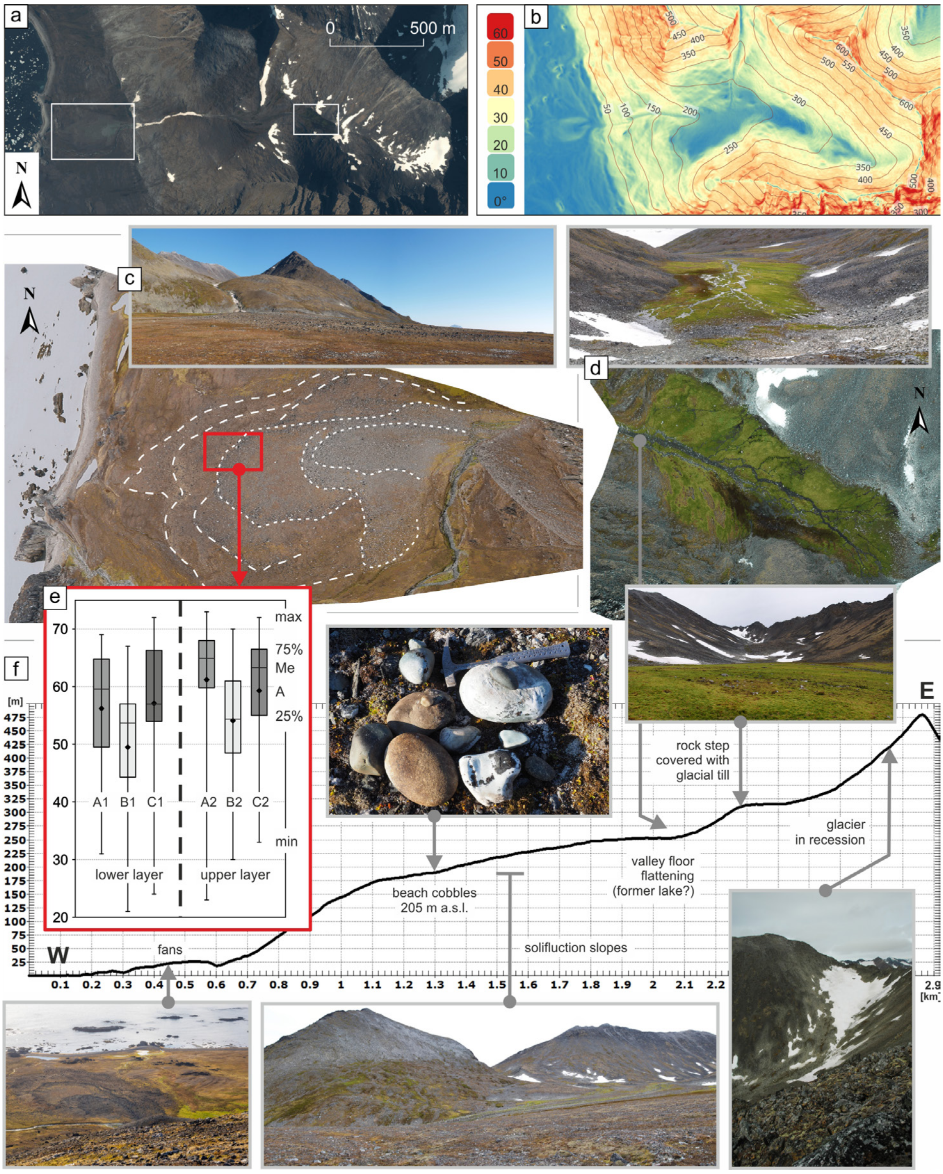

Figure 3. Landforms and sediments of Steinvikdalen: a – orthophotomap with framed areas shown in sections c and d; b – slope map; c – alluvial fan with marked two different generations of debris on which Schmidt hammer measurements were carried out (e); d – flattening of the valley bottom; e – results of measurements with the Schmidt hammer of blocks (quartzites, mica schists, amphibolites); f – longitudinal profile of the valley and its geomorphological features.

The longitudinal profile of the valley contains two distinct terrain steps (Figures 3b and 3f), probably of neotectonic origin. However, geologists did not interpret this as such when mapping this area (Czerny *et al.* 1993). The shape of the valley floor and the finds of marine cobbles prove that it contains two levels of marine terraces, raised to heights of 200–210 and 220–230 m a.s.l. Marine gravels were not found in the highest level of the valley bottom 300–310 m a.s.l., possibly due to their weathering. Above the valley head is a patch of firn and a debris cover, hiding the remains of glacial ice. The trace of the small glacier, which evolved in the past, is a coarse-grained till covering the bottom of the highest section of the valley and a weakly outlined trimline on the slopes. The trimline descends, reaching the valley bottom in the area of the rock step (Figure 2b). It marks the maximum extent of the glacier during the LIA, the scale of which does not differ from the small glaciers of the neighbouring valleys (Wołoszyn & Kasprzak 2023).

Based on the terrain features and surface moisture differences, it can be assumed that in the past, a shallow proglacial lake with a surface area of approx. 0.022 km^2 (Figures 2 and 3d) existed in the Steinvik valley, the bottom of which was at a height of approx. 250 m a.s.l. The lake could have been emptied rapidly under the episodes of glacier degradation, a type of slush flow resulting from melting snow and ice or snow avalanches descending the steep slope of the valley. Evidence of the rapid nature of the water outflow is the alluvial fan formed below the valley mount (Figures 2b and 3c), continuing towards the sea. It was not recognised on the geomorphological map of the Hornsund area (Karczewski *et al.* 1984), on the geological map of Birkenmajer (1990), it was incorrectly marked as an outcrop of crystalline rocks, and on the map of Czerny *et al.* (1993), it was ignored. It is a sediment of debris cones lying on an older accumulation landform, covering an area of 0.067 km^2 (Figure 3c). The described complex of fans rises to 8–10 m above the terrain surface. Based on the orthophotomap made, at least six separate cones can be distinguished here. Differences in the degree of weathering of the rock material forming them are noticeable.

The Schmidt hammer was used to check the age separation of the block-boulder-debris material between two levels of the fan, where the weathering contrast of rock elements is evident (Figure 3e). This demonstrated significant differences in the mechanical resistance of blocks within three lithological groups A–C (quartzites, greenstones, and mica schists), as presented in the box plot (Figure 3e). The interpretation of this result suggests that the flood episodes occurred over a significant time interval, likely thousands of years.

Jens Erikfjellet massif

The Jens Erikfjellet massif (575 m a.s.l.) mainly comprises greenstones and greenschist (Czerny *et al.* 1993). At its foot are accumulative landforms composed of debris with a coarse fraction. Over 40 years ago, they were the subject of consideration by a team of geomorphologists (Karczewski *et al.* 1981b). At that time, they classified all footslope accumulation landforms as nival moraines, unaware of the formation process of rock glaciers, including most of the sites they described (Hartvich *et al.* 2017). The best example is the rock glaciers at Hytte Bay (Figure 1). They also did not see the effects of extreme mass movements.

At the foot of the Jens Erikfjellet massif, in addition to the usual taluses, the proximal parts of which have turned into rock glaciers, there is also a convex terrain of a different origin (Figures 4 and 5). On the strongly weathered surface of the marine terrace remnant, rock material is deposited, rising to 30 m above the terrain surface (Figure 5a). The height of the terrace remnant reaches 16–18 m a.s.l. and more, rising above the surrounding level of the terrace 8–12 m a.s.l., which was not indicated in the study of Karczewski *et al.* (1981a). Due to the small tonal diversity of the orthophotomap (Figure 4a), it is difficult to determine the extent of the debris. The debris is arranged in fans directed from the slope towards the west. The sediment consists of blocks and boulders exceeding 5 m in size, sometimes resembling a tors (Figure 4d). Observations of random foliation directions prove that boulders are not a stable bedrock element but haphazardly scattered. The debris is partially separated from the slope and contemporary scree deposits by distinct depressions.

The western part of the Jens Erikfjellet slope also has certain features that distinguish it from its surroundings. In the described section, its relative height reaches 440 m. The shape of the slope is convergent (Figure 4b). Directly above the accumulation landforms, up to 300–350 m a.s.l., the slope morphology is not diverse, in contrast to its neighbouring parts (Figure 4d). It resembles a slip surface for sliding rock masses before the scree development. It can be assumed that this is a scarp of the old landslide, and the debris below is partly colluvium formed due to a sudden movement. It cannot be

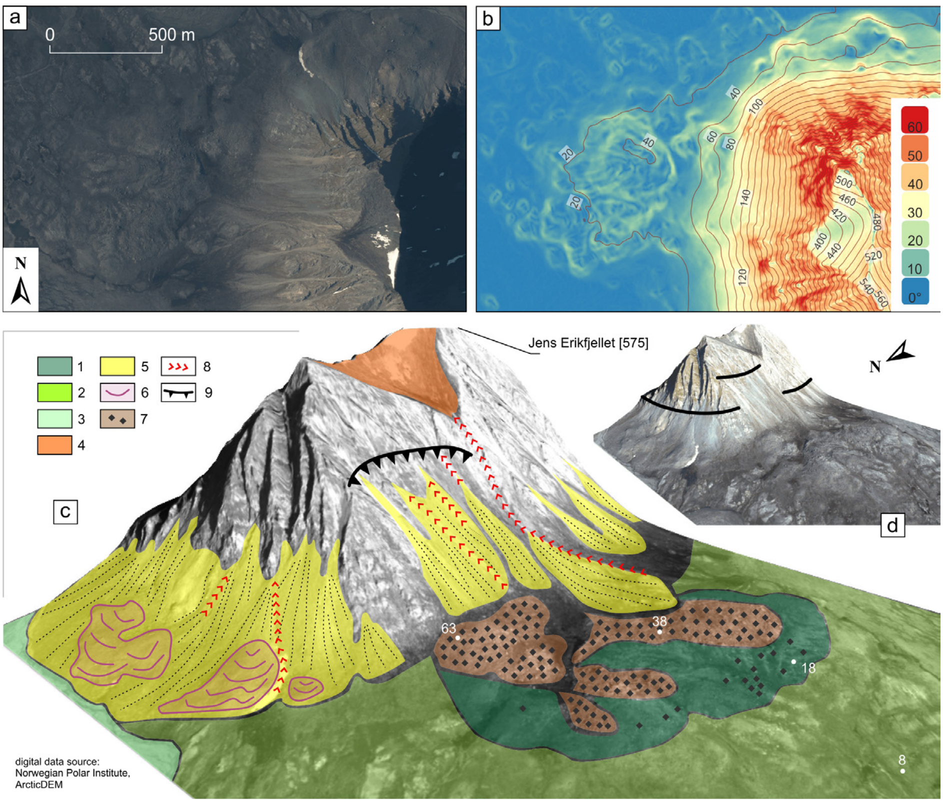

Figure 4. Landforms in the Jens Erikfjellet area: a – orthophotomap; b – slope map; c – simplified geomorphological sketch; 1 – terrace 16–18 m a.s.l., 2 – terrace 8–12 m a.s.l., 3 – Vimsa River bed, 4 – denudation surface, 5 – taluses, 6 – rock glaciers, 7 – colluvium, 8 – debris flow channels with lateral levees, 9 – probable landslide scarp; d – schematically marked differences in the height of the slope with diverse morphology.

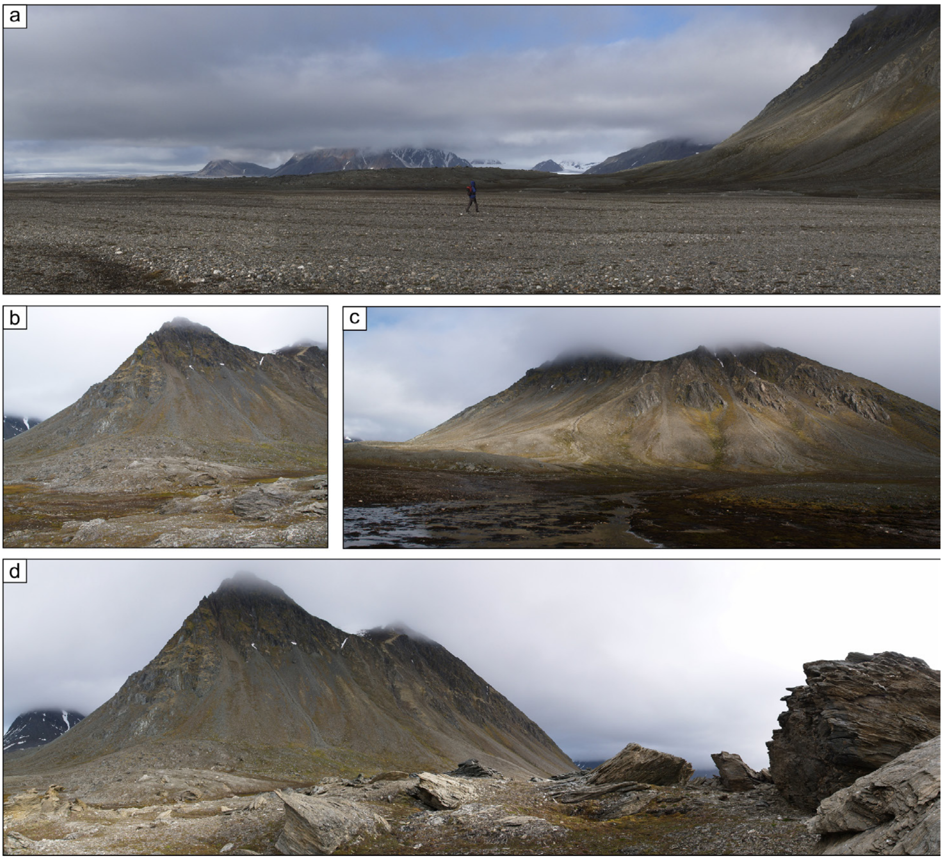

Figure 5. The debris accumulation under the Jens Erikfjellet slope: a – general view from Elveflya towards the north, b – generations of rock debris, c – differences in slope morphology, d – scattered, strongly weathered blocks and boulders.

ruled out that a large-scale rock avalanche also occurred on the slope in addition to the landslide. The indicated area requires a deeper analysis and verification of the proposed scenario.

Discussion

The landforms described in the previous chapter witness extreme events on a scale not observed in recent decades on Wedel Jarlsberg Land, between Horn Fjord and Austre Torell Glacier. In light of the collected materials,reconstructing their course and timing is challenging without more detailed studies, which is not the direct purpose of this study. Nevertheless, a few facts can be presented for discussion.

The alluvial fan, first described by Jahn (1967) as a slushflow effect from the Steinvik Valley, was formed by several outflows containing a large amount of debris. In the Steinvikdalen, apart from the ravine developed by the draining stream, no significant traces of erosion or a moraine barrier could have been breached, as is usually the case in GLOFs. The source of the debris could have been the eroded till and solifluction covers, as well as the sediments of a shallow lake filling the depression of the raised marine terrace. This scenario is supported by an unnaturally flat and saturated part of the valley in front of the rock step and the local glacier at its maximum LIA stage. The lack of contemporary growth of the alluvial fan and the cessation of rapid outflows are potentially related to the filling of the lake. There is not enough water here to be pushed out as a mudflow. In an alternative scenario, glacier deglaciation reduces runoff, which could have episodically formed debris-mud flows in the past.

The alluvial fan rests on a system of 5 marine terraces rising 30–40 m a.s.l. (Karczewski *et al.* 1981). Their dating remains an open issue. Attempts were made to determine the age of the terraces using ^{14}C determinations of shells, whale bones, plant remains in fossil soils and driftwood, and the thermoluminescence method. The material found in the sediments of the most extensive terraces 7–9 and 8–12 m a.s.l. was determined to be 7,690 ± 90 – 7,230 ± 50 B.P. (Chmal 1987) and 16,000 ± 2,500 – 12,000 ± 1,800 BP (Lindner *et al.* 1991), respectively. Radiocarbon dating of whale remains and driftwood on the surface of the lower beach level 4.5–6 m a.s.l. suggests that it was formed 1,000–800 years ago (Lindner *et al.* 1991). The alluvial fan developed after the formation of the terrace system and is younger than it. Unfortunately, the authors of the cited papers determined the ranges and heights of the marine terraces in the study area in different ways. This problem should be solved in the future by objectively distinguishing the terrace levels using high-resolution DEM and geomorphometric tools. Determining the absolute age of the marine terrace levels is difficult because the rate of neotectonic uplift is very diverse on Svalbard. Perhaps better data in this respect will be provided by dating rocks using cosmogenic nuclide methods. It should also be added that the analysed alluvial fan was formed before 1936. On oblique aerial photos taken at that time (toposvalbard.npolar.no), one can see a stream flowing around this landform, i.e. a situation similar to the present one.

More recent reconstruction of landscape evolution close to the study area focused on the Horn Glacier (Osika *et al.* 2022). It indicates significant environmental changes that occurred in the Early and Middle Holocene. Local glaciers retreated at that time, 10.9 and probably around 1.3 ka cal. BP, respectively. This means that Svalbard experienced many changes during the Holocene that affected the activity of hydrological and geomorphological processes. Due to the significant variation in the degree of weathering of debris, it is difficult to reject the conclusion that the fan below Steinvik Valley was formed at different times of substantial environmental changes. It is also possible that its genesis is more complex and results from the action of other processes (e.g. older moraine degraded by sea waves?).

Today, we can observe the intensive environmental changes in the slope system. Landslides, debris flows, and erosive cutting of the surface are facilitated by thawing of the ground and climate wetting. On Svalbard, snowfall gives way to rain, which can occur even in winter (Nowak & Hodson 2013). Compared to previous decades, more rapid thaws and increased precipitation with high intensity are being recorded, which have a thermo-erosive effect on the ground (Christensen *et al.* 2021). Precipitation efficiency can reach even half of the annual total, as recorded on August 13–16, 2013, in the Bellsund area (Kociuba 2023). At the same time, the most severe episode of shallow landslide and debris flow activation observed by people occurred near Longyearbyen after heavy rainfall on July 10–11, 1972 (Larsson 1982). It was determined then that the risk of landslides and flows increases significantly with rainfall intensity higher than 2 mm per hour. However, the most spectacular sudden changes in the Svalbard landscape result from GLOFs (Wołoszyn *et al.* 2022) and deep-seated landslides (Kuhn *et al.* 2019).

The issue of rock debris interpreted with some caution as landslide colluvium and potentially accompanying rockfalls in the Jens Erikfjellet massif also requires explanation. The author believes it is sediment after an event or series of events in the distant past. The resulting colluvium could also have been, at least partially, subjected to the action of sea waves. This can explain its fragmentation. The colluvium deposition could have been the direct cause of the preservation of the higher marine terrace. At the same time, in the surrounding area, this level underwent denudation. The older age of the colluvium is evidenced by the high degree of weathering, much more than a weathering effect on taluses at the slopes of Jens Erikfjellet. Significantly, the rock elements of the colluvium also exceed the grain sizes of scree, which is forming contemporarily. No detailed measurements were made in this respect, but this situation is easily noticeable. The largest boulders rest far from the slope. This, in turn, is currently modelled by rock falls and snow avalanches, leading to taluses growth (Senderak, 2023). This rate was determined by Eckerstorfer *et al.* (2013) at 0.2–14 mm per year, examining similar slopes in the central part of Spitsbergen. Active geomorphological processes have not yet led to a varied slope topography on the section interpreted as a potential landslide scarp.

Any determination of the landslide time without specialist dating will remain risky. This event could have occurred after forming the 16–18 m marine terrace and probably earlier than the development of lower terrace levels. In the central part of Spitsbergen, in Billefjorden, attempts were made to date the activity of large, deep-seated landslides based on organic remains in the depressions of fault scarps (Kuhn *et al.* 2022). It was proven that they have a postglacial age of at least 6 ka. A similar age to other large landslides, including those on the slopes of Jens Erikfjellet, cannot be ruled out. In these considerations, not only the climatic factor is essential, but also the tectonic factor, which could have played a triggering role, especially since even today, earthquakes in Svalbard reach M=6.1 (February 21, 2008; earthquake.usgs.gov). The Hornsund area is a moderately active seismic area related to the geotectonic situation in the Barents Sea shelf, isostatic adjustment and stresses induced by glacier movement (Górski & Teisseyre 1991; Mitchell *et al.* 1990; Stemberk *et al.* 2015).

The presented analysis provides only some basic information, provoking more questions. The author declares that further work will be undertaken to clarify the details discussed above. This will be possible by reopening the issue of the age of the elevated sea terraces in the Hornsund area and by using better research methods, including terrain models created photogrammetrically from drone photos (SfM-UAV) and absolute dating of organic and mineral sediments according to the latest standards.

Conclusions

The summary of the presented material will be several basic theses based on field observations, analysis of digital materials and the discussion:

1. On the coast of Wedel Jarlsberg Land, between (the glacier) Austre Torellbreen and Horn Fjord, some landforms indicate extreme geomorphological events on a scale not observed in this area today.
2. In the Steinvik Valley, debris-mud flows were formed, the effect of which is a multi-level alluvial fan on the surface of raised marine terraces below the valley mouth hung 200 m above. The debris-rich flows could have been caused by

the expulsion of water from a shallow proglacial lake due to episodes of rapid thawing of ice and snow or snow avalanches. Other morphogenic factors cannot be ruled out. The age of the fan sediments is difficult to determine without specialist dating, but based on current knowledge, it can be assumed that their oldest generations were formed later than 7 ka BP.

3. A section of the slope in the Jens Erikfjellet massif is morphologically different from the rest. At its foot, there is strongly weathered debris with blocks and boulders larger than in the surrounding scree deposits and debris glaciers. This situation can be considered the effect of a large-scale landslide, possibly combined with rockfalls. The colluvium preserved a higher level of the marine terrace. The potential landslide event took place in the postglacial period.
4. The presented landforms created as a result of extreme events are evidence of environmental changes in the Holocene, at least as significant for the landscape evolution as the currently recorded ones related to the rapid warming of Svalbard.

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Research article

The causes and consequences of 21st century global sea level rise on Morecambe Bay, U.K.

Holly W. Watson[a] & Alun Hubbard[b,c]

Abstract

As 21st Century anthropogenic carbon emissions increasingly perturb Earth's atmospheric composition, an accessible understanding of how greenhouse gas driven climate change manifests on natural and human systems becomes crucial to public awareness. Here, we investigate the contemporary causes and consequences of global sea level rise (SLR), focusing on the impacts of coastal flooding on Morecambe Bay, Northwest England. We review and summarize current literature regarding terrestrial ice loss and ocean thermal expansion, delving into the uncertainties and assumptions. We define three SLR scenarios through to 2100 AD: 1) the Green Road (GR: 0.44m SLR), 2) Business as Standard (BS: 0.77m SLR) and, 3) Impending Doom (ID: 1.55m SLR). We adjust these SLR scenarios for regional isostatic and gravitational effects, and map them to local flood projections for Morecambe Bay. Even under the most optimistic - GR - scenario, we find permanent flooding is inevitable by 2100, necessitating adaptation strategies. Under BS and ID scenarios, significant inundation of industrial and residential areas is projected, with permanent displacement of up to 15000 homes and moderate to severe disruption to national transport networks, including the UK's West Coast rail-link. Moreover, national power and industrial infrastructure at Heysham Nuclear Power Station and BAE Systems, Barrow would be impacted under our worse-case scenario. Directed mitigation and informed decision-making are crucial for minimizing economic and social impacts, emphasizing a need for public awareness of the future impacts of environmental change and its local manifestation.

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Introduction

Climate change is an inherently societal problem both in its causes and consequences. The trajectory that Earth's near-future climate will take radically depends on how effectively global greenhouse gas (GHG) emissions can be managed through decarbonization and how well society can adapt to the abrupt climate transition already underway. Much stress is placed on individuals, and it is understandable that many, particularly the younger generation, can become overwhelmed by it. This outlook is partially due to the confusing, contradictory manner by which climate change and its impacts are reported in the media: often in the bleakest terms that invokes a sense of futility or even nihilism and, at the opposite end of the political spectrum, denial, along with accusations of conspiracy.

In this paper, we wish to summarize the current state-of-knowledge on climate change and global sea-level rise from the most recent peer-reviewed scientific literature. We will try - in layman's terms – to review what is known with certainty and is well constrained, but also to outline the main limitations and uncertainties regarding future model projections. Our intention is to broaden the discussion and the language to include those who may have found the science impenetrable, providing the reader with accessible but robust science, and with sufficient knowledge to inform opinion and to make positive, personal decisions. We then define three potential future climate scenarios, and through application of accessible flood-risk mapping tools, will illustrate how sea-level rise (SLR) manifests on flooding across the locality of Morecambe Bay, NW England to the end of this century.

Having made this grandstand claim, we find that climate change and SLR is an extraordinarily complex and nuanced topic. There are myriad drivers, controls and sources contributing to an increased overall volume of water contained within the Earth's oceans, that ultimately results in what is termed *eustatic SLR* (Figure 1). Moreover, there are modulating feedback processes that can reduce or amplify SLR across regional and

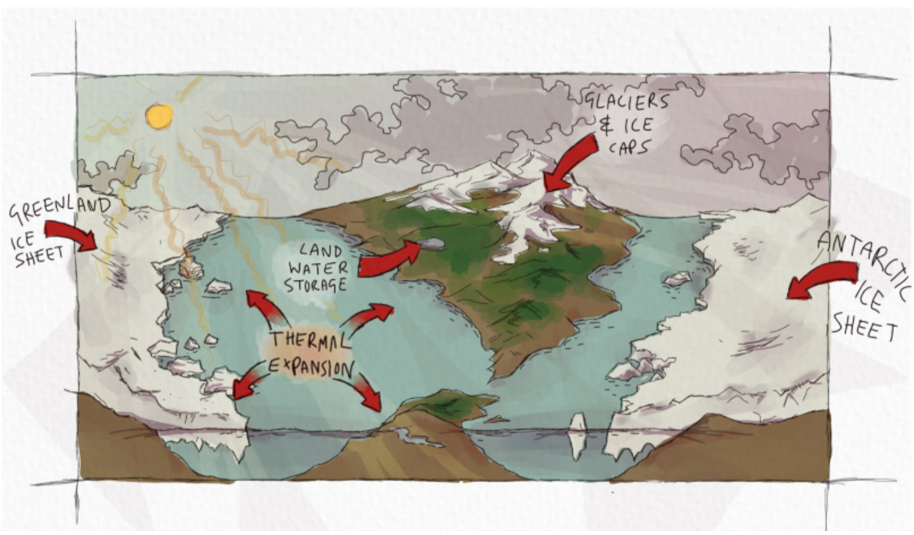

Figure 1. Schematic of primary sources of global (eustatic) SLR: Thermal expansion (42%), Polar Ice Sheets (36%), Glaciers and Ice Caps (20%), and Land Water Storage (2%). Polar Ice Sheet loss is increasing and set to surpass losses from other sources in the next decade (original artwork - this study).

local scales. As part of our study, we will also briefly discuss these regionally interacting causes and, by illustration, consider how they can actually moderate future SLR-driven flooding on Morecambe Bay. We finally assess the impact of the three flood-risk scenarios on local communities and discuss the wider consequences for regional and national transport hubs and networks, power and industrial infrastructure.

We find that even under the most optimistic scenario there will be some, but not catastrophic, permanent flooding across Morecambe Bay. Hence, preventative adaptation strategies, such as the construction of coastal defenses and managed retreat/land-use changes, would be a pragmatic solution to maintain key infrastructure, industry and protect communities. However, under less optimistic scenarios, where emissions targets to limit the temperature increase to 1.5°C above pre-industrial levels in accordance with the COP21 (2015) Paris Agreement are not met (as per our current trajectory), then levels of coastal inundation increase significantly. Such flooding severely impacts residential, commercial and industrial zones at major conurbations where permanent displacement and disruption occurs including to national transport networks and power generation infrastructure. In these cases, mitigation strategies could limit the economic and social impacts but at enormous cost, emphasizing the importance of public education, awareness and preventative action to transition and attain net-zero economies within the next decades.

Current understanding

Our review of eustatic SLR follows the roadmap of the sea-level "jigsaw" (Palmer *et al.* 2018), where each component of SLR is calculated separately before being summed up along with regional adjustment offsets (Figure 2). The main drivers are influenced by multiple variables, themselves modulated by positive and negative amplifiers and feedbacks. The first-order control on eustatic SLR is atmospheric Carbon Dioxide (CO_2) concentration - the primary GHG - and its impact via global radiative forcing which results in planetary temperature change.

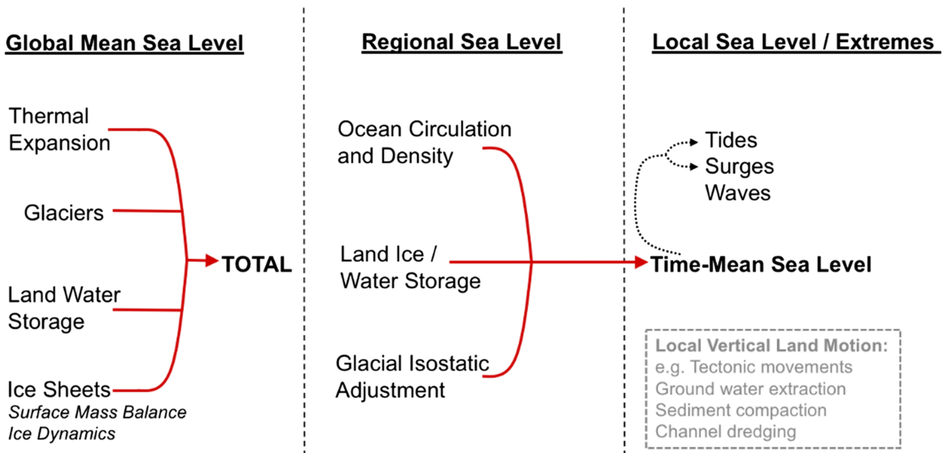

Figure 2. Unpacking the sea-level jigsaw: the multiple global components that determine eustatic SLR (from Palmer *et al.* 2018, CC BY 3.0 license).

The greenhouse effect and global temperature

There exists a near linear correlation between cumulative GHG emissions and global temperature rise which is now unequivocally recognized to be driven by increased anthropogenic activity related to fossil fuel combustion (IPCC 2021a). The link between atmospheric CO_2 concentration and global temperature was first identified in the 19th century (Tyndall, 1861). Since the onset of the industrial revolution, the concentration of GHGs in the atmosphere has increased at a rate unprecedented in the last 0.8 Ma (IPCC 2021a). Yet, despite these strong causal links, long-term global climate forecasting remains an exceedingly difficult task.

The Earth's atmosphere, oceans and land-surface are inherently complex systems - with interdependent flows of mass and energy operating across multiple scales through widely different mediums – all of which have to constrained and modelled in four dimensions. Moreover, how future climate evolves is dependent on multiple human actions that compound the myriad natural "background" processes, many of which we do not fully understand. Primarily, the Earth's temperature varies directly in response to atmospheric GHG concentrations, which in turn, is partially influenced by anthropogenic emissions as well the natural carbon cycle. Because of this incipient uncertainty, climate scientists have defined a system of potential "future pathways" by which to model climate projections, the leading proponent of which is the Intergovernmental Panel on Climate Change. The IPCC is a scientific body established by the United Nations in 1988, with 195 member states to monitor the state and evolution of climate change, and the aim to inform global policy makers.

The most recent report - IPCC Assessment Report 6 (AR6 – IPCC 2021a) uses a system of shared socioeconomic pathways (SSPs), defined by specific CO_2 emissions and their associated radiative forcing. The concept of an SSPs deviates slightly from previous IPCC reports as well as other scientific and government bodies (e.g. UK Meteorological Office - Palmer *et al.* 2018) who use Representative Concentration Pathways (RCPs). While they have key differences - notably SSPs are applied with added context of what policies and change are associated with each scenario - both SSPs and RCPs use similar broad parameters based on radiative forcing, allowing for direct intercomparison (Figure 3).

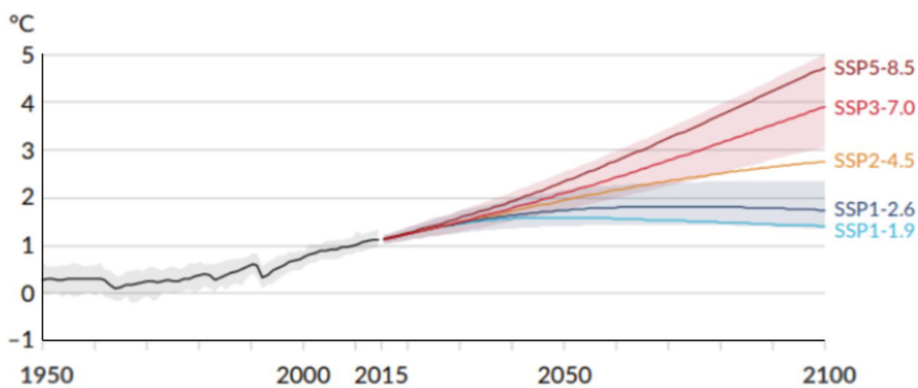

Figure 3. Global surface temperature change relative to 1850-1900 obtained by combining CMIP6 simulations with observations based on simulated warming (from IPCC 2021a, Figure SPM.8a).

IPCC Climate projections are calculated using the latest generation of General Circulation Models (GCMs) and, most recently, rely on the Coupled Model Intercomparison Project Phase 6 (CMIP6) as the leading ensemble of temperature forecasts. IPCC-AR5 did though, use CMIP5 projections (IPCC 2013) which pose an issue in comparing different SLR projections, as CMIP6 forecasts predict a greater temperature range than CMIP5 (Payne *et al.* 2021). This in turn has ramifications on the primary findings of, for example, UN and other Governmental reports which may rely on outdated RCP-based (CMIP5) projections.

Despite the rapidly changing science and forecasts, the most recent CMIP6 and associated ice mass loss assessments demonstrate that we are tracking one of the worst-case IPCC (2021a) emissions scenario of SSP5-8.5 (Slater *et al.* 2020). These findings act to emphasize the importance of generating accurate regional SLR data, particularly for the upper-end predictions, to create adaptation strategies that effectively mitigate impact. It also serves as a warning to policy makers, as rapid temperature rise will accelerate SLR through rapid cryospheric retreat and ocean thermal expansion (IPCC 2021a), leading to extensive flooding and coastal inundation.

Increased temperatures through enhanced GHG emissions are also driving more extreme weather events - which yields more frequent and intense storms and precipitation, including for example, enhanced winter snowfall events which can offset ice mass loss (Bailey and Hubbard, 2025), or on the other hand, increase the risk of inundation within river basins (Bates *et al.* 2023). Temperatures are increasing almost four times faster across high latitudes than the global mean (Rantanen *et al.* 2022). Such warming is amplified through positive feedback mechanisms, such as albedo reduction across Greenland's dark zone causing its ice surface to absorb increased incoming radiation and enhancing melt (Ryan *et al.* 2017a).

The current rate of eustatic SLR of 4.6 – 5.5 mm per year is unprecedented over the last three millennia (IPCC 2021a). Well-established and documented casual mechanisms exist between global temperature rise and SLR (Palmer *et al.* 2018) and the four main contributors driving an increased volume of water in the oceans are: 1) thermal expansion of the ocean, 2) loss of polar ice sheets, 3) glacier retreat, and, 4) reduced land-water storage.

The polar ice sheets

The Greenland and Antarctic Ice Sheets (GrIS and AIS) store the equivalent of ~65 m of SLR between them and are the largest contributors to SLR, but are also the source of the greatest uncertainty (Shepherd *et al.* 2017; Figure 4; Figure 5). These uncertainties are attributed to poorly understood processes within ice sheet models (ISM), compounded by implicit limitations related to boundary conditions, resolution, and by an insufficient satellite remote-sensing archive that does not capture the timescales of internal variability in the climate-cryosphere system (Bamber *et al.* 2019). The relatively low levels of confidence in current ISM predictions, compounded by emerging potential amplifiers, such as hydrofracture-damage (Chandler & Hubbard, 2023) that could accelerate deglaciation and SLR - represent a significant wildcard.

Despite this, ISM skill and accuracy has improved remarkably from the first IPCC report (FAR - IPCC, 1990), when ice sheets were assumed to be static entities. The fourth report (AR4 – IPCC 2007) was the first to implement transient models of polar ice sheets, and the fifth report (AR5 – 2013) presented "dynamic" ISMs but those

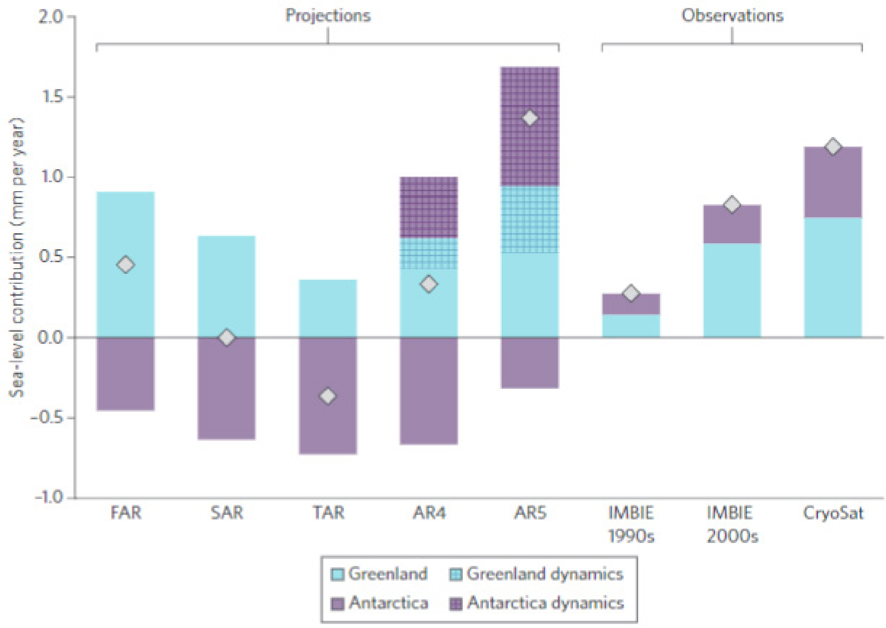

Figure 4. Mean global SLR contributions from polar ice sheets (mm/a). Blue and purple bars represent Greenland and Antarctica; hatching denotes dynamic contributions. Grey diamonds represent net contribution to eustatic SLR. FAR = first assessment report, SAR = second assessment report, TAR = third assessment report (from Shepherd and Nowicki 2017, with the permission from Springer Nature).

processes included were severely limited and heavily parameterized. More recently, a consensus has been attained from an observational perspective, and the Ice sheet Mass Balance Inter-comparison Exercise (IMBIE) delivered much-needed agreement revealing a direct relationship between temperature and SLR from the GrIS (IMBIE, 2020). The data from IMBIE tracks the past contributions of the GrIS and AIS through multiple satellite measurements, which have been directly compared with AR5 SLR models to validate and predict future contributions (see Figure 7). The IPCC AR6 (2021a) yield significantly different SLR outcomes compared to AR5 (2013), and such predictions will continue to evolve as ISMs and constraining data improve.

While there is a strong relationship between global warming and mass loss for the GrIS (IMBIE 2020), this is not the case for Antarctica (IMBIE, 2018). This is due to more complex processes operating in Antarctic as its mass loss is primarily driven by submarine melting and calving; its loss though is also largely counteracted by enhanced precipitation (Payne *et al.* 2021). Major uncertainties due to positive "dynamic" feedback processes - marine ice sheet and marine ice cliff instabilities - could though drive abrupt collapse of the West AIS with SLR contributions of 1m or more speculated (DeConto & Pollard 2016). Similar processes are also apparent at marine terminating sectors of the GrIS - such as in the NE at 79 Glacier, which is currently undergoing similar instability and frontal retreat, though the GrIS is generally considered to be less vulnerable than the Amundsen Sector of Antarctica.

Coupled ISMs are the primary method of determining future contributions from ice sheets, though there are notable shortcomings and challenges ahead. A recent alternative, that yields a minimum SLR commitment from the GriS was analytically determined by

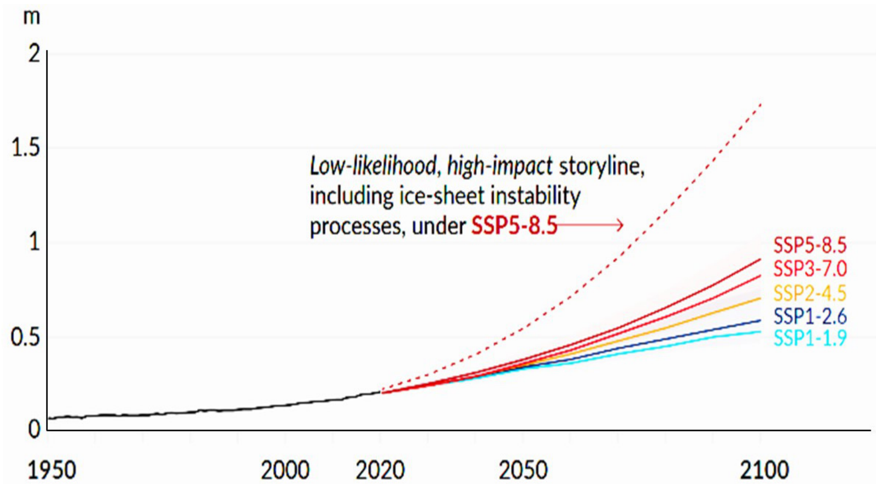

Figure 5. Mean global SLR relative to 1900. Historical observations from tide-gauges pre-1992, and from altimeter measurements thereafter. The dashed curve indicates the potential impact of ice dynamic processes that remain very uncertain, and this (dashed) curve does not constitute part of the likely range calculation (from IPCC 2021a, Figure SPM.8d).

Box *et al.* (2022). Their analysis - which calculates the ice sheet's disequilibrium with its 2000 to 2019 mean climate yields a conservative 27cm committed SLR that can be directly communicated to the public, though the approach does lack a timeframe.

The contributions from Greenland and Antarctica to SLR increased by a factor of four between 1992-2019 (IPCC 2021a). Global atmospheric and oceanic warming has driven these contributions either though ice sheet "dynamic losses" related to flow acceleration, thinning and retreat or from reduction in the surface mass balance (SMB) – the net sum of mass increase primarily through snow accumulation and mass loss through melt and sublimation (Hubbard *et al.* 2000), due to enhanced surface melt (Payne *et al.* 2021; Ryan *et al.* 2017b). From 1992 - 2018, SMB contributed to just over 50% of Greenland's net mass loss, and is attributed to human induced climate change with a direct relationship between warming and ice loss (IMBIE 2020).

Satellite ensemble studies reveal that Greenland is tracking the upper-end scenario of ice loss, with the most negative year in 2011, due to changes in cloud cover and air circulation (IMBIE, 2020; Slater *et al.* 2020; Box *et al.* 2022). There is a high confidence that these losses are attributed to human activity, and that the losses will continue into the 21st century under all emissions scenarios (IPCC 2021a; Figure 6). SMB changes will account for over 80% of future GrIS contributions (Goelzer *et al.* 2020), primarily due to atmospheric forcing, which is predicted to have a greater impact on surface melt than ocean forcing. During the last interglacial, temperature rise over Greenland was linked to peak SLR in the period, providing additional evidence of the link between temperature and GrIS mass loss (IPCC 2013).

While precipitation and snowfall has increased over the AIS since the 1970s - acting to offset SLR, the East and West, as well as the Peninsula ice sheets, have all lost ice at their retreating marine-terminating margins (IPCC 2021a). The Peninsula has contributed to SLR at an increasing rate from 1992 onwards due to ice shelf and tidewater glacier retreat, and the West AIS due to warm ocean driven undercutting where ice shelf thinning has induced the accelerated flow of the fast-flowing ice streams, such as at Thwaits and Pine Island Glaciers (IMBIE, 2018). In Antarctica, ice dynamics

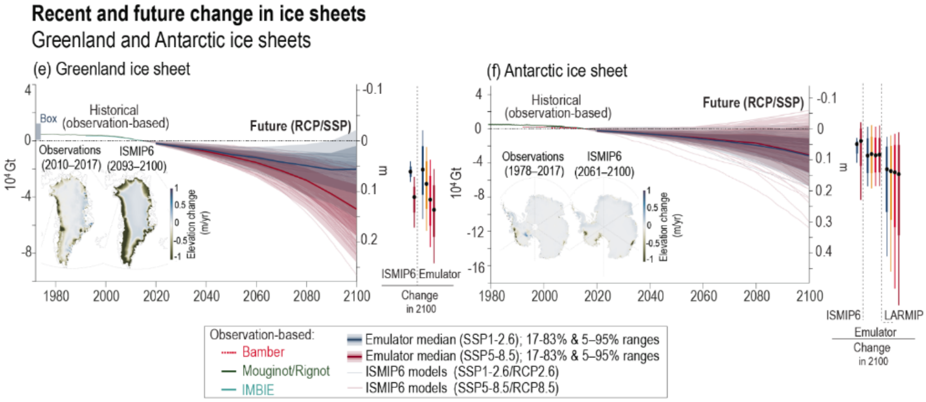

Figure 6. Projected ice sheet changes are shown a median, 5-95% range (light shading), and 17-83% range (dark shading) of cumulative mass loss and SLR equivalent from ISMIP6 simulations under SPP1-2.6 and SSP5-8.5 (shading and bold lines), with individual simulations as thin lines (from IPCC 2021b).

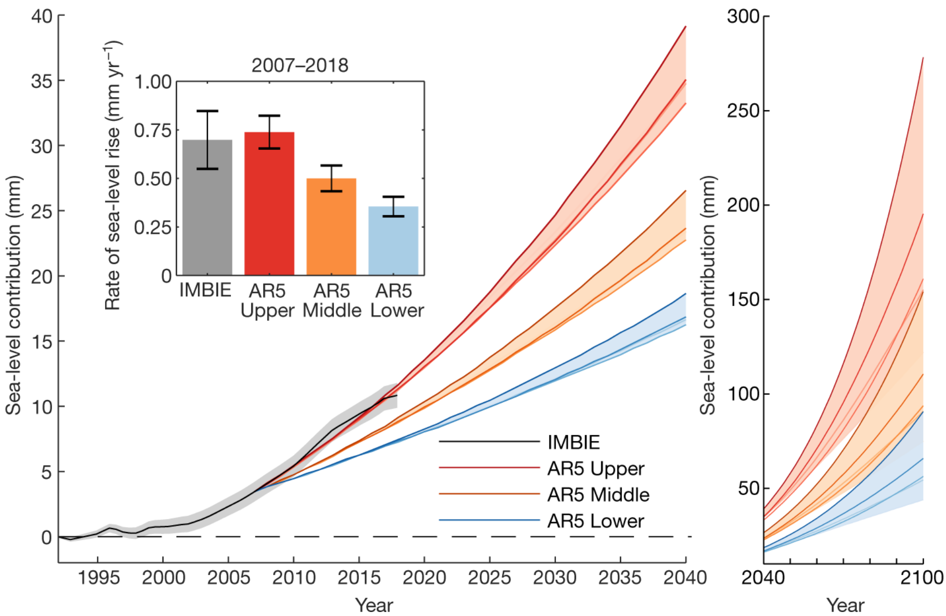

Figure 7. Observed and predicted mass changes and SLR contribution from Greenland according to IPCC AR5 projections from 1992-2040 (left) and 2040-2100 (right), including upper, mid and lower estimates of modelled SMB and rapid ice dynamic contributions. Darker lines represent pathways from the five AR5 scenarios in order of increasing emissions: RCP2.6, RCP4.5, RCP6.0, SRES A1B and RCP8.5 (from IMBIE team 2020, reproduced with the permission of Springer Nature).

are considered to be the dominant contributor to SLR, and hence become somewhat decoupled from actual warming (Payne *et al.* 2021). The positive feedback mechanisms: marine ice cliff and grounding line instabilities, introduce deep uncertainties into SLR predictions, especially related to contributions from the West AIS, which drive current AIS contributions to SLR at ~0.4 mm per year (IPCC 2021a). The uncertainties regarding the possible collapse of the Amundsen Sector with multimeter SLR (>1 m) are hotly debated, but are considered highly improbable, at least by 2100 (IPCC 2021a).

Thermal expansion and other controls

As the oceans warm, the density of its waters decreases (Oppenheimer 2019), yielding a linear relationship between the "thermostatic expansion" of the ocean and temperature rise (IPCC 2021). The rate of ocean warming has doubled between 1970 and 2017 along with the rate of thermostatic SLR, and is likely to continue responding to anthropogenic forcing for centuries to come (IPCC 2021a).

From 1971-2018, thermal expansion accounted for 42% of all SLR (Global Sea Level Budget Group, 2018). Due to good physical understanding, long observational records and well constrained boundary conditions, there is greater certainty and high confidence in predictions of its future eustatic SLR contribution (van de Wal *et al.* 2022). CMIP6 output is used to drive ocean thermostatic expansion forecasts and, whilst results are considered robust, the magnitude of SLR is dependent on the specific SSP and warming scenario applied (Oppenheimer, 2019).

Two further components contribute to global SLR: changes in the global inventory of glaciers and ice caps and changes in land-based water storage (Palmer *et al.* 2018). There are over 200,000 glaciers and ice masses globally outside of the Greenland and

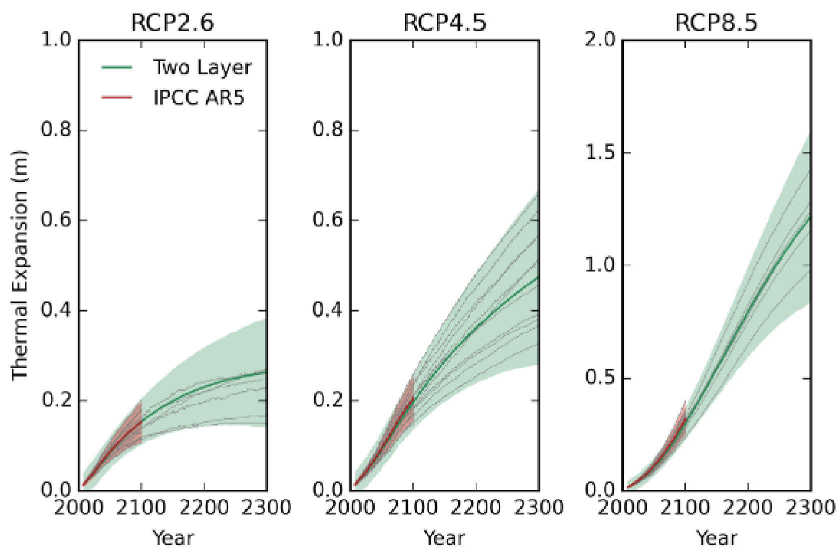

Figure 8. Global mean SLR associated with thermal expansion relative to baseline period 1986-2005. Time-series include i) 21 member AR5 ensemble (red – with shaded area indicating 90% confidence); ii) 14 member two-later model ensemble (green), and iii) individual CMIP5 projections (grey lines, table 2 - from Palmer *et al.* 2018, CC BY 3.0 license).

Antarctic ice sheets, covering ~706,000 km^2 with an estimated volume equivalent to ~0.324 m SLR (IPCC 2021a; Glambie 2025). The limited observational record of these glaciers has led to relative uncertainty in modelling future glacier contributions from specific glacierized regions such as Patagonia and Himalya, though aggregated global projections appear to smooth out regional variations and are more consistent with the results from regional-scale studies using more sophisticated models (Oppenheimer 2019). Though there is limited potential for SLR contribution from glaciers due to the relatively small net proportion of ice they store (Grinsted 2022), due to their smaller area and wider latitudinal range, they are highly sensitivity and have already undergone dramatic shrinkage in response to recent global warming, contributing ~0,75 mm SLR per year since 2000. Glacier response times vary from years to decades due to their widely varying thermal regimes and flow rates, refreezing of meltwater downstream, and this SLR contribution will likely remain roughly constant over the next 75 years (IPCC 2021a; Glambie 2025).

Land-water storage fluctuations include changes in surface water, ground water, soil moisture, snow and permafrost. They have primarily been attributed to increased irrigation in dryland agricultural areas such as mid-eastern Australia and mid-western USA, that have severely depleted ground water storage sources, though shrinkage of lakes is also linked to climate variability (Cazenave *et al.* 2012). These changes currently represent a relatively small proportion (<5%) of total SLR and are driven through both direct human impact, such as dams and the draining of groundwater, and indirectly though changes in the hydrological cycle (Cooley *et al.* 2021). Changes in land-water storage cause short term variation in sea level due to interannual changes in the water cycle, but also longer-term changes, especially related to the melting/drying of permafrost and decreasing surface moisture. Overall, there is low confidence in predicting some processes, such as long-term groundwater storage which are further compounded by uncertainties related to changing precipitation recharge and intensity (IPCC 2021a).

Future eustatic SLR scenarios

The sum of these four primary components yield the net change in ocean volume that drives eustatic SLR. Based on our review, we define three scenarios that encompass the best, the most likely and the potentially worst-case SLR outcomes for 2100 (Table 1):

1. The most recent AR6 low emissions scenario SSP1-2.6, where warming is limited to below 2°C in accord with the Paris (COP21) Agreement - we refer to as the "Green Road" (GR). Here, net-zero emissions are attained by the second half of this century, yielding 0.44 m of SLR that plateaus by this time.
2. The AR6 "Business as Standard" (BS) scenario SSP5-8.5 associated with 0.77 m of SLR due to a 4.4°C rise under a doubling of current GHG emissions.
3. We include an "Impending Doom" (ID) scenario including important amplification processes currently not included in ISMs which drive non-linear deglaciation of Greenland and Antarctica, with 1.55m SLR (van de Wal *et al.* 2022).

The GR and BS scenarios attempt to encompass the range of possible SLR scenarios where processes with low confidence related to ice sheet instabilities are ignored. For these scenarios the IPCC (2021a) provides the most accurate and peer reviewed predictions using advanced GCMs coupled to ISMs verified though available observations. We hence use the SSP1-2.6 (warming below ~2°C), and SSP5-8.5 (warming below ~4.4°C) scenarios for the GR and BS respectively. Our worst-case (ID) includes ice sheet processes with deep uncertainty that are considered low probability (IPCC 2021a). We scanned the most recent research by Van de Wal *et al.* (2023) for this scenario, as it considers the potential of each component and explores how currently unknown and poorly understood ice sheet processes could drive abrupt SLR.

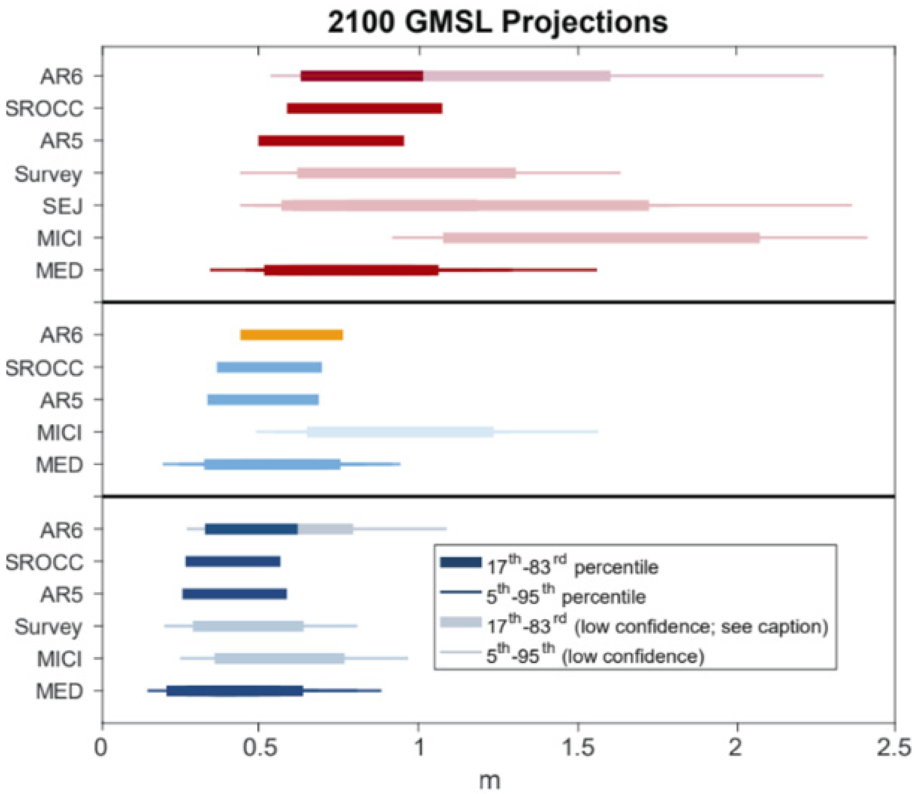

Figure 9. Global mean SLR projections for 1995-2014 (right), for RCP8.5/SSP5-8.5 (top), RCP4.5/SSP2-4.5 (middle) and RCP2.6/SSP1-2.6 (bottom). Thick bars span the 17-83 percentile projection range, and the thin bars span the 5-95% projection range. Different assessments are represented by MED (including only those ISM processes that are of at least medium confidence), MICI (ISM projections that include dynamic marine ice-cliff instability), and SEJ (structured expert judgement) of SLR contributions, including to a 2020 "survey" of glaciological and climate experts (from IPCC 2021a, Figure 9.25).

Table 1. Our SLR projections for 2100 broken down into their constituent contribution components. Green Road (GR) taken from the IPCC AR6 predictions based on SSP1-1.26 (IPCC 2021a) and Business as Usual (BS) from SSP5-8.1. Impending Doom (ID) scenario is adopted from high end forecasts for practitioners which includes low confidence Greenland and Antarctic ice sheet dynamical instabilities (van de Wal 2022).

Regional SLR	**Contributions by 2100 / m**		
Source	Green Road	Business as usual	Impending Doom
Antarctic Ice Sheet	0.11	0.12	0.59
Greenland Ice Sheet	0.06	0.13	0.29
Thermal Expansion	0.14	0.3	0.36
Glaciers and Ice Caps	0.09	0.18	0.27
Land-water Storage	0.03	0.03	0.04
Total/m	0.44	0.77	1.55

Impact on Morecombe Bay

Regional modulators of sea level rise

The local manifestation of eustatic SLR varies significantly due to regional modulators. Though investigations into the local impacts of SLR have improved (IPCC 2021a), miss-information is rife and there are no standard protocols for determining local flooding for the majority of countries. In the UK, for example, assessment reports by Bates *et al.* (2023) and the Govt Office for the Institute of Studies (Edwards, 2017) evaluate the consequences of SLR and flooding in terms of *expected annual damage* (EDA). Though directed towards policy makers and planners, this approach fails to explore the full scope of impacts that concern public understanding. Edwards (2017) discusses the potential social and economic impacts in a general manner for the whole of the UK, but there is little regional, and no local information.

Before application of the three SLR scenarios to Morcombe Bay, they must be adjusted for regional effects (Table 2). Eustatic SLR is modulated regionally due to changing gravitational fields associated with the redistribution of Earth's mass and as a result of the vertical uplift of continents due to post ice-age unloading - known as glacial isostatic adjustment (GIA, e.g. Patton *et al.* 2024). In terms of gravitational effects, we specifically refer to changes in ice sheet mass loss (melting) and water redistribution across the planet. Palmer *et al.* (2018) provide maps of how each major gravitational contributor impacts regionally across the UK. To determine these regional adjustments, we multiply the contribution from each SLR scenario by the ratio between the global and local effects ("mass fingerprint") of each source. At Morecambe Bay the gravitational multipliers are -0.1 for Greenland, 1.1 for Antarctica and 0.7 for glaciers and icecaps (Palmer *et al.* 2018). The localized GIA over the 75-year timescale is effectively constant at ~0.7 mm of vertical uplift per year (Kuchar *et al.* 2012). These regional effects are complex but surprisingly, act in tandem to mitigate SLR across much of the North and West of UK, coincident with the maximum footprint of the late glacial ice sheet at ~20ka BP (Hubbard *et al.* 2009). Once these regional offsets are applied, our three regionally adjusted SLR scenarios are projected onto Morecambe Bay, to assess their potential for coastal inundation.

Table 2. Local SLR scenarios adopted for Morecambe Bay with regional adjustments. The contributions (excluding glacio-isostatic rebound) are adapted from Palmer *et al.* (2018). Glacio-isostatic adjustment is updated with regional values from Kucher *et al.* (2012).

Regional SLR	**Contributions by 2100 / m**		
Source	Green Road	Business as usual	Impending Doom
Antarctic Ice Sheet	0.121	0.132	0.649
Greenland Ice Sheet	-0.006	-0.013	-0.029
Thermal Expansion	0.14	0.3	0.36
Glaciers and Ice Caps	0.063	0.126	0.189
Land-water Storage	0.027	0.027	0.036
GIA	-0.071	-0.071	-0.071
Total/m	0.274	0.501	1.134

Assessing flood risk across Morecambe Bay

We focus on three case studies within Morecambe Bay to explore the range of possible SLR flooding consequences within a location-specific context (Figure 10):

1. The rural wetland coastline between Silverdale and Carnforth.
2. The extended conurbation of Morecambe and Heysham.
3. The industrial town of Barrow-in-Furness

We achieve this using the Coastal Risk Screening tool (https://coastal.climatecentral.org/) - an interactive mapping tool that identifies areas threatened by SLR and coastal flooding. The tool utilizes a high resolution digital model of coastal elevations, yielding projections of future flooding. As inputs for this tool, the location of each of our case-study areas were applied under the three localized SLR scenarios defined above. The toolbox provides high resolution maps of predicted flooding based on the "bathtub" method that in-fills ("floods") all areas of land that fall beneath the projected RSL scenario applied above the mean higher high water (MHHW) line that has coastal connectivity.

Case study 1: Silverdale to Carnforth

Silverdale-Carnforth is a designated Area of Outstanding Natural Beauty (AONB), mostly comprised of wetlands and marshland, and is home to the RSPB Leighton Moss nature reserve (Figure 11). Its geography represents what might be considered a "low impact buffer zone" with capacity to absorb significant marine incursion. Such buffer zones act to protect coastlines from erosion and flooding by absorbing both water and its wave-force, so that any moderate SLR should have a relatively low-impact. The area also includes grazing farmland, some low-density residential areas and is a tourist destination for walkers and ornithologists.

We find that the GR and BS scenarios result in permanent loss of 1.14 and 1.36 km^2 respectively to marine incursion, which is doubled in the ID scenario, with 2.51 km^2 of

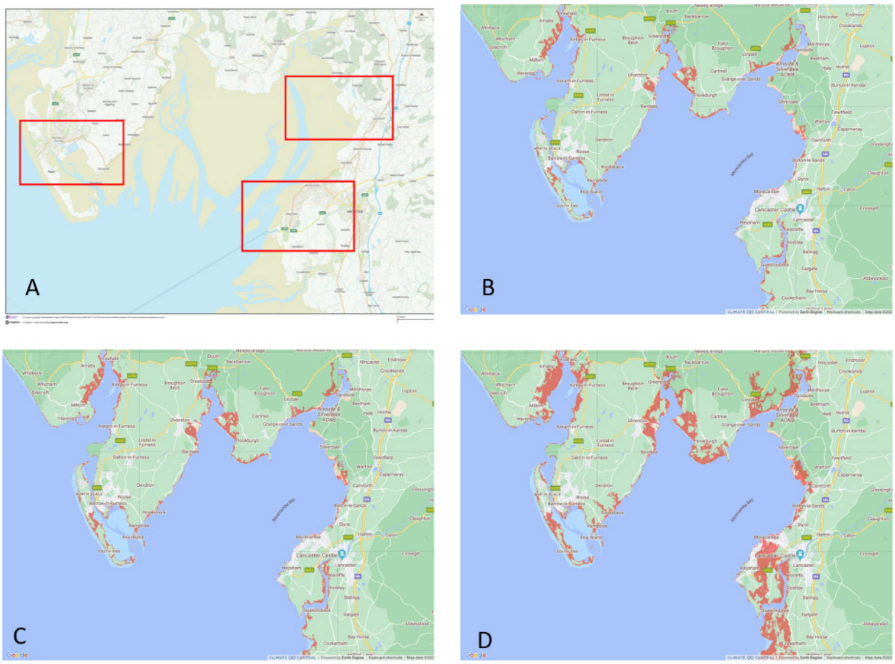

Figure 10. SLR projections for Morecambe Bay for 2100. Panel A is the topographic map of the entire area with our case studies (CS). CS1 - Silverdale to Carnforth (top right), CS2 - Morecambe and Heysham (bottom right), and CS3 - Barrow-in-Furness (top left). Panel B is the permanent area flooded (red) from the GR scenario. Panel C is the flooded area equated to BS scenario. Panel D is the area permanently inundated under the ID scenario.

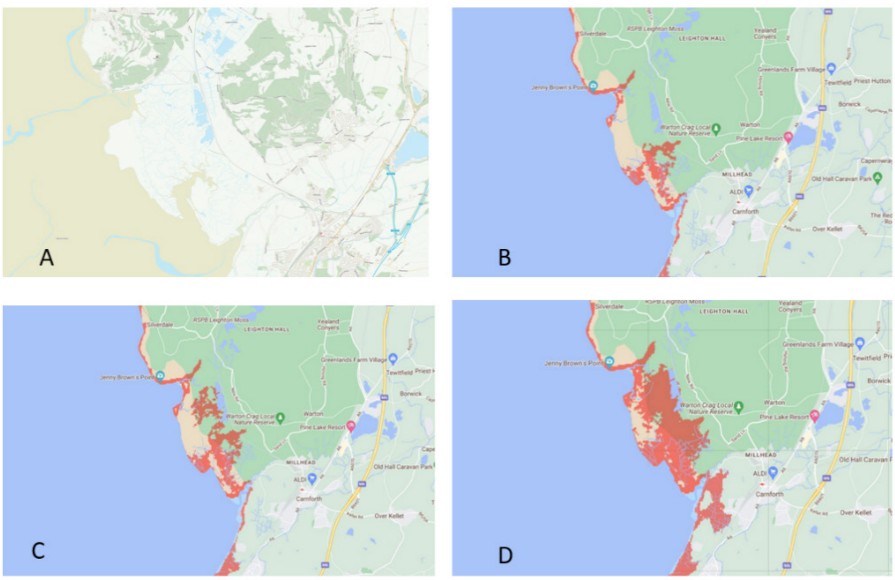

Figure 11. Projections for CS1 – Silverdale-Carnforth by 2100. Panel A is the O.S. map for this area. Panel B is permanent area flooded from the GR scenario. Panel C is the flooded area equated to BS scenario. Panel D is the area permanently inundated under the ID scenario.

land lost. It is anticipated that the effect of buffering by the wetlands would reduce the severity of flooding, arguably leading to some positive environmental consequences such as the inundation of grazing areas that may lead to a potential expansion in wetland, creating additional habitat for wading birds and promoting peat-formation to sequester atmospheric carbon. Such benefits potentially offset local economic losses due to reduction in farmland. While the loss of grazing agricultural land will have some negative economic impacts, it may be argued that the potential benefits outweigh the economic losses.

This area does though have critical infrastructure comprising the A6 trunk road, M6 motorway, West Coast mainline, as well as a regional rail network. In all three SLR scenarios, the M6 is safe from direct flooding, being ~1.5 km distant from inundation in the worst-case ID scenario. The A6 is though vulnerable, becoming permanently flooded at Carnforth, where it would either require diversion, or levee construction.

The national and regional rail network follows a coastal route and carries the highest risk. Even under the best-case - GR scenario - with little defensive infrastructure in place, these key transport networks are vulnerable (Edwards 2017). The Carnforth-Carlisle railway link is critical for transportation of industrial freight serving, for example, BAE Systems in Barrow and for transport of spent nuclear fuel (SNF) to the Sellafield plant. This rail network is already frequently disrupted due to climate-driven flooding, landslides and embankment erosion (e.g. https://www.bbc.com/news/articles/cqj0jw025kdo).

Case study 2: Heysham and Morecambe

Morecambe is a traditional coastal tourist town of ~36,000 with attractions that include a sea front promenade, the art-deco Midland Hotel, shops, parks, and entertainment facilities, and the new Eden Project North (Figure 12). Morecambe also has an industrial zone - centered mostly on franchise retail and service outlets, but also hosts some small-scale industrial and manufacturing. Heysham, population ~17,000, was a traditional fishing settlement but since the 1970s has developed significantly with the expansion of Heysham Port, and Heysham Nuclear Power Station, owned by the energy provider - EDF.

Heysham port is predominantly a freight terminal that has routes to the Isle of Man, Republic of Ireland and Northern Ireland. Heysham Nuclear Power Station with a 1000-strong workforce, and with a generation capacity of 11,500 GWs, supplies the Northwest region via the National Grid. While the Heysham nuclear power plants are situated directly on the coast, they are elevated on bedrock.

Under GR, BS and ID scenarios, areas corresponding to 1.42, 1.76 and 12.16 km^2 are permanently inundated. Morecambe's entire seafront is increasingly impacted in all scenarios, with flooding, erosion and damage to commercial and tourist infrastructure - including the Midland Hotel and the Eden Centre site. Furthermore, the River Lune floodplain – including the White Lund Industrial Estate and the Lancaster "Marshes" with populations of ~7,000 and ~6,000 respectively, are permanently flooded under the ID scenario, displacing communities, residential and business zones, with significant economic and social upheaval.

Under all scenarios, Heysham Nuclear Power Station is safe from direct inundation, due to its elevated situation (~15 m asl). However, the 160-year planned life span of power plants, as well as the threat of storm-surges, means that protective measures are necessary to meet the requirements of such infrastructure to ensure protection under 1-in-10,000 year storm-event (Edwards 2017). Numerous outbuildings, support infrastructure, and the road and rail network are though susceptible and will be impacted.

UK's Ports are identified as particularly prone and at risk to flooding, with local SLR above 50 cm being highlighted as of grave concern (Edwards 2017). This is primarily due to the consequences of disruption of established commercial and industrial goods, with a high potential to impact negatively on the regional economy. In all scenarios, Heysham port infrastructure and road/rail network faces some degree of local flooding under its current defenses, and therefore considerable investment and protection will likely have to be made in future to reduce disruption and economic losses.

Case study 3: Barrow-in-Furness

The area chosen centers on Barrow Island, the UK's primary ship-building site that constructs nuclear submarines and other warships. It also consists of the port of Barrow, the Barrow/Walney Island Airport and extensive residential zones (Figure 13). BAE Systems shipyard is one of the UK's largest workforces and is of national strategic importance, with the Navy's most recent nuclear-powered fleet submarines (SSNs) under construction since 2023.

Even in the best-case - GR - scenario, a substantial area is flooded (3.26 km^2), primarily on Walney Island, across agricultural areas inland of Biggar sands, isolating the south and north. The village of Biggar is severely threatened, with permanent inundation of its residential areas, and complete inundation in the ID scenario. To the north of the Walney Island, the impact of flooding is less severe though the A590 linking it to the mainland is severed under all scenarios. Vickerstown, built for workers of Barrow's shipyard with a population of 11,000 will become permanently flooded and hence, coastal management of these conurbations is necessary either through managed withdrawal or sea defenses.

The key industrial areas are relatively well protected under all scenarios, with minor flooding to the runways of the Barrow/Walney airport. While this is only permanently flooded in the ID scenario, then high precipitation and seawater storm surges would likely lead to temporary flooding in either of the two - BS and ID - scenarios. The port, like Heysham, is at particular risk of flooding leading to significant economic impacts as this is a commercial nexus for goods and components for BAE Systems. It is also the site for launching ships and submarines produced by the shipyard. Despite this, the central infrastructure of BAE systems and its submarine building subsidiaries is protected from permanent inundation, apart from some supporting infrastructure such as minor service roads and carparks.

The island of Roa, with a population of ~100, is home to the local RNLI lifeboat station, which similarly experiences permanent flooding under all scenarios. While it is currently connected to the mainland by Roa transit road, this connection would be severed from the mainland under all scenarios and an extensive area flooded under the ID scenario. Raising the road would be viable, though this would also render it susceptible to storm surges and flooding, and thereby compromise RNLI services, potentially at times of greatest need.

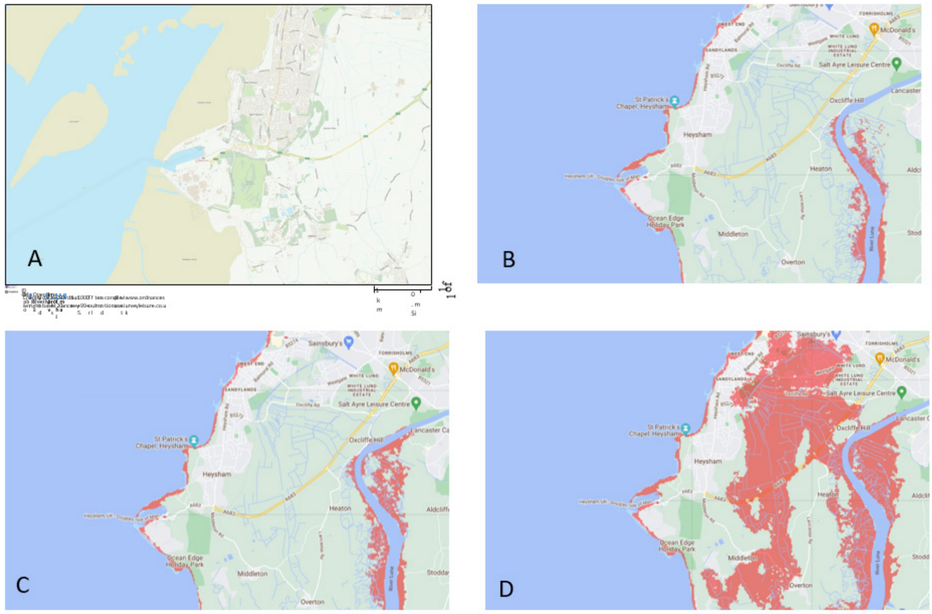

Figure 12. Projections for CS2 – Morecambe-Heysham by 2100. Panel A is the map for this area. Panel B is permanent area flooded from the GR scenario. Panel C is the flooded area equated to BS scenario. Panel D is the area permanently inundated under the ID scenario.

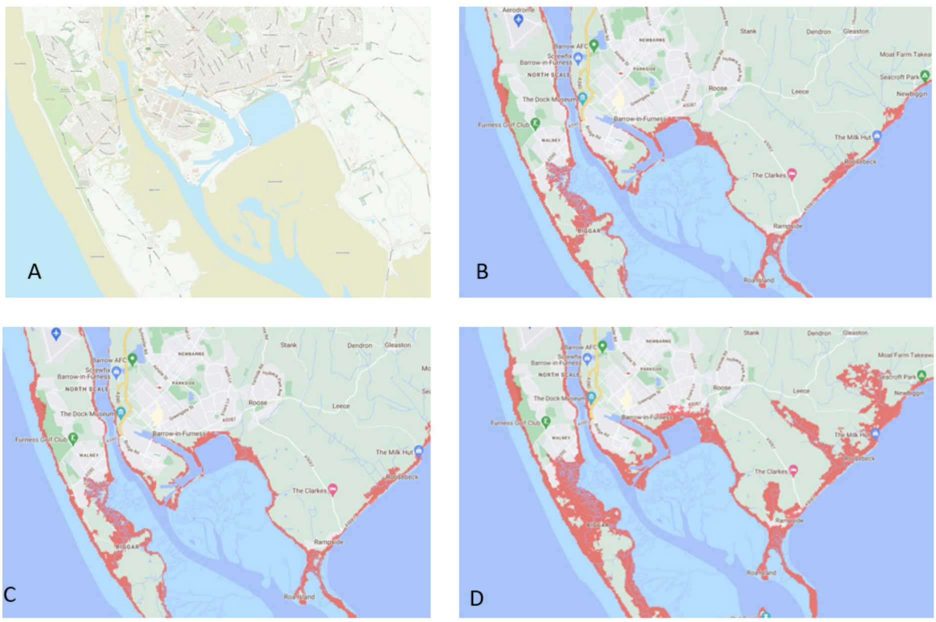

Figure 13. Projections for CS3 – Barrow-in-Furness by 2100. Panel A is the area map. Panel B is permanent area flooded from the GR scenario. Panel C is the flooded area equated to BS scenario. Panel D is the area permanently inundated under the ID scenario.

Summary and outlook

This paper set out to briefly summarise and assess the drivers and local manifestations of rising sea-levels, and to gain a fuller appreciation of the key uncertainties and complexities surrounding this topic. It is why the potential consequences of SLR cannot be disentangled from its causes. A new appreciation of the fundamental components that contribute to the net global ocean volume enables us to evaluate current knowledge, and take a range of informed scenarios, rather than accepting headline statements without critical evaluation. We find low confidence in the predictions from Greenland and Antarctica subsequently leading to large uncertainties - up to 1 m – in future SLR estimates. Despite this, it is well established that anthropogenic GHG forcing is now driving global eustatic SLR of 3.7 - 4.5 mm/a (2006 – 2018), some three times greater than the rate between 1901 - 1971 of 1.3 mm/a (IPCC 2021a). Of this, thermal expansion accounts for just under half, Greenland for ~1 mm/a, glaciers and ice caps up to 0.75 mm/a and Antarctica ~0.5 mm per year (Slater *et al.* 2022).

Looking forward, circulation models driven by GHG emissions under our best (GR) and moderate (BS) yield 2.0 to 4.4 C of global temperature rise by 2100. Our resulting eustatic SLR scenarios range from 0.44 to 0.77 m but should the potentially vulnerable marine sectors of the polar ice sheets undergo dynamic instability and partial collapse, then abrupt SLR of up to ~1.5 m is possible, though highly unlikely, which forms the basis of our ID scenario. These eustatic SLR forecasts are modulated regionally through glacio-isostatic rebound and gravitational effects - which significantly mitigate potential inundation and impact resulting in a considerably lower net SLR for some localities, such as our case-studies in NW England.

Our SLR and flooding projections do not capture the full spectrum of characteristics of coastal flooding using a fully integrated hydrological model that considers all dynamics - including flash rainstorm and river flooding events coupled with erosive processes. In this light, our findings should be interpreted as conservative. One of the largest sources of inaccuracy is in the application of a simplistic 'bathtub' model that fills-up the low-lying land surface to the projected SLR datum. As the severity of flooding increases, dynamic effects such as prevailing wind and the attenuation of flood height from friction become more important, rendering the bathtub approach less accurate. Application of sophisticated hydrodynamic models provide an alternative approach by physically modeling storm and tide combinations, yielding more reliable flood risk predictions but come at a cost, as they do require significant computational resources and setup. Bathtub models assume that any land under the predicted SLR datum tidal stand will be permanently flooded, however in areas such as flood plains and wetlands there will likely be less flooding, while low-lying areas adjacent to coasts may experience more (Bates *et al.* 2023). Despite this, their advantage lies is in their efficiency when used with precise digital elevation models and realistic SLR forecasts, resulting in accurate maps for areas threatened by permanent SLR alone and for minor floods that may rise and fall slowly.

Across Morecambe Bay – all three of our coastal areas are impacted significantly under all climate and SLR scenarios. In the worst-case (ID) scenario there is extensive inundation of coastal areas with permanent and significant disruption to transport, industrial and residential infrastructure impacting ~40,000 people and ~15,000 homes. In our best-case (GR) scenario – relatively moderate flooding occurs in Silverdale to

Carnforth - which may even be considered to enhance local wetland conservation - but even this minor flooding requires mitigation and defenses to protect the rail network, and to preclude flooding of industrial and residential areas in Heysham, Morecambe and Barrow.

Figure 14. Eric Morecambe fleeing future rising seas at Morecambe promenade (original artwork – this study).

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the geographical society of northern finland

Discussions and interventions

Science–tourism intersections onboard Arctic expedition cruise ships: Reflective insights from a fieldwork at the geographic North Pole

Alix Varnajot[a] & Élise Lépy[b]

Abstract

In August 2023, we both embarked on an icebreaker cruise ship in order to conduct fieldwork with and among cruise passengers and together with four other scientists. Departing from Longyearbyen, Svalbard, this two-week ship-time fieldwork took us to the geographic North Pole, across the Arctic Ocean sea ice, and to several locations in northern Svalbard. While cruise vessels operating as platforms of opportunity for researchers are not new, cruise tourism in the polar regions has raised ethical and sustainable concerns in times of increasing awareness regarding climate change. In addition, cruises bringing together tourists and scientists are currently objects of vivid discussions both in academia and the media. Drawing from our ship-time fieldwork experience, we aim to contribute to these recent debates. Building on the work of Lamers et al. (2024), we argue that misunderstanding on the concept of platform of opportunity can lead to potentially poor data collection, scientists' disappointment, and detrimental reputation for both science and tourism actors. We argue that carefully selecting research projects that align with the specificities of expedition cruise tourism, and facilitating nighttime research are effective strategies to avoid these misunderstandings. This may also enhance the credibility of cruise companies that may often be accused of science- and greenwashing.

Keywords: *Arctic tourism, expedition cruise tourism, fieldwork, North Pole, sustainable tourism*

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Introduction

Seaborne tourism is regarded as the fastest-growing segment of polar tourism (Bystrowska & Dawson 2017), with expedition cruise tourism rapidly growing in terms of newly commissioned passenger vessels, of ports of call, or of sailed kilometers by passenger ship (Dawson *et al.* 2018). In the Arctic, new itineraries are explored every year by cruise operators, reaching increasingly remote locations, such as the central Arctic Ocean, Greenland's East coast, or the Northwest Passage (Palma *et al.* 2019). As opposed to conventional cruises, expedition cruise tourism is characterized by smaller vessels of a capacity of 20 to 500 passengers; involving (relatively) flexible itineraries, shore landings (with dinghies), and environmental, geographical, historical onboard lectures and ashore interpretations (van Bets *et al.* 2017). In this context, increasing expedition cruise vessel traffic becomes an opportunity for facilitating research on the many challenges facing the polar regions.

Indeed, due to higher expenses of travel and shipping, conducting fieldwork in the high Arctic is particularly cost-prohibitive for researchers. Mallory *et al.* (2018) showed that conducting research in the Arctic is on average eight times more expensive than pursuing studies at a more accessible location. In line with this, expedition cruise companies have stepped in and have put forward the meaningful role they may have in such situations, as their ships will be traveling to these remote regions regardless (Taylor *et al.* 2020). Therefore, expedition cruise vessels have quickly become platforms of opportunity for researchers to be able to access remote fieldwork locations and to collect data (Löf *et al.* 2023). While using cruise ships as platforms for fieldwork is not a recent strategy (Graham *et al.* 2024), cruise tourism – particularly in polar regions – has raised ethical and sustainable concerns in times of increasing awareness regarding climate change, carbon footprint, and more generally our anthropogenic impacts on planet Earth (see Eijgelaar *et al.* 2010). Therefore, conducting fieldwork onboard cruise vessels merits careful considerations, especially when we, as scientists, are faced with credibility gaps in advocating for others to reduce their carbon footprint (Favaro 2014).

In August 2023, we embarked on an Arctic expedition cruise ship for our fieldwork. Departing from Longyearbyen, Svalbard, we embarked on a two-week journey across the Arctic Ocean sea ice, to the geographic North Pole, before heading back to Svalbard. Drawing from our personal experiences, we aim to contribute to recent and ongoing discussions in academia (see Graham *et al.* 2024; Lamers *et al.* 2024; Löf *et al.* 2023; van Soest 2023) and in the media (see Martinussen 2024; Øien 2024) on conducting fieldwork onboard expedition cruise vessels operating in remote and fragile destinations. More so, in times of warming Arctic (see Rantanen *et al.* 2022) and of sea ice retreat (IPCC 2019), human activities (e.g., military, tourism, shipping, etc.) are increasingly present and diversifying in the Arctic Ocean (Palma *et al.* 2019), and as such, this discussion on the science-tourism collaboration becomes particularly timely.

Setting the scene: our fieldwork to the geographic North Pole

Although the first ice-free summer could occur as early as the 2030–2050s (Kim *et al.* 2023), the geographic North Pole is still, at the moment, surrounded by perennial sea ice. Thus, the most common and comfortable way to get there is onboard an icebreaker. In order to reach the North Pole, we embarked onboard M/V Le Commandant

Charcot, a cruise vessel built with a Polar Class 2 icebreaking hull. She is operated by the French luxury cruise company Ponant, has been commissioned in 2021 specifically to bring tourists in ice-infested waters, and can host up to 245 passengers (plus 235 crew members). Generally, every year from May to September, Le Commandant Charcot operates in the Arctic (Greenland's East Coast, the geographic North Pole, the Northwest Passage), while she offers itineraries around Antarctica from November to March. As such, like many expedition cruise vessels, Le Commandant Charcot offers the same cruise routes multiple times within seasons and across years (see Taylor *et al.* 2020).

Le Commandant Charcot is also designed as a research platform with two permanent laboratories, including a 'wet lab' with direct sea access for deploying sensors or collecting samples below the hull. As such, she can host scientists from various disciplines (e.g., climatology, oceanography, marine biology, sea ice physics, as well as psychology, geography, etc.). In the summer of 2023, Le Commandant Charcot conducted 4 cruises to the North Pole, using the same route over the summer, and together with a team of two oceanographers from the University of Washington (UW) (USA) and of two sea ice physicists from the Alfred Wegener Institute (AWI) and the Hamburg University of Technology (TUHH) (Germany), we joined the third leg of these North Pole trips. For our German colleagues, these repeated voyages proved valuable for several reasons, such as for measuring sea ice thickness changes due to rising temperatures or shifting winds over the summer; better tracking monthly ice melt; and ultimately better improving Arctic Ocean sea ice modelling, prediction, and satellite data validation. They conducted a series of ice corings and deployed snow buoys measuring snow depth and surface atmospheric conditions, and thermistor string sea ice mass balance buoys to measure temperature profiles of air, snow, sea ice, and ocean over the course of four ice stations. They in addition conducted a series of drone flights in order to capture sea ice properties like ridged ice, melt ponds, open-water areas, floe sizes and shapes, and surface roughness. Collected images have then been used to generate Digital Elevation Models and orthomosaics. Lastly, they were in charge of the maintenance of the onboard Sea Ice Monitoring System (SIMS, Fig. 1), located at the bow and designed to continuously measure sea ice thickness, as well as of various temperature sensors that are constantly surveying temperature changes in the hull's structure (see von Albedyll *et al.* 2024).

Our colleagues from UW, however, had deployed in 2022 an Arctic Bottom Pressure Recorder (ABPR) on the Arctic Ocean floor. This device, developed to measure ocean bottom pressure variations in the perennial ice-covered Arctic Ocean, currently lies about 4000 m deep, in the vicinity of the geographic North Pole. It is equipped with acoustic modem technology and has been programmed to store and transmit data acoustically, without the need to recover the instrument (see Peralta-Ferriz *et al.* 2014). Thus, the team was onboard to collect uninterrupted data of ocean bottom pressure variability recorded from summer 2022 to summer 2023, with the goal of comparing their data with those collected by NASA's satellites.

Additionally, Le Commandant Charcot is equipped with devices and sensors that continuously measure water salinity, temperature, etc. as well as sea ice thickness – via the SIMS – and is able to share this data with institutes like AWI. Onboard, a science officer oversees the research teams; coordinates data collection, ensuring each team returns home with valuable data; and assists with duties like ice coring, and installing buoys. The science officer's role also includes liaising with the ship's captain if, for example, a team needs to reach specific coordinates for ABPR acoustic transmission

Figure 1. The SIMS consists of two measuring instruments: a sonar recording the distance to the air/snow interface and an EM31 recording the distance to the ice/ocean interface (von Albedyll *et al.* 2024). Photo: Alix Varnajot.

or to immobilize the ship for capturing drone images. Overall, by facilitating long-term observations, expanding international buoy networks, and contributing to the validation of satellite data, Le Commandant Charcot provides a modern and reliable research platform, participating in international Arctic marine-based research.

These various actions in favor of science are also increasingly promoted by expedition cruise companies on their respective websites and marketing campaigns (Varnajot *et al.* 2024). Expedition cruise companies, together with industry associations like the International Association Antarctica Tour Operators (IAATO) and the Association of Arctic Expedition Cruise Operators (AECO) argue that this type of collaboration between tourism and science leads to many benefits for tourists, including increasing passengers' knowledge and understanding of the Arctic (or Antarctic); thus positively impacting tourists' attitudes and triggering pro-environmental behavior changes after they return home (Øien 2024; Taylor *et al.* 2020). In this context, our objective was to investigate passengers' motivations to visit the most remote parts of the Arctic and to situate and assess citizen science in the span of travel motivations. Therefore, for us and as opposed to our colleagues from UW, AWI, and TUHH, Le Commandant Charcot was not a platform of opportunity allowing us to reach a remote location. Rather, the vessel itself and the passengers were our objects of study. In line with this, our fieldwork included surveys with passengers, semi-structured interviews with passengers, guides, and fellow scientists, as well as participant observation. Specifically, the participant observation consisted of spending time with passengers (e.g., during lectures, science-related activities, excursions, dinners, etc.), with the guides in charge of delivering the science education program, and with our colleagues during their fieldwork to better grasp their respective projects, objectives, and methods.

Some reflections: expedition cruise ships as platforms of opportunity

Following their participation in two cruises (in 2015 and 2022) combining scientific and tourism purposes around Svalbard, Lamers *et al.* (2024) brought new light on this relatively recent form of cruise tourism wherein scientists, tourists, and guests from the media coexist on an expedition cruise ship. Interestingly, drawing from the same cruises – organized by the Netherlands and called the Scientific Expedition Edgeøya Svalbard – other participating scientists recently shared thoughts and perspectives on this type of science-tourism expedition (see Löf *et al.* 2023; van Soest 2023). In a nutshell, van Soest (2023: 4) questioned the goals of such expeditions, raising issues related to "the politics of knowledge, the commercialization of science, how science is reported in the media, and the relationship between science and tourism." van Soest (2023) also raised the imbalances between the amount of data collected during the cruise on the one hand, and the luxury, the carbon footprint, and the visibility in the media promoting the benefits of such expedition on the other hand. In fact, van Soest (2023: 1) even warned us as she considered these expeditions "a supposedly useful thing [she'll] never do again".

Similarly to van Soest (2023), Löf *et al.* (2023) also questioned the sustainable nature of these cruises, although *sustainability* was the main motive of such operation, which raises ethical issues including science- and greenwashing (see Varnajot *et al.* 2024). Moreover, Löf *et al.* (2023) highlighted the conflicting nature of such expeditions between the needs for fulfilling tourists' experiences of Svalbard and the Arctic and scientists' needs for landing in order to collect data. In a similar vein, Lamers *et al.* (2024) raised the organizing challenges of which of science or tourism is given priority. While they identify benefits of such expedition in terms of visitor experience, diversification of tourism practices, networking opportunities and scientific outreach, they in parallel highlight several limitations that may hinder the success of these specific cruises. These limitations include, among others, surprises due to regulatory complexities; flexibilities in the itinerary specific to expedition cruises potentially impacting data collection; and lack of communication between the tourism and science parts (Lamers *et al.* 2024). Lastly, Lamers et al. (2024: 11-12) also raise misunderstandings as a potential conflict between tourism and science, which require "careful preparation and communication, continuous on-board reflection […] and ensuring that the roles and expectations of groups of carriers of practices are clear before, during and after a combined performance."

While we agree with all points, issues and limitations raised by van Soest (2023), Löf *et al.* (2023) and Lamers *et al.* (2024), *misunderstanding* seem to be central to the ongoing discussions about tourism-science expeditions. Based on our experience, it seemed passengers' experiences, activities, and schedules were not disturbed by the presence of scientists working on their respective research projects, including us and our significant and extensive presence among them. On the contrary, passengers seemed pleased, positively intrigued and interested in our work. The misunderstanding highlighted implicitly by van Soest (2023) and Löf *et al.* (2023) and explicitly by Lamers *et al.* (2024), however, seems to stem from the scientific side of these expeditions. Indeed, as raised earlier, these cruises are platforms of opportunity, and in other words, are first and foremost tourism products. As such, they are designed to please and fulfill tourist experiences and to meet passengers' expectations. Thus, of course they come with luxury amenities and services for which they pay a substantial fare. In the context of our discussion, platforms of opportunity aim to take advantage of an existing (and growing) traffic of vessels, including cruise vessels and cargo ships (see Graham *et al.* 2024). When cargo ships serve as platforms of opportunity for marine biologists, for example (see Correia *et al.* 2020), the priority remains the route and the schedule they need to follow to be on time at the next harbor. They do not stop along the way or make detours to please the scientific protocol. Rather, scientists design their protocol and adapt their methodology to the cargo ships' priorities.

One main difference with cargo ships remains, however. As opposed to expedition cruise operators, shipping companies do not promote their connections with science or embark journalists for promotional purposes. Nevertheless, scientists must understand that not all scientific protocols can be adapted to the specific conditions of expedition cruise tourism, with the need for flexibility in data collection being the most challenging requirement for researchers. In addition, as van Soest (2023) noted, scientists are also drawn to the polar regions for various reasons, including the desire and longing to visit these vulnerable places – just like tourists. We, too, had little hesitation when we were offered the opportunity to reach the North Pole onboard Le Commandant Charcot. This eagerness can lure and lead many to expect meaningful research opportunities and successful data collection, only to face misunderstandings and disappointment when passengers' experiences and schedules take priority. This supports the need for beforehand and continuous clear communication raised by Lamers *et al.* (2024). It is worth noting that these conditions apply to those scientists using expedition cruise ships as platforms of opportunity. For those, like us, studying passengers, these considerations do not apply since we share the ship's premises 24/7 with our objects of study (Hardy et al., in press). While the need for flexibility is also critical for conducting our ethnographically-oriented fieldwork, it is always possible to catch up with passengers before the cruise ends.

On a side note, while van Soest (2023), Löf *et al.* (2023) and Lamers *et al.* (2024) have rightly raised the conflicting aims between tourism and science, it is also important to highlight that onboard research vessels too, there are competition and conflicts between research projects over the use of given equipment or facilities. Scientific projects and data collection are also dependent on the variable weather and the sea ice conditions. On these missions, researchers can frequently compete for the use of the helicopter, for example, which might be needed by different teams at the same time during a favorable weather window. These priorities and considerations seem less problematic even though research vessels are not, by definition, platforms of opportunity. This reflects on a general level the priority given to science, scientific knowledge as opposed to accounts from those associated with tourism, which are held less valuable, less authentic, and less legitimate (Saville 2019). For the sake of the ongoing discussion on science-tourism collaborations, we feel it was necessary to bring that issue up.

Besides the imperative need for scientific protocols to be able to adapt to tourism priorities, some scientific operations may be conducted at night. Indeed, in the high latitudes, cruises take place in the summer, when the midnight sun provides constant daylight. Tourists' activities typically end in the late afternoon for dinner, evening festivities and sleep. This leaves the night open for researchers to work. For instance, on our return to Svalbard after leaving the sea ice, our colleagues from UW needed to deploy a series of buoys at specific coordinates (Fig. 2). In practice, they were communicating with the bridge via the science officer, to inform the captain of the exact locations and timing for stops. Although these maneuvers involved several stops and slight detours from the direct route to northern Svalbard, they went largely unnoticed by passengers as they occurred between 11pm and 2am. In the end, carefully selecting research projects that align with the specificities of expedition cruises, rather than inviting numerous researchers for marketing purposes, and facilitating nighttime research are effective strategies to avoid misunderstandings. This may also enhance the credibility of cruise companies that may often be accused of science- and greenwashing.

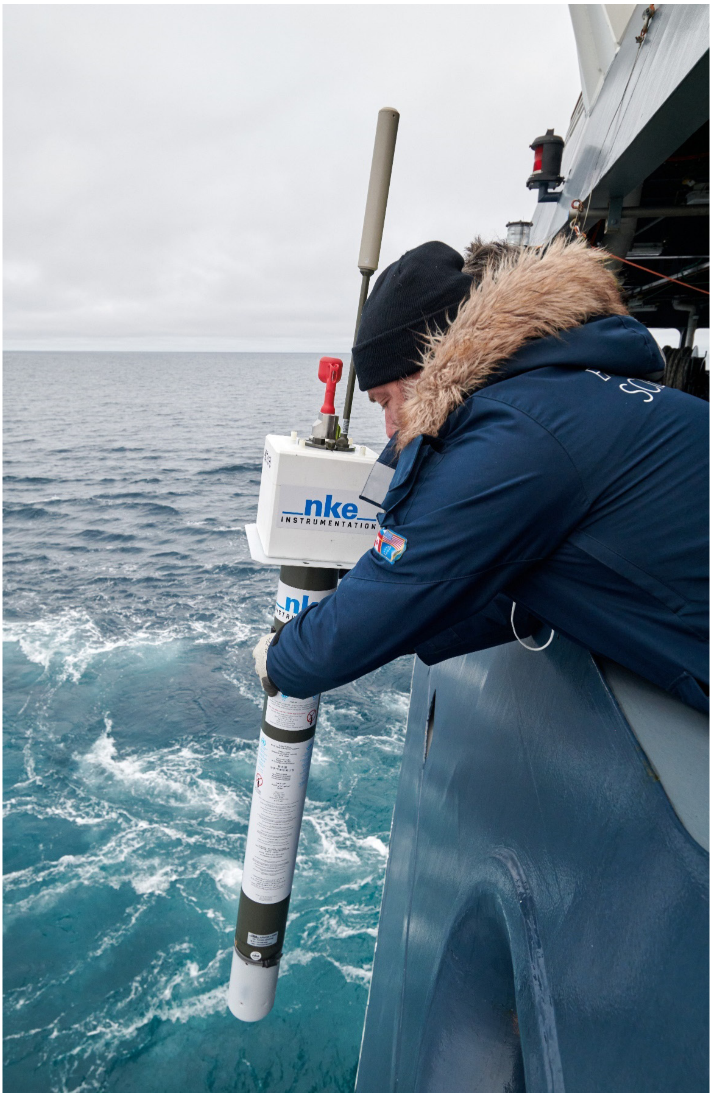

Figure 2. Deployment of a series of buoys, from the stern of Le Commandant Charcot, in the middle of the night and following specific coordinates. Photo courtesy: Mike Louagie.

Conclusion

Platforms of opportunity like expedition cruise ships can become key tools to address global change in polar environments. These cruise ships largely follow the same routes over the summer, year after year, and as such, may play a critical and favorable role in further monitoring and understanding environmental changes in the Arctic (and Antarctic). Nevertheless, while these science-tourism initiatives also come with ethical, sustainable, and practical limitations, it seems that misunderstanding – particularly on the role and definition of platforms of opportunity – might be the main source of conflict between the science and tourism sides, as identified by Lamers *et al.* (2024). As long as scientists will think cruise ships should act at the service of science as soon as a bunch of researchers are allowed to embark on them, this will lead to poor data collection, disappointment among onboard scientists, and a lack of credibility for cruise companies, which in the end is detrimental for both science and tourism actors. A more careful selection of research projects, together with clear communication between the cruise company and research teams beforehand may allow scientists to tailor their scientific protocol to the specific cruises they will join.

It is often said that tourism does not take place in a vacuum, it is connected to historical, cultural, political and socio-economic dimensions (Saarinen & Varnajot 2019) and the same can be argued about science. Indeed, overall, this ongoing discussion on science-tourism collaborations in the context of expedition cruise tourism in polar regions offers the opportunity to reflect on the role of science in our society. Scientists are perceived as more legitimate than tourists in fragile ecosystems (see Saville 2019), even if it has been shown that scientists regularly break environmental and safety rules for recreational purposes during their fieldwork (see Braun *et al.* 2017). Nevertheless, critics like environmental NGOs have promptly raised concerns on these collaborations and have incriminated the tourism industry of using science for commercial purposes in fragile and remote areas, reflecting this legitimacy imbalance. We contend that there is a need for nuances in these too-often polarized activist debates. Under some conditions, some research projects can be perfectly suitable with expedition cruises and serve our need for knowledge regarding climate change; and in such cases, wouldn't it be science taking advantage of the tourism industry?

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nordia geographical publications

Discussions and interventions

Freshwater plant macroecology needs to step forward from the shadows of the terrestrial domain

Janne Alahuhta[a*], Jorge García-Girón[a, b], Eugenio Molina-Navarro[c] and Kevin Murphy[d]

Abstract

Freshwater plants, or macrophytes, make up only 1-2% of all plant species on Earth but play a crucial role in aquatic ecosystems. They are key to primary production, provide habitat and food for various organisms, and influence water quality. Despite their importance, freshwater plants face significant threats from global changes, which necessitates research at broader scales. Historically, freshwater plants have been less studied than terrestrial plants, partly due to a lack of global data and a focus on local scales by aquatic ecologists. Unlike terrestrial plants, freshwater plants do not always follow the same ecological patterns. In this text, we summarise current knowledge on three well-known macroecological patterns and how they differ between freshwater and terrestrial plants: latitude-species richness gradient, Rapoport's rule and species turnover vs. nestedness components of spatial beta diversity. For example, terrestrial plants follow the latitudinal diversity gradient hypothesis, whereas species richness peaks in the sub-tropics for freshwater plants. Although findings on Rapoport's rule are less clear, research on terrestrial plants in North America shows that turnover (i.e., species replacing each other from one site to another) is more significant in areas with high species richness and environmental stability, whereas nestedness (i.e., species

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composition at one site being a subset of a richer site) is more common in species-poor areas with high environmental variability. For freshwater plants, beta diversity patterns vary with latitude, but species turnover generally dominates over nestedness in a spatial context. Overall, freshwater plants exhibit unique macroecological patterns that differ from terrestrial plants, highlighting the need for more extensive research to understand their biodiversity and ecological roles. This can be achieved with more harmonized data sets and equal research efforts in both realms. Better knowledge of macroecological patterns and their drivers for freshwater plants is crucial for conservation efforts and policy-making aimed at preserving plant species diversity and sustaining ecosystem services in freshwater environments.

Keywords: *aquatic macrophytes, biogeography, macroecology, macrophytes*

Freshwater plants in a changing world

Freshwater plants (i.e. macrophytes) constitute only 1-2 % of all plant species growing on Earth (Cook 1999). Yet, their importance as foundation species and ecosystem engineers (O´Hare *et al.* 2018) exceeds their expected ecological value given their relatively low richness compared to plants in terrestrial ecosystems in those lakes, rivers and wetlands, where freshwater plants are primarily responsible for primary production, provide food, habitat, reproduction and prey areas for other aquatic and terrestrial organisms and influence water quality (Lacoul & Freedman 2006). Freshwater plants are also involved in producing and sustaining numerous vital ecosystem services of inland waters (Engelhardt & Ritchie 2001). At the same time, global change is threatening freshwaters more severely than other natural ecosystems in the Anthropocene, for example, by facilitating the spread of invasive species (Gillard *et al.* 2017; Reid *et al.* 2019; Albert *et al.* 2021; Bolpagni 2021; Hussner *et al.* 2021). Many of the global change pressures affect biodiversity beyond local ecosystems, requiring ecological research efforts to focus on regional and global spatial scales. Although these facts highlight the need to study freshwater plants more intensively at broad scales, until recently these species have been examined less rigorously than their terrestrial counterparts (e.g., Alahuhta *et al.* 2017; 2018; Murphy *et al.* 2019; García-Girón *et al.* 2020a, 2020b; Murphy *et al.* 2020; García-Girón *et al.* 2023a; Lobato-de Magalhães *et al.* 2023; Pan *et al.* 2023; Azzella *et al.* 2024; Lobato-de Magalhães *et al.* 2024; Luukkonen *et al.* 2024), due in part to the lack of comparable data from across the world. The shortage of studies on the macroecology of freshwater plants may also stem from the fact that many freshwater ecologists and limnologists are concerned with describing assemblage-environment relationships at local scales (for example, within a single drainage basin) or are ecosystem-oriented (Heino 2011), thereby hindering attempts to further examine the mechanistic basis of broad-scale biodiversity patterns on these plant species.

Ecological generalities evidenced using terrestrial plants may not be used to explain macroecological patterns and their underlying mechanisms in freshwater plants. For example, terrestrial plants follow the latitudinal diversity gradient hypothesis, although anomalies to this positive trend exist regionally (Sabatini *et al.* 2022). For freshwater plants, species richness peaks in the sub-tropics (Murphy *et al.* 2019). Many other ecological hypotheses and theories lack clear evidence for freshwater plants, show incongruent patterns or are driven by different mechanisms compared with terrestrial plants. These inconsistencies originate from differences in accessibility to water and atmospheric gases between terrestrial and aquatic plants, which also experience less extreme temperatures in inland waters. Thus, catchment properties related to local environmental conditions are often highly important drivers of freshwater plant biodiversity (Iversen *et al.* 2019).

Contemporary climate and historical factors also contribute to distribution of freshwater plants, as found at northern latitudes (Figure 1). Regions with higher temperatures related to Gulf Stream dynamics in Central and northwestern Europe and eastern North America include more freshwater plant species than colder regions in the same latitudes (Murphy *et al.* 2019; Alahuhta *et al.* 2020), a pattern that is partly associated with the distribution of introduced and invasive freshwater plant species to these regions (Lobato-de Magalhães *et al.* 2023). Moreover, most northern latitudinal areas which were covered by ice sheets during the Last Glaciation Maximum have fewer plant species than ice-free areas located at the same or lower latitudes (Murphy *et al.* 2019). The number of endemic freshwater plant species also follows similar geographical patterns (Lobato-de Magalhães *et al.* 2024), the western Europe macroregion having many more ecozone-endemics (134 species) than northern Europe (72) or the Arctic macroregion of the Palaearctic as a whole (just 17 species). A similar trend is seen in the Nearctic, where eastern North America has many more endemic macrophyte species (129) than are present in the Arctic-Canadian Shield macroregion north of 50°N (56 endemic species). These endemism patterns are mostly explained by birds acting as dispersal vectors for freshwater plant species and historical factors (Lobato-de Magalhães *et al.* 2024). However, spatial patterns of rare freshwater plants at northern latitudes differ depending on definition of rarity and scale used for the study as well as the precise taxa set involved. For instance, García-Girón et al. (2021) studying hydrophytes in Europe and North America (50 km x 50 km grid cells) evidenced high rates of rarity in freshwater plants in Central Europe and northwestern Europe and in the US state of Florida and eastern coast areas. On the other hand, medium-sized levels of rarity were found in eastern and western coastal areas of Eurasia and North America for all freshwater plants at a resolution of 10° × 10° grid cells (Lobato-de Magalhães *et al.* 2024).

For invasive freshwater plant species, the current pattern of occurrence at high latitudes mirrors the overall diversity pattern seen in Figure 2. At present there are no invasive species in either the Nearctic or Palaearctic north of 70°N. In the 60-70°N band there are only four species invasive, in a limited set of localities in the Palaearctic (and one of these, *Elodea densa* in Arctic Iceland, is a special case, having been introduced there to naturally-heated thermal pools), while the Nearctic has only three invasive freshwater plant species in this latitude band. The biggest differences are seen in the 50-60° latitude band. There are six invasive freshwater plant species occurring in the Nearctic section of this latitude band, and a further three (all from the New World) invasive in the corresponding latitudes of the central and eastern Palaearctic. However, in the western Palearctic section of this latitude band, warmed by the influence of the Gulf Stream, no fewer than 15 invasive freshwater plant species occur, with the biggest numbers present in the Low Countries and British Isles. Together with the example of *Elodea densa* in Iceland, this perhaps gives notice of what might be expected to happen in high latitudes in response to global warming, in terms of the spread of invasive species.

Differences in three key macroecological patterns between terrestrial and freshwater plants

To further highlight differences but also similarities in broad-scale patterns and their underlying mechanisms between freshwater and terrestrial plants in general, we here focus on three well-known macroecological patterns: latitude-species richness gradient, Rapoport's rule and species turnover vs. nestedness components of beta diversity (Figure 2). As noted above, the patterns of species richness-latitude relationship differ between terrestrial and freshwater plants. Kreft & Jetz (2007) found that water-energy dynamics were among the most important drivers of latitudinal gradient in species richness in terrestrial plants. Similarly, Field *et al.* (2009) discovered in their meta-analysis that climate or productivity is generally the key driver of species richness patterns. Murphy *et al.* (2019) found that the presence of water (or lack of it) is an important contributor to the latitudinal gradient in species richness in freshwater plants, but altitude and land area are also important, highlighting the importance of catchment properties as found elsewhere (e.g. Iversen *et al.* 2019).

Rapoport's rule is an iconic macroecological pattern where species range size decreases from high to low latitudes (Stevens 1989). Yet, consensus over this gradient has been difficult to reach for both plant and animal groups, and our knowledge of the determinants driving these geographical patterns is limited in general (Sheth *et al.* 2020). For example, range sizes of terrestrial plants increased with latitude in North America and decreased in South America, with short- and long-term climate stability and availability of habitat area being the main drivers of the patterns (Morueta-Holme *et al.* 2013). Likewise, Alahuhta *et al.* (2020) reported support for Rapoport's rule in North America but found no evidence for it in Europe for freshwater plants. Both of these opposing patterns were determined by contemporary climate. In a recent global study, Murphy *et al.* (2020) provided strong evidence that Rapoport's rule applies to freshwater plants, though their global range size is also influenced by agricultural land-use, altitude and climate-change velocity. Differences between these findings likely originate from the use of different sets of species and spatial scale (both resolution and extent). With these differences in mind, it is evident that more research is needed on Rapoport's rule for both terrestrial and freshwater plants (e.g., Willig & Presley 2018).

Beta diversity describes compositional variation among communities across space (for a discussion on consistency in the terminology and interpretation of different aspects of beta diversity, see Heino et al. 2024), and is related to two processes (Legendre 2014): species turnover (i.e. where one species replaces another with no change in richness between localities) and nestedness (i.e. which is a type of richness difference pattern characterized by the species composition at a site being a strict subset of the species at a richer site). Pinto-Ledezma *et al.* (2018) found for terrestrial plants of North America that taxonomic beta diversity patterns vary strongly across the continent. Turnover was more influential in areas with higher species richness and greater environmental stability, whereas nestedness was more important in species-poor areas having high environmental variability. For freshwater plants, overall total beta diversity has either decreased or increased with latitude worldwide, depending on the data set and quantitative method used (Alahuhta *et al.* 2017; García-Girón *et al.* 2020a). Yet, species turnover is typically predominant over nestedness in explaining spatial beta diversity of freshwater plants (Alahuhta *et al.* 2017). Differences between terrestrial and freshwater plant beta diversity patterns emphasize the need to study both realms with equal efforts and harmonized data sets (*sensu* García-Girón *et al.* 2023b) for both basic and applied research, and further highlight the need for ecosystem- and region-specific assessments to guide conservation prioritization.

Ways forwards for freshwater plant macroecology

Examples of these three macroecological rules illustrate that mechanistic understanding of broad-scale diversity patterns of freshwater plants is far from complete. A challenge associated with macroecological studies of freshwater plants is the high degree of phenotypic plasticity. For example, a species recorded in a region may be characterized as a fully water-dependent freshwater plant, whereas the same species may grow on land in another region. The extreme of this is seen in the Cyperaceae, where all but 12 of the 556 species known to have macrophyte populations also have non-macrophyte populations growing in wetland, riparian or terrestrial habitats. This complicates our definition of which species are true freshwater plants, further possibly affecting observed macroecological patterns. Our knowledge of fundamental ecological phenomena is not only limited for taxonomic diversity patterns, but even more so for functional and phylogenetic dimensions of freshwater plant ecology (García-Girón *et al.* 2023b). In this regard, both high-quality trait and species-specific evolutionary data for freshwater plant species are, at best, patchy and often restricted to certain geographical areas and lineages (Iversen *et al.* 2022). First attempts to reveal functional and phylogenetic diversity patterns at broad scales suggest that processes acting along latitudinal and elevational gradients have left a strong footprint in the current diversity patterns of freshwater plants (García-Girón *et al.* 2020a). These intriguing findings emphasize the pressing need for efforts to extract well-curated distributional, functional and phylogenetic datasets of inland plants in different catchments, biomes and continents in order better to understand different biodiversity facets of freshwater plants (Alahuhta *et al.* 2021; García-Girón *et al.* 2023b; Pan *et al.* 2023). Such a research agenda is also of interest to environmental managers, conservation practitioners and policy makers aiming to reduce or halt the continued decline of plant species diversity in freshwaters and to sustain inland ecosystem services (e.g., Reid *et al.* 2019). These conservation targets would benefit from a metaecosystem approach, which integrates freshwater and surrounding terrestrial systems, as organisms, energy and matter flow from land to water, to better understand how different human-induced pressures affect freshwater biodiversity (e.g. Soininen *et al.* 2015). However, first we need to understand their macroecological patterns and determinants in spatially extended areas. By doing so, we should be able to forge an exciting new frontier in plant macroecology research that allows us to step forward from the shadows of the terrestrial domain and further bridge gaps between freshwater and terrestrial macroecology.

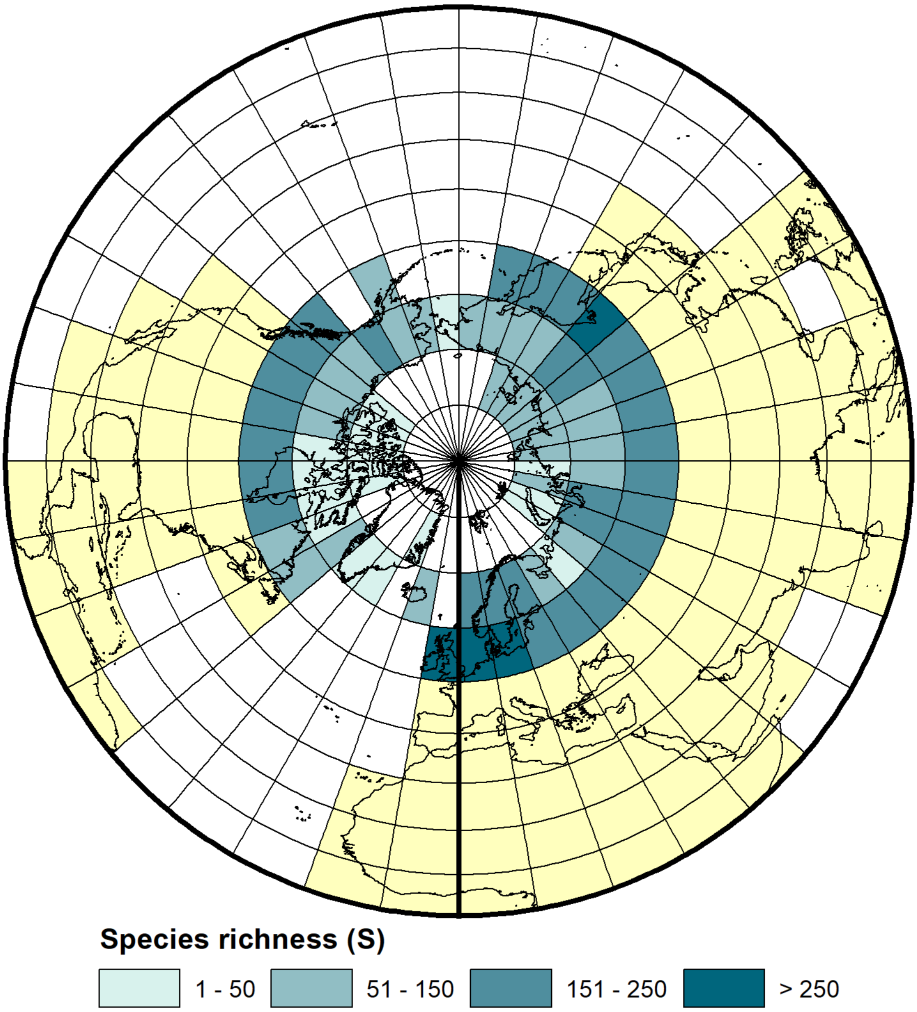

Figure 1. Map of species richness (in blue palette) in 10×10° latitude x longitude grid cells at northern latitudes (for more information on species data, see Murphy *et al.* 2019). Land areas are in yellow and oceans in white.

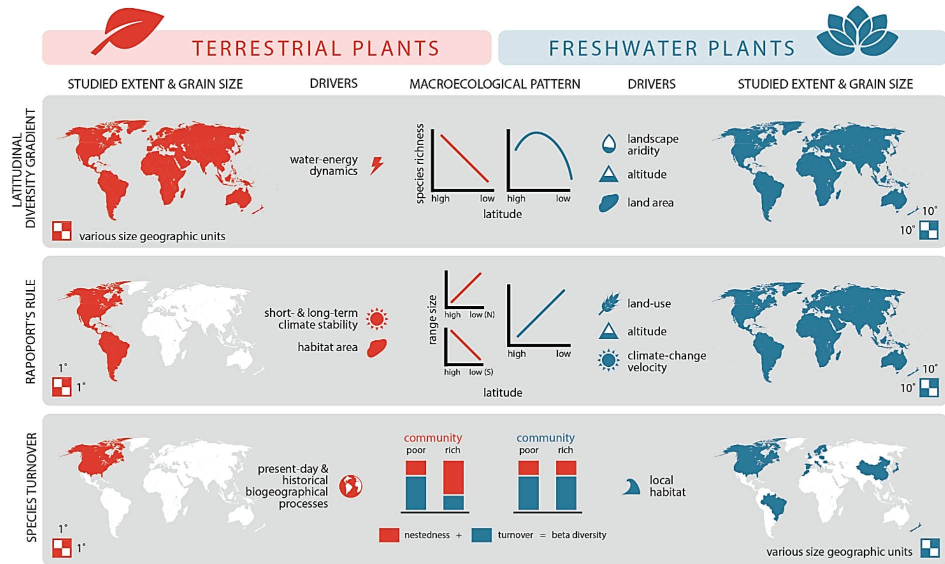

Figure 2. Examples of how terrestrial and freshwater plants decouple in their macroecological patterns and underlying mechanisms. These two groups differ in terms of the studied extent and grain size (data availability), detected patterns and underlying mechanism. Terrestrial and freshwater patterns presented are based on studies by Kreft & Jetz (2007) and Murphy *et al.* (2019) for latitudinal diversity gradient, Morueta-Holme *et al.* (2013) and Murphy *et al.* (2020) for Rapoport's rule, and Pinto-Ledezma *et al.* (2018) and Alahuhta *et al.* (2017) for species turnover, respectively.

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the geographical society of northern finland

Discussions and interventions

What on Earth is geodiversity?

Helena Tukiainen[a] and Maija Toivanen[b]

Abstract

The concept of geodiversity is gaining recognition in many scientific fields, as well as in practical applications such as conservation and tourism. Although the importance of geodiversity is now widely accepted, its precise definition, scope and broader applicability continue to be debated and discussed. In this paper, we explore the variety of viewpoints that relate to geodiversity and scrutinize the importance of geodiversity for different audiences. These viewpoints include definitions, assessment, research fields, terminology and its applications. To help explore and convey the different viewpoints and values commonly attributed to geodiversity, we invoke the Rokua UNESCO Global Geopark in Finland as a specific case study. Finally, we present potential future directions for geodiversity research, including key knowledge gaps, and highlight the vulnerability of geodiversity to increasing human pressures that threaten its integrity and long-term sustainability.

Keywords: *biodiversity, geodiversity, geology, geopark, nature*

Introduction

Have you encountered the term "geodiversity"? Although it may sound unfamiliar, it is gaining recognition in both scientific research and practical applications, with northern environments being among the actively studied regions. Much like biodiversity, geodiversity is a multifaceted concept that can be explored from various viewpoints, and which are linked to global change from many perspectives. While certain practices and interpretations of geodiversity have become widely accepted, the core concept and many areas of geodiversity research are still developing and evolving. Thus, for

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someone encountering the term "geodiversity" for the first time, it might be challenging to grasp its full scope.

In this article, we explore current discussions and interpretations of geodiversity, offering a contextual introduction to this important yet often overlooked concept. We scrutinize the definitions of geodiversity and the related debates and explore the different viewpoints from which geodiversity has been approached, as well as scrutinize the values that can be related to geodiversity by using Rokua UNESCO Global Geopark as an example. In addition, we write about the essence of geodiversity for science, practical applications, and for any one of us. Finally, we introduce important new discussions and directions related to how the concept of geodiversity might evolve in the future.

Defining geodiversity

The journey to a unified definition of geodiversity has not been straightforward and is still ongoing. According to Gray (2021), the concept began to take shape in the early 1990s, particularly in Tasmania, where scientists began drawing parallels between biological diversity and geomorphological diversity, and their interdependence. By 1992 and the Rio Convention on Biological Diversity, geoscientists introduced geodiversity as a concept deserving protection alongside biodiversity. Geoscientists advocated for its recognition as an equally significant phenomenon as biodiversity, with major implications for nature conservation (e.g., Dixon 1996; Sharples 1993: 7–8).

Today, it is commonly accepted that geodiversity is defined as the diversity of geological (rocks, mineral, fossils), pedological (soil), geomorphological (landforms, topography, physical processes) and hydrological features, including their assemblages, structures, systems and contributions to landscapes (Gray 2013; also Fig. 1). This definition highlights the complexity of Earth's non-living components, emphasizing both their intrinsic values and their contribution to broader natural systems.

Figure 1. Natural diversity consists of biological, geological, and climatic components. Geodiversity encompasses the abiotic features of the Earth's surface and subsurface, such as rocks, soils, hydrology, geomorphology, and topography. It can be studied on its own or in connection with biodiversity and/or climate. The distinct features of geodiversity are easily recognizable in northern, barren landscapes. Photo: Helena Tukiainen, in Kilpisjärvi, Finland.

Defining geodiversity has often taken a natural scientific perspective, focusing on physical features or taxonomic classifications (e.g., Hjort *et al.* 2024). However, as our understanding of nature continues to evolve, discussions increasingly emphasize the need for a more inclusive perspective. Traditionally, "nature" has been primarily associated with biodiversity and living components (e.g., see glossary in IPBES N.D.), but recent discourse highlights the need to expand this view. An IUCN issue paper by Sophie Justice and others (2025) recommends redefining nature as "*encompassing both the non-living components (i.e., geodiversity) and the living components (i.e., biodiversity) of the natural world*" (Justice *et al.* 2025). This shift reinforces the importance of geodiversity in conservation and management, further highlighting its intrinsic connection to broader natural systems.

While geodiversity is generally described as the diversity of non-living nature, its interpretation can vary across different cultural and philosophical contexts. In many Indigenous cultures and religions—broadly labeled "Animistic"—geological features are perceived as active, living entities with spiritual significance and deep cultural meaning (Gray 2019; Verschuuren *et al.* 2021). This highlights the cultural and spiritual values associated with geodiversity, challenging the notion of "non-living" nature in certain contexts.

From a broad, multidisciplinary perspective, Karjalainen (1986) defined geodiversity as the spatial diversity of the Earth, including both physical (or factual) diversity and the diversity of one's lived experience. This definition suggests almost a conceptual parallel between geography and geodiversity. As Karjalainen (1986, p. 22) states, *"geography is the orderly knowledge of the Earth's diversity as the world of humans"*, which renders geodiversity an intriguing paradigm within geographical studies (see also Claudino-Sales 2021). The field of geography, with its inherently interdisciplinary approach, provides a natural platform for exploring geodiversity from diverse perspectives beyond its current popularity in natural sciences.

A new paradigm in development?

Despite the progress in defining the term geodiversity, some key debates remain. One ongoing discussion centers on whether geodiversity should be regarded as a broad, multi-scale concept analogous to biodiversity (e.g., Gray & Gordon 2020), or if it should be applied more strictly in regional or local contexts (e.g., Brocx & Semeniuk 2019, 2020). The former emphasizes the intrinsic value of geodiversity, including its various contributions to nature and humans, of which underpinning biodiversity is just one example. In the latter context, the value of geodiversity is primarily recognized through its key role in supporting, and interdependence upon, biodiversity.

Another ongoing debate centers on whether, and to what extent, climate should be included in the definition of geodiversity (e.g., Bailey *et al.* 2024; Parks & Mulligan 2010; Zarnetske *et al.* 2019). Even professor Murray Gray, whose definition of geodiversity in his book "Geodiversity" (Gray 2013) is widely acknowledged, has recently proposed expanding the concept to include atmospheric components (Gray 2025). This discussion often arises from the common description of geodiversity as the "non-living" or "abiotic" diversity of nature, which can include both climate and geological, geomorphological or hydrological features. Furthermore, climate, as well as geology, are crucial aspects of environmental heterogeneity, which is a roof concept for variables that can be used in explaining species diversity patterns in ecological research (Stein, Gerstner & Kreft 2014).

While climate is undoubtedly part of abiotic nature and closely linked to geodiversity, just as it is to biodiversity, treating climate as part of geodiversity could potentially undermine the distinct value and application of both entities. Climate science is a well-established field with its own goals, methods, and applications. Keeping climate and geodiversity separate may, therefore, be more beneficial for advancing the agendas of both fields and for ensuring clarity in research and practical applications (see also Maliniemi *et al.* 2024). However, this separation does not preclude the study of how climate and geodiversity intersect and interact (Fig. 1).

In general, the development of geodiversity concept and geodiversity research illustrates the essence of scientific progress, where ideas emerge and evolve simultaneously across different regions, disciplines, and purposes. In this way, geodiversity research reflects the "paradigm" approach in modern science, where multiple discussions and competing perspectives eventually converge into a dominant paradigm, a common and coherent set of ideas about the world (Gray 2021, 2024; Inkpen 2005). As such, geodiversity is not exclusively a scientific concept but also represents the dynamic and iterative nature of scientific progress and the myriad ways science aims to understand physical reality.

Multidisciplinary concept

Although the concept of geodiversity has evolved during the last three decades, the idea of including a holistic perspective on abiotic nature in environmental research is not new. Over 200 years ago, Alexander von Humboldt (1769–1859) explored the connections between non-living and living nature from an interdisciplinary, interconnected perspective. Von Humboldt's research was grounded in a holistic approach, relying on systematic empirical observation, and as such, he is often regarded as the father of multiple "geo-" disciplines, such as environmental science, earth system science, modern geography and geosciences (Schrodt *et al.* 2019).

Humboldt's holistic view of nature has faded over time as science has become fragmented into specialized disciplines. However, his approach has resurfaced in fields like biogeography. For instance, Schrodt *et al.* (2019; in a theme issue in Journal of Biogeography dedicated to von Humboldt) highlight the importance of "Humboldtian" thinking in addressing current global challenges, and how studying the links between geodiversity and biodiversity can specifically contribute to this need. Here, knowledge across various disciplines and research fields is essential for exploring geodiversity from diverse viewpoints, including those from both the humanities and natural sciences (Fig. 2).

Today, geodiversity is studied across a broad range of disciplines, each bringing their unique perspectives and terminologies. Major research fields include, for instance, geology, environmental science ecology, geography, science and technology[1], physical geography, paleontology, biodiversity conservation, and water resources (based on Web of Science 7.10.2024, search word "geodiversity"; Fig. 2). Although much of this research

[1] In the field of telecommunications and computer sciences, "geodiversity" is used to describe geographical diversity of networks (i.e., it does not relate to diversity in nature).

is grounded in the natural sciences, a large portion is published in multidisciplinary geoscience journals, such as *Geoheritage*, highlighting the cross-disciplinary appeal of geodiversity.

Each research field (Fig. 2) emphasizes different aspects of geodiversity. In multidisciplinary geosciences, research often focuses on geoconservation (e.g., Brilha 2016), geoheritage (e.g., Németh *et al.* 2021) and geotourism (e.g., Dowling 2011), highlighting the value of geodiversity, geological features, geosites, and landscapes for their historical, conservation, and educational significance. In ecology, studies usually examine how geodiversity shapes ecosystems and is related to its biotic counterpart, biodiversity (e.g., Salminen *et al.* 2023 in northern tundra environments). Geographic research often centers on spatial and temporal assessments of geodiversity, including producing maps of geodiversity at various scales (e.g., Toivanen *et al.* 2024). It also contributes to system-level research, including aspects from geodiversity, biodiversity and climate change (e.g., Brazier *et al.* 2012).

In the diverse collection of research fields, geodiversity is further conceptualized with a multiplicity of terminology. Going through geodiversity literature, you will encounter a set of terms beginning with "geo" (Fig. 2). Some terms, such as "geoheritage" and "geoconservation," have become well-established. These terms emphasize the protection and preservation of significant geological features, sites and landscapes, an effort supported by organizations like International Association for the Conservation of Geological Heritage (ProGEO), which has promoted geoheritage

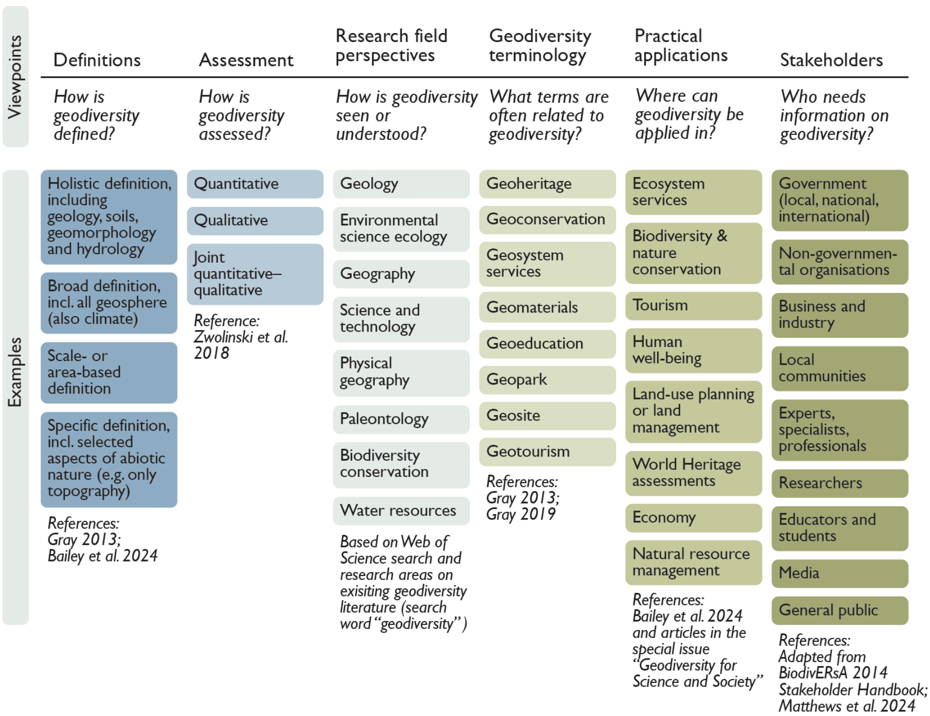

Figure 2. A collection of viewpoints in geodiversity research and applications which contribute to the diverse interpretations of geodiversity.

and geoconservation since 1993. For instance, the international *Geoheritage* journal was founded in 2009 by ProGEO (currently published by Springer), and the IUCN Guidelines for Geoconservation were published in 2020 (Crofts *et al.* 2020). Emerging terms like "geosystem services" represent newer interdisciplinary approaches still under active discussion (e.g., debate between Chen *et al.* 2023 and Gray *et al.* 2024). These and many other terms, such as "geoeducation" or "geomaterials", essentially emphasize the geodiversity related contributions, which are often overlooked in the context of nature's contributions to people.

Beyond purely scientific perspective, which can be dense with terminology, geodiversity also intersects with literary traditions. For instance, "geopoetics" blends geography, poetry, and human experience, originally emerging as a response to more analytical geographic approaches (White N.D.). The complex connections between language, human experience, and nature also span popular literature, from Aleksis Kivi (1834–1872), Finland's first professional writer, whose works infused landscapes with symbolic and emotional meanings (Turunen 2018), to contemporary authors, such as Anni Kytömäki, who vividly portrays Finland's diverse terrain in her novels, such as in the year 2020 Finlandia prize winner *Margarita*. Whether through research or storytelling, the way we speak about nature shapes how we see and protect it. As British writer Robert Macfarlane argues in his book Landmarks (2015): our ability to perceive and value nature and landscapes is deeply connected to the words we use to describe it.

While the diversity of perspectives enriches the study of geodiversity, it also presents challenges. The multiplicity of approaches can make it difficult to establish a unified definition of geodiversity on which can be agreed upon. On the one hand, this diversity allows for a more nuanced understanding of geodiversity's roles and values. On the other hand, the variety of interpretations and applications can diminish the concept's impact, making it harder to communicate its significance to varying audiences. Achieving a balance between contrasting perspectives and a coherent, shared understanding of geodiversity will be crucial for advancing both research and practical efforts.

Assessing geodiversity

Measuring geodiversity is essential in understanding the spatial and temporal patterns of geodiversity, tracking environmental changes and in guiding nature conservation efforts. How to assess geodiversity is an active topic of debate among researchers and practitioners across various fields and there are two primary approaches: quantitative and qualitative (Zwoliński *et al.* 2018; Fig. 2).

Quantitative assessments involve numerical methods to evaluate geodiversity across different areas. These assessments often rely on digital spatial data and geographic information systems (GIS), such as geological maps. In some cases, particularly at the local scale, geodiversity data can be gathered directly through fieldwork (e.g., Hjort *et al.* 2022). The results of these efforts are typically expressed as geodiversity indices or maps, with some datasets being made openly accessible (see e.g., European geodiversity data by Toivanen *et al.* 2024). However, despite technological and methodological advances, quantitative geodiversity datasets are still largely lacking and scattered (see also discussion in Schrodt *et al.* 2024).

Qualitative geodiversity assessments draw on expert classifications, descriptive documentation, or methods that emphasize the values and benefits associated with geodiversity. These assessments use various data sources, such as photographs, literature, or expert evaluations (Zwoliński *et al.* 2018). They can also explore more subjective elements, such as how people experience and perceive landscapes and their abiotic components. Such approach can also link geodiversity to broader contexts like human and planetary health (e.g., Alahuhta *et al.* 2022).

Quantitative geodiversity assessments are conducted and developed actively in northern environments. For instance, geodiversity of Finnish Lapland in northern Europe has been explored across many perspectives, from local (e.g., Salminen *et al.* 2023, based on field data from study circles of 5 m radius) to landscape scales (e.g., Hjort & Luoto 2010, based on field data and aerial photographs in a grid of 500 × 500 m cell size). Northern environments and specifically, their inherent wealth of geodiversity are also the focus and inspiration for our own geodiversity-themed PhD theses (Toivanen 2024; Tukiainen 2019).

Quantitative geodiversity measures have faced criticism for lacking a clear purpose or being too generalized, as they may overlook certain qualitative aspects of geodiversity, such as unique cultural, conservational, or aesthetic values (Gray 2021). Qualitative assessments, in turn, are considered to be more nuanced and context specific. On the downside, qualitative data collection is often more labor-intensive and time-consuming. Given the strengths and weaknesses of both quantitative and qualitative methods, the most comprehensive approach could be to integrate both perspectives (Zwoliński *et al.* 2018; Fig. 2). This would allow for a more complete and balanced understanding of geodiversity, capturing both its measurable properties and its broader, sometimes intangible, values. These values range from intrinsic to aesthetic, economic, functional and scientific values (Gray 2005; Hjort *et al.* 2015; see Box 1 where the values of Rokua UNESCO Global Geopark are explored in detail).

Essential geodiversity

Geodiversity is an essential yet often overlooked aspect of the natural world, playing a critical role in shaping landscapes, supporting ecosystems, and fostering human well-being. It forms the physical framework of natural environments and healthy ecosystems, but also influences human culture, identity, and our connections to nature. From mountains and rivers to caves and coastlines, geodiversity represents many things we depend on, from material resources to profound cultural and spiritual value (see also Box 1). Recognized in global initiatives, such as UNESCO Global Geoparks, Natural World Heritage Sites, and International Geodiversity Day by UNESCO, geodiversity emphasizes Earth's historical, aesthetic, and ecological complexity (IUCN 2024).

In everyday discussions, geodiversity is easily reduced to mere natural resources as we are accustomed to viewing minerals, sand, and other geological materials primarily in terms of their practical use, for example as building materials or parts of the electronic devices that we use daily. Sand, for example, is a key component of concrete, glass, and even modern technology, yet it is increasingly becoming a scarce resource due to overexploitation (Finite sand resource needs better governance 2024). Similarly, materials like lithium—critical for renewable energy technologies such as batteries for electric vehicles—highlight the tension between economic demands and sustainable management of geodiversity (Rentier *et al.* 2024).

Box 1. Case study: Unpacking geodiversity values at Rokua UNESCO Global Geopark

Geoparks are designated areas where geodiversity is actively studied, managed, and valued. This case study explores the diverse values of geodiversity through the example of Rokua UNESCO Global Geopark in Finland (Fig. B1.1), illustrating how geodiversity shapes landscapes, ecosystems, and human history. By examining the geological, biological, and cultural heritage of Rokua—all in the heart of the geopark concept—we can gain deeper understanding of the multifaceted significance and presence of geodiversity in practice. More specific examples of 30 different geodiversity-related values are given in Table B1.1. They are adapted and developed from the frameworks presented by Gray (2005) and Hjort *et al.* (2015).

Geological heritage. Rokua Geopark is home to some of the oldest bedrock in Europe, including gneisses that date back 2.9 billion years. The post-glacial landscape features regionally unique assemblage of geofeatures such as eskers, kettle holes, and sand dunes. In addition, the sedimentary rocks of the Muhos formation, which were once part of a shallow sea and river delta, contain fossils of primitive unicellular organisms, offering a glimpse into the history of life on Earth and the development of ecosystems (Huttunen *et al.* 2012). Different water elements are an important part of the landscapes of the geopark, including rapids, rivers and lakes of different sizes.

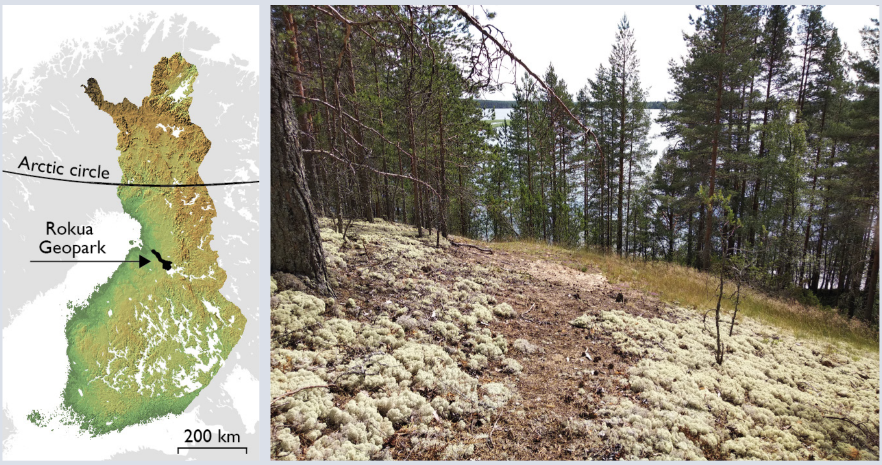

Figure B1.1. Rokua UNESCO Global Geopark, one of the northernmost geoparks in the world, is located in Finland, in northern Europe. Rokua National Park is located within the geopark area and is characterized by lichen-covered pine forests and lakes. Background maps are from the National Land Survey of Finland (topographic map) and Natural Earth (grey background map). Photo: Helena Tukiainen.

Table B1.1. Values of geodiversity with examples from Rokua UNESCO Global Geopark. Values are adapted from Gray (2005) and Hjort *et al.* (2015).

Value		**Examples**
Intrinsic value	Intrinsic value	biotic nature free of human valuations
Cultural value	Archaeological/Historical	Early settlement comb ceramics; Stone Age settlements; peasant culture in *Lamminaho House*; museums
	Folklore	Folktales in national epoch *Kalevala* from the village of Ahmas
	Spiritual	Old wooden churches from 16th and 17th centuries
	Sense of place	Local livelihoods and traditions (e.g., tar burning); *The Birch and the Star* tale by Zachris Topelius
Aesthetic value	Local landscapes	Post-glacial landscape features; dune landscapes; river valleys and channels; aapa mires; Lake Oulujärvi
	(Geo)tourism	Rokua National Park; nature attractions; cultural attractions
	Leisure activities	Trail network (e.g., *Tar route hiking trail*); foraging; fishing; canoeing; skiing; wellness
	Remote appreciation	Virtual reality experience initiative (*Aikamatka*); "story database" initiative (*Kiehtovat tarinat Rokua Geopark -alueen vetovoimatekijöiksi*)
	Voluntary activities	Dune habitat restoration in the national park
	Artistic inspiration	"An expedition into art" initiative (*Löytöretki taiteeseen*); *Kassu Halonen Art House*
Economic value[1]	Business support and collaboration	*Humanpolis Oy* (Geopark operations for residents, businesses and tourists); Geopark entrepreneurship; *Smart and Transformative Oulu Region* initiative
	(Geo)tourism, recreation and health	Geotourism as a tool for developing nature-based tourism (e.g., *Geoparks – attractive sustainable travel destinations* initiative); wellness (e.g., *Rokua Health & Spa*); outdoor activities (e.g., equipment rental)
	Cultural and heritage branding	*Rokua Skincare*; Local hand-made jewellery
	Energy	Hydropower (now also preserved as cultural history sites)
	Soil	Food production (e.g., GEOfood initiative)
Functional value	Platforms	Waterways as historical travel and trade routes
	Storage and recycling	Groundwater; peatlands as carbon sinks
	Health	Outdoors and variable landscape promotes physical and mental human health
	Burial	Graveyards
	Pollution control	Soil and rock as water filters
	Water chemistry	Drinking water
	Soil functions	Agriculture; forestry; water filtration
	Geosystem functions	Groundwater and surface water processes; flood regulation; carbon fixation
	Ecosystem functions	Habitat provision; supporting biodiversity

Value		Examples
Scientific value	Knowledge of Earth history, materials, and processes	*Kilonniemi* gneiss outcrop; *Luokkiniemi* diabase vein; *Pyhäkoski* granite cliffs; *Kieksi* conglomerate outcrop
	Fossils	Fossils in the *Muhos formation*
	Geoscience research	Post-glacial landscape and processes; groundwater processes; geodiversity
	Environmental monitoring	Microclimate; groundwater
	Education and training	Geopark as a "living textbook"; local Geopark schools; camp schools and excursions; research collaboration; GEOclimGOME-PRO initiative

[1]Traditionally, the economic values of geodiversity have been associated with its role as a resource (e.g., for energy or mineral extraction) (Gray 2005), but geodiversity also provides resources and assets for other aspects of economic development, such as tourism (Hjort *et al.* 2015).

Biological heritage. The diverse landscapes of Rokua support a range of distinct habitats, from lichen-covered pine forests to aapa mires and lush groves in the river valleys. For example, in Rokua National Park, which is located inside the geopark, sandy soils and hydrology influence vegetation patterns, creating specialized microenvironments (e.g., sunny and dry esker habitats) that sustain rare and endangered species (e.g., *Thymus serpyllum* subsp. *serpyllum* and insects feeding on them, such as *Pyrausta cingulata*) (Maliniemi *et al.* 2023).

Cultural heritage. Human interaction with Rokua Geopark's landscapes dates back to the Stone Age, as evidenced by early settlement sites and comb ceramics, among the oldest in Finland (Huttunen *et al.* 2012). The region's waterways historically served as trade and travel routes, shaping local livelihoods such as fishing, farming, tar production and forestry. Folklore inspired by the region's natural heritage in the village of Ahmas is reflected in folktales such as the Finnish national epoch *Kalevala*. Today, environmental art and different educational activities are one way of reaching people living, and visiting, in the geopark area (Fig. B1.2).

Figure B1.2. Geoparks highlight the many values of geodiversity, including artistic inspiration and educational activities. The image on the left features an environmental art project on a bridge crossing the Muhosjoki River, showcasing silver-barred sable (*Pyrausta cingulata*). The image on the right shows university students exploring the delicate nature of Rokua National Park during a physical geography field course. Photos: Helena Tukiainen (left) and Maija Toivanen (right).

Beyond natural resource management, geodiversity is integral in many other applications (Fig. 2). Ecosystems are shaped by their physical environment, and without protecting the geological and geomorphological features that sustain them, nature conservation efforts may be incomplete. Conservation has traditionally focused on biodiversity, but there is growing awareness of geodiversity's foundational role in these efforts (e.g., Gordon *et al.* 2022). Recent initiatives, such as the IUCN's guidelines for geoconservation (Crofts *et al.* 2020), the introduction of International Union of Geological Sciences (IUGS) Geological Heritage Sites since 2022, and the introduction of Essential Geodiversity Variables framework (Schrodt *et al.* 2019, 2024) are examples of integrating geodiversity into conservation applications. This evolving perspective has led to calls for a more inclusive definition of "nature" that fully acknowledges geodiversity's role in conservation applications, alongside biodiversity (Justice *et al.* 2025).

Beautiful landscapes and conservation areas, with unique geological features like mountain ranges, canyons, and coastlines, attract tourists. Destinations such as UNESCO Global Geoparks emphasize geodiversity by identifying sites of global geological significance, fostering conservation, and promoting sustainable tourism. These sites preserve unique geology and contribute to local economies and environmental education, showcasing the broad impact of geodiversity. However, the cultural and aesthetic value of geodiversity extends beyond tourism, inspiring art, literature, and a deeper human appreciation of the Earth's landscapes and physical properties. For instance, the concept of "national landscapes" (such as the landscape from Koli, Finland, in Fig. 3), demonstrates how geodiversity can also shape national identity and cultural heritage.

Figure 3. National landscape of Finland from the highest peaks of Koli to lake Pielinen. Painting by Eero Järnefelt (1923). Picture is retrieved from the Finnish National Gallery / Yehia Eweis under CC0 licence (https://www.kansallisgalleria.fi/fi/object/506760).

Future discussions

In this paper, we have explored a variety of current geodiversity discussions that essentially present it as a highly diverse concept with multiple interpretations, depending on the viewpoint of how it is approached or utilized (Fig. 2). There are ongoing discussions related to the terminology, assessment and application of geodiversity, but from whatever viewpoint, it represents an invaluable component of our planet's natural diversity, and an essential provision to its inhabitants. In the future, there are multiple aspects of geodiversity that can be acknowledged and developed by researchers, practitioners and by all in our everyday lives—from admiring and conserving beautiful scenery to using natural resources in a sustainable way. Researchers will be tasked with geodiversity knowledge production across many research fields and from different perspectives. For example, in the face of global land-use change from natural to human-impacted environments, it is increasingly important to study urban or man-made geodiversity (see e.g., Del Monte *et al.* 2016; Wolniewicz 2022). Many questions also remain under the topical theme of sustainability and its links to geodiversity (see e.g., Gray 2024; Matthews *et al.* 2024).

In turn, a wide range of stakeholders can benefit from improved access to, and knowledge of geodiversity (Fig. 2). For example, government bodies for policy-making, NGOs for conservation advocacy, and businesses for guiding sustainability strategies (e.g., Nokia 2023). Geodiversity information will be used by experts and professionals in regional planning, such as environmental impact assessment procedures (e.g., Sitowise 2024), while local communities could use knowledge on geodiversity to enhance their cultural identity and economic opportunities in such areas as tourism. Educators and students can play key roles in fostering environmental awareness across the greater public, with media serving as an essential link between different stakeholders.

In the face of global, human-induced environmental change, such as climate warming and growing natural resource extraction, information on geodiversity is essential. While biodiversity and climate are routinely included in international conventions, geodiversity is often overlooked, resulting in poor policy and management decisions regarding surface and subsurface features and resources (Bailey *et al.* 2024). The acknowledgement of geodiversity is especially timely in vulnerable northern areas, where for example, Arctic warming over the past decades has been almost four times larger than the global mean (van Oort, Lund & Brisebois 2022). As a consequence, it is predicted that unique landforms called palsas (peat hummocks with permafrost cores, found in regions of sporadic and discontinuous permafrost) will face dramatic or even complete loss during the next 60 years in the Northern Hemisphere (Leppiniemi *et al.* 2024).

Knowledge and appreciation towards geodiversity can broaden our perspectives towards reshaping our understanding of nature into a holistic, "Humboldtian" view by which to approach the Earth's natural heterogeneity (Schrodt *et al.* 2019). As Gray (2008, 2021) suggests, geodiversity is a multi-faceted and evolving paradigm that fundamentally shapes our understanding of Earth's diversity. By engaging with geodiversity—whether through scientific study, exploration of natural sites, or artistic expression—we can foster a greater appreciation for the diverse physical "stage" upon which life unfolds.

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Discussions and interventions

2024 ice jams and spring flooding across Ostrobothnia: observations and prospects

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Abstract

Seasonal snow and ice play a key role in the hydrological regimes of Arctic and sub-Arctic river catchments that differentiate them from their lower latitude counterparts. Against a backdrop of assumed reduced spring flooding due to ongoing Arctic warming resulting in shorter winters with less snowfall, we examine the prevailing conditions that led to spring-melt flooding, its impact and mitigation management strategies across Northern Ostrobothnia in April, 2024. We find that sustained freezing temperatures in early 2024, combined with thicker than average snowpack in March, preconditioned the region's catchments to two episodes of flooding driven by abrupt warm events and widespread snowmelt in early March and April. Due to their predominantly shallow, east to west long-profiles, the region's rivers received large fluxes of snowmelt runoff simultaneously along their entire courses, responding rapidly with rising levels and discharge. Thick river ice formed during the colder than average winter, causing ice jams at constricting pinch-points including bridges, dams and where rivers naturally shallowed or narrowed, leading to backup and flooding. Numerous effective civil interventions - including the release of discharge into managed agricultural areas – prevented extensive flood damage and major disruption to infrastructure other than temporary closure of some roads. We conclude that the event was pragmatically managed, precluding significant material damage and disruption. However, projected long-term climate scenarios indicating increased temperature fluctuations and extreme precipitation – including snowfall - events associated intense warm air intrusions, coupled with potential meter-scale relative sea- and base-level rise could act in consort to increase the region's winter and spring flood risk, rather than mitigate it.

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Key Points

- At the turn of March and April 2024 – earlier than average – severe floods occurred in the Northern Ostrobothnia River basins; flooding was greatest on the Kalajoki River.
- The floods were associated with intensive thawing of snow cover and ice crumbling, and was accompanied by ice phenomena, including ice jams.
- Civil intervention and rescue operations, with early anticipation of the situation, meant that the floods were effectively managed with no significant material loss or disruption.

Introduction

The hydrological regimes of Arctic and sub-Arctic River catchments modulated by seasonal freezing and interceded by abrupt thawing and snowmelt, contrast markedly with their lower latitude counterparts. The onset of warmer spring temperatures kickstarts these hydrological systems after sustained sub-zero temperatures throughout winter. Such extreme meteorological conditions co-determine the timing and magnitude of potential spring snowmelt river flooding, which remains the primary factor responsible for natural hazards and related infrastructure and other material losses (e.g. Grigorieva & Livenets, 2022). Major sub-Arctic Siberian rivers – the Ob, Yenisei, Lena – and their tributaries are typically associated with high magnitude, seasonal snowmelt floods. These rivers are of considerable length with a strong meridional profile that traverses numerous climatic zones. As a result, the spring thaw typically migrates northwards from southern latitudes, causing the formation of snowmelt floods in the upper (southern) reaches of rivers, which subsequently encounter ice barriers within the still-frozen riverbeds downstream to the north (Myglan & Vaganov 2011; Kichigina, 2020). In Siberia, such ice jams result in high magnitude flood waves that are amplified by specific drainage basin configurations and catchment hypsometries where initially, snowmelt and subsequent thawing ground across extensive areas within their southern (upper) zones, act to overwhelm the system and the resulting flood hydrograph (Shiklomanov *et al.*, 2007).

In northern Europe, the scale of the river systems and the associated spring floods are considerably smaller. Floods across Scandinavia, particularly Finland, are a frequent and well-documented phenomenon. Despite this, spring floods remain difficult to forecast due to variable meteorological conditions and difficult-to-determine water storage accumulated in heterogeneous snow distributions with contrasting density and thermal profiles. The ice situation on rivers is also a key factor, itself determined by the magnitude, duration and consistency of winter cold-spells, and the associated formation of ice jams that impede river discharge.

In Finland's Ostrobothnia and Lapland regions, complex yet shallow gradient river network systems and their associated hydrological regimes can result in severe spring snowmelt flooding. The main rivers flowing into the Gulf of Bothnia run longitudinally from east to west, and the spring thaw, which generally progresses northwards from southerly latitudes, in contrast to Siberian systems, impacts river networks along their entire lengths over just several days. This also distinguishes these river systems from those in southern Finland, where large floods can occur at any time of the year and are most often driven by intense rainfall in the summer.

In this paper, we briefly describe the flood events in Ostrobothnia during the spring of 2024 and present the hydrological causes and impacts of the specific river systems flowing into the Gulf of Bothnia. We utilise data collected by the Finnish Meteorological Institute and their joint hydrological monitoring network with, for example, Kemijoki Oy and draw on information from a summary published by the Finnish Environment Agency, ELY information centres, the Finnish Meteorological Institute and the Flood Centre. We further illustrate our study with observations from the Kalajoki River valley in April and May 2024.

Conditions of flooding

Finland's river systems can be hydrologically characterised and grouped by area into three primary regimes: 1) catchments of the lake regions of Southern and Central Finland with high retention capacities and low flow variability, 2) small river catchments in the coastal areas of the Gulf of Finland and the Gulf of Bothnia with high flow variability and, 3) large rivers of Northern Ostrobothnia and Lapland with efficient, seasonal flow regimes (Mustonen, 1986). It is notable that all of Finland's largest rivers are regulated, at least in their lower catchments through dams and storage structures primarily purposed for harnessing hydropower, but as a by-line regulating discharge. The large latitudinal gradient and the influence of variable air masses with very different meteorological conditions mean that thermal-pluvial conditions are diverse across Finland, particularly in winter (Veijalainen *et al.* 2010). Over the 1971–2000 reference period, the mean annual temperature across Finland varied between 5°C and −2°C, and the mean precipitation rate between 450 mm and 700 mm per year (Drebs *et al.*, 2002). The thermal winter defined by daily mean sub-zero temperatures, lasts in northern Finland 100 days longer on average compared to southern Finland, and terrestrial snow-cover persists on average for 150–190 days per year.

In northern Finland, just over 95% of the annual peak river discharge events occur in spring, coinciding with the onset of abrupt snowmelt, which contrasts with southern Finland where such floods occur year-round (Korhonen & Kuusisto 2010; Veijalainen *et al.*, 2010). Ostrobothnian rivers are particularly sensitive to spring floods, mainly in April and May. These rivers drain low-lying areas with only a few shallow lakes able to alleviate the flood wave and buffer the flood hydrograph (Figure 1). The highest daily discharge recorded instrumentally in Finland was 4824 $m^3 s^{-1}$ at Isohaara on the Kemijoki River in Lapland in May 1973, compared to a mean annual maximum discharge at this location of just ~2900 $m^3 s^{-1}$ (Albrecht, 2023). In Northern Ostrobothnia, floods occurred in 1977, 1982, 1987, 1997, 1998, 2000 and 2002, and on the Kalajoki River, the largest flood recorded was on 25 April 2000 when a discharge of 384 $m^3 s^{-1}$ was recorded in the town of Ylivieska (Räsänen, 2021).

Not only are the long profiles of these rivers very shallow, but they also flow east to west, which favours snow and river ice melt along their length simultaneously, leading to abrupt increases in discharge and water levels over a relatively short period of a few days. They mainly drain agricultural areas with a moderate population density across rural Finland, though these rivers also flow through some major towns and cities with high population density. Due to the behaviour of river ice, a number of natural or man-made obstructions to flow along river courses become critical foci during spring floods, where there is channel narrowing, shallowing across rapids and low bridge profiles, dams and other structures. It is the low-lying agricultural or built-upon land areas around these constricted channel zones - pinch-points - that are susceptible to flooding.

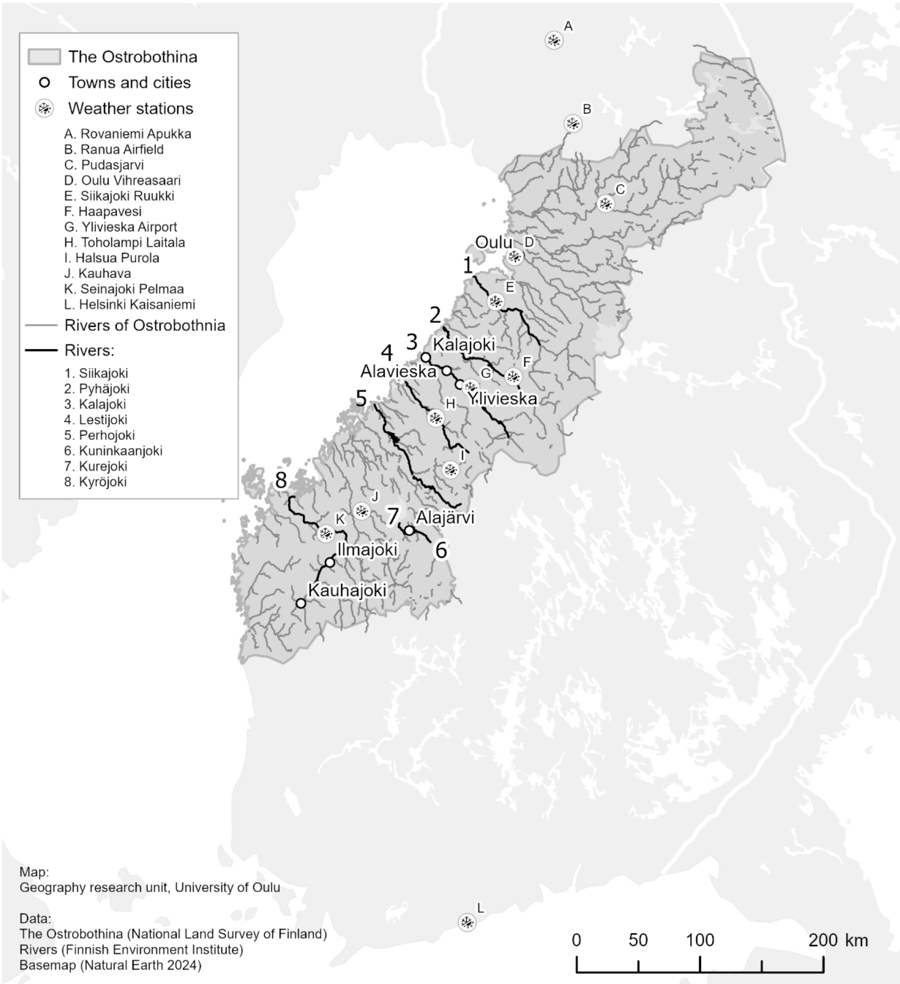

Figure 1. Study area of Ostrobothnia – main rivers and catchments discussed.

Flood in spring 2024

Towards the end of March 2024, snow accumulation across Ostrobothnia was well above average. Snowpack thickness in the upper parts of individual catchments was 100 to 130 mm w.e., and up to 150 mm w.e. in some areas (https://www.vesi.fi/en/karttapalvelu/). The ice cover on rivers was also thicker than the long-term average after winter temperatures well below -15°C sustained over long periods. The spring snowmelt occurred in several stages. The first warm period occurred in mid-March (Figure 2), and melting impacted mainly the southernmost reservoirs. Stronger warming and accompanying rainfall occurred over the Easter period; for example, in Kauhajoki (Suupohjan seutukunta), which received ~22 mm of rain. More intensive snowmelt occurred on 8 April when air temperatures rose to 5°C accompanied by rainfall of 15 – 25 mm. This warm spell led to a situation that favoured river flooding, and which abated in mid-April with the re-establishment of sub-zero temperatures for ~10 days.

Though the local discharge primarily reflected prevailing weather conditions, the key importance lay in the flow control of numerous water-storing structures. The Lapväärtinjoki, in Southern Ostrobothnia region, received its highest discharge on 12 April. Earlier, on 10 April, high water levels were recorded in the neighbouring upper reaches of the Kyrönjoki. Here, the impending flood wave was flattened by the managed diversion of ~12.5 million m^3 of water into natural overspill areas, predominantly composed of agricultural areas where a floodplain of 1,900 ha was formed. This affirmative action was carried out to protect the city of Ilmajoki. Similar management and active flood prevention measures were also carried out on the Lapuajoki, with the resulting peak flow of its lower sections occurring on 13 April, with high water levels sustained from the end of March through to mid-May. Within the Ähtäväjoki catchment, particularly high floodwater discharges were observed on the Kuninkaanjoki, which flows into Alajärvi, and also the Savonjoki, which flows into Lappajärvi, with peak discharge from these reservoirs recorded at ~50 $m^3 s^{-1}$. Ice dams also appeared, causing a flood hazard for the recreational cabins and other infrastructure on and near the riverbanks. Ice dams also posed a hazard on the Perhonjoki River, when its peak flow was recorded on 14 April.

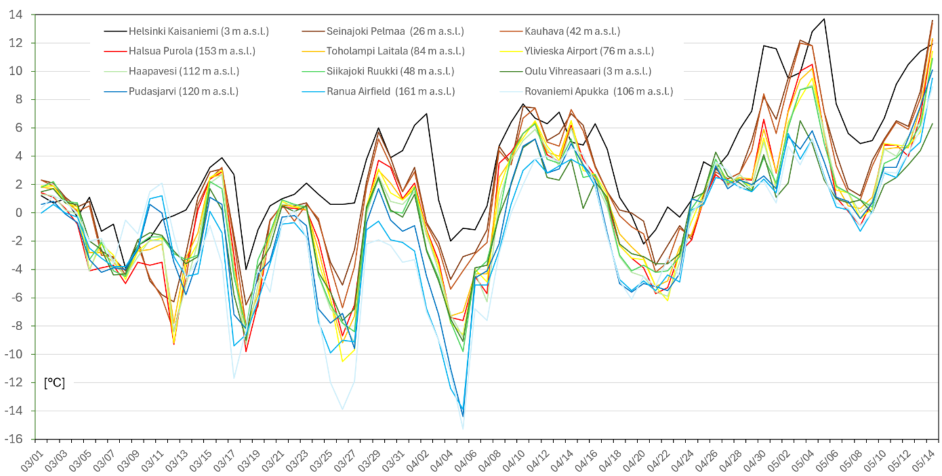

Figure 2. Daily air temperatures across Finland in spring 2024 (data source: Finnish Meteorological Institute).

The spring melt and associated flood events drew significant media attention. The Finnish news services focused on the Lestijoki and Kalajoki river valleys further north. At Lestijoki, the observed hydrograph reveals three distinct peaks (Figure 3) with the Saarenpää gauge indicating a marked increase in daily discharge from 30 March onwards. On 3 April, the flow attained 29 m^3 s^{-1} and subsequently started to decrease. The next major event began on 8 April, with the subsequent flood peaks occurring on 14 and 15 April, with corresponding discharges of 152.6 and 153.1 m^3 s^{-1}, respectively. The third peak was on 1 May with a moderate discharge of 64 m^3 s^{-1}, after which the discharge tailed off to its mean base-flow rate of 13 m^3 s^{-1} on 22 May. The main discharge peaks and high-water flows were accompanied by major ice jams, resulting in a critical situation that threatened the bridge in Saarenpää on the border of the municipalities of Kannus and Himanka.

The spring flooding of 2024 had a moderate impact on residents of the municipalities along the Kalajoki River (Figures 4 and 5) that were well documented. At the Hamari gauge in Ylivieska, above-average discharge of 21.2 m^3 s^{-1} was measured on 2 April, followed by a significant increase in the river's water level from 8 April. This spring flood wave culminated with a discharge of 276 m^3 s^{-1} on 15 April, after which it subsided. However, two weeks later, the river level rose again on 1 May with a corresponding discharge of 155 m^3 s^{-1}, which was sustained through until 21 May.

River ice and ice-related phenomena accompanied and compounded the 2024 spring snowmelt floods. An ice-dam formed in the centre of Alavieska on 11 April, which lasted for two days until it disintegrated on 13 April. The loose, flowing ice then subsequently accumulated at the village of Tynkä. The excess backed-up discharge overtopped the river banks and flowed extensively across the natural floodplain zones between the towns of Ylivieska and Alivieska, with the flooded area up to 2 to 4 km wide in the village of Niemelänkylä. This village is one of the three key flood risk areas identified in Northern Ostrobothnia, and accordingly, local rescue services anticipated that its 140 inhabitants would need to be evacuated. Ultimately, only four people needed direct assistance from the municipality. Rescue and mitigation efforts were mainly concerned with pumping water from basements and securing low-lying houses against flooding, as well as providing advice on property protection and safety. There were, though some knock-on, indirect issues particularly concerned with floodwater interference with the sewage system and disposal.

On 13 April, rescue operations focused on Ylivieska, where significant ice-jams dammed and raised the river level, resulting in moderate local flooding that inundated several roads. On the evening of 14 April, all traffic was closed on roads Ämmäntie and Letontie in Kalajoki, Sievinmäentie (between Koivuoja and Markkula) in Sievi, Kiveläntie (Junno and Mönkö) in Nivala and Hamarintie in Ylivieska due to this extensive flooding. Earlier, the road to Väätintie (Akanneva and Väätti) in Alavieska was also partially flooded. Water levels were also anticipated to rise on rivers further north. An ice-dam formed in the municipality of Pyhäjoki, backing-up the discharge and raising the river-level along the Pyhäjoki, resulting in floodwater that inundated several local roads. The cold-snap and return to sub-zero temperatures from mid-April for 10 days thereafter acted to suppress the risk of further flooding across Ostrobothnia.

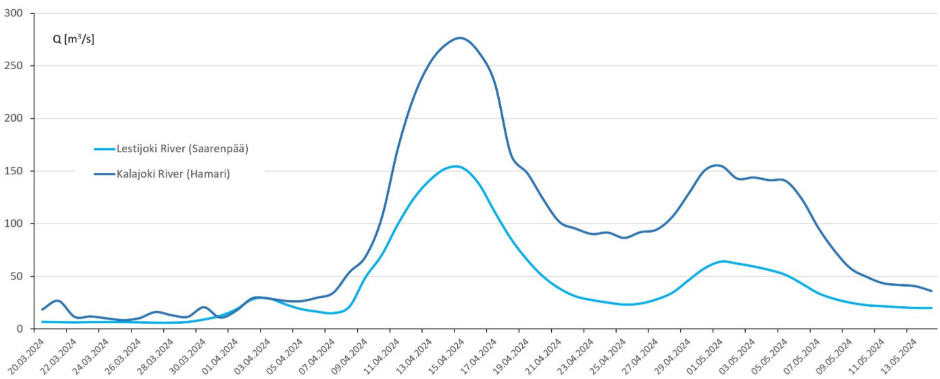

Figure 3. Average daily discharge for the Lestijoki and Kalajoki rivers in spring 2024 (data source: vesi.fi).

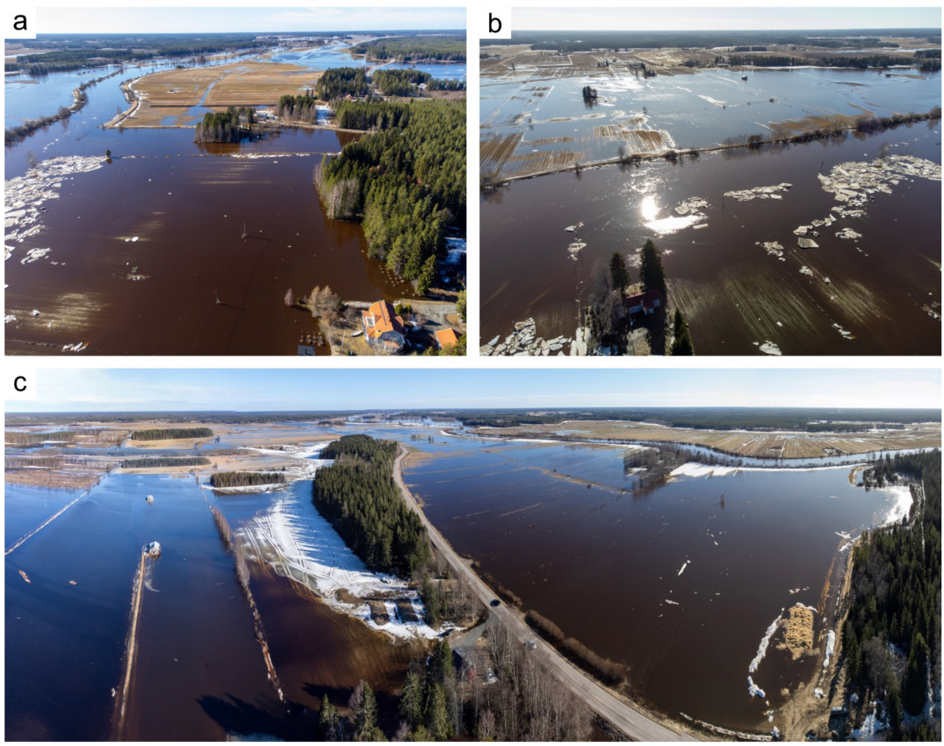

Figure 4. Flood of the Kalajoki river (April 14, 2024): a–c – inundation on the Niemelänkylä–Korteperä section (photographs M. Kasprzak).

Discussion

During the events of April 2024, the rescue services in Northern Ostrobothnia were called on and performed over 80 flood-related tasks. Press reports reveal that the response services were highly effective in their flood control activities, as had been previously reported for specific rivers in spate – such as Kemijoki – in the last few years (Räsänen 2021; Albrecht 2023). Although it was reported that the Kalajoki flood was exceptionally large, events of a similar magnitude have occurred in recent decades that neither caused major damage, material losses or threatened the population. Its course and floodwater extent was well within the scenarios assumed in the planning documents for flood risk management (Kettunen *et al.*, 2015; Parjanne *et al.*, 2018).

Our observations along the Kalajoki river catchment confirm that the region is well prepared and protected for flood risks. This has been achieved through completed flood control measures in the formation of riverbeds, the construction of flood embankments and levees, and the raising of road surfaces. It would be unrealistic and exceptionally expensive to attempt to entirely preclude excess water from the river's natural floodplain areas. Hence, the designation of specific flood areas combined with public dissemination are equally important in long-term mitigation strategies. Despite the direct flood threat to some low-lying buildings, along with additional risk from fast-flowing ice, the inhabitants of the region were well prepared for the events and there was no panic or undue emergency. One notable consequence of the build-up of river ice and subsequent jams in 2024, was the direct impact on river bank erosion. Large blocks of river ice, once released and packed tightly can exert large mechanical forces on the river channel in numerous places, resulting in selective, but significant bed and bank erosion, impacting on the rivers sediment load and downstream water quality.

Work is ongoing to improve flood prediction in high-latitude regions, where snow accumulation and its subsequent spring melt play a key role in the hydrological regime of complex river systems. Veijalainen *et al.* (2010) argued that snowmelt floods will be less frequent in Finland with ongoing increasing temperatures and climate warming. Similar forecasts were recently summarised by Parjanne *et al.* (2021), with the reduction in the scale of spring floods expected to mainly impact southern and central Finland. In the rivers of the north of the country, this trend may not be noticeable in the short term or may even be contrary, due to an observed increase in precipitation and particularly extreme snowfall (Bailey *et al.*, 2021; Bailey & Hubbard, 2025) despite generally milder temperatures and a shortened winter season. This is against the general backdrop of a predicted increase in flood frequency observed across Europe due to a corresponding increase in high-magnitude rainfall events (Fang *et al.*, 2024).

In the case of Ostrobothnia, future flood scenarios should also consider accounting for eustatic sea level rise, which may well exceed the long-term glacio-isostatic uplift response over the next decades (Rosqvist *et al.* 2013; Pellikka *et al.* 2018; Watson Hubbard & Hubbard, 2025). Around the Gulf of Bothnia, where the mitigating isostatic rebound response to the deglaciation of the Fennoscandia at around 15ka BP (Patton *et al.*, 2016) remains strong, current eustatic sea-level rise of ~4.5 mm a^{-1} is largely offset, resulting in only a minor incremental increase or even a lowering in relative sea-level. However, such conducive conditions are unlikely to sustain even under current greenhouse gas emission scenarios, not to mention faster-than-forecast mass loss from the Greenland and Antarctic ice sheets (e.g. Box *et al.*, 2022), that could potentially drive meter-scale eustatic sea-level rise. Considering the most recent round of IPCC projections (AR6, 2021), the incremental sea-level rise in the Gulf of Bothnia

Figure 5. Ice jams and other phenomena on the Kalajoki river (April 14, 2024): a, b – ice floe beyond the riverbed in the town of Ylivieska; c, d – ice floe in front of local barriers on the Niemelänkylä–Korteperä section; e – ice jam near the village of Tynkä; f, g – traces of flood in the vicinity of the Vetenoja village (photographs M. Kasprzak).

occurs even under best-case scenarios (Watson Hubbard & Hubbard, 2025). Under worst-case scenarios, multi-meter elevation of river catchment base levels will occur, compounding local and upstream flood risk.

One indirect and somewhat unexpected consequence is that Spring floods have resulted in a new phenomenon dubbed "flood tourism" in the press. While curiosity regarding natural processes and observations of ice jams and raised water levels is understandable, the deliberate driving of vehicles through flooded areas is an undesirable and somewhat counter-productive consequence, further complicating, and occasionally leading to new rescue operations. General interest regarding the new phenomena of "flood tourism" led the Kotimaisten kielten keskus (Institute for the Languages of Finland) to announce it as its "word of the year" for 2024.

In conclusion, we find that existing hydrological scenarios related to climate change cannot assume a decreased flood risk across Ostrobothnia despite warmer and shorter winters. With increasing global temperatures, particularly across the Arctic, spring floods may occur earlier or otherwise become more vigorous as more frequent warm-air incursions, occurring throughout winter as well as spring, will become the norm. As a result, river ice regimes will continue to change – generally becoming shorter but also potentially undergoing multiple ice formation/breakout cycles each season (Yang *et al.*, 2020). Our observations of the spring snowmelt floods in 2024 appear to confirm this. It must not be ruled out that floods caused by rainfall and storm events in other seasons will also occur with increased intensity and frequency, and may be further compounded by such intense rain falling on impermeable frozen ground, with high runoff potential and significant flash-flood potential. Despite Finland's rapid and pragmatic civil response to managing increasing flood-risks, as evidenced by the minimal infrastructure damage, disruption and cost of the April 2024 floods we observe here, there is no room for complacency as baseline climatological, meteorological and hydrological system parameters will continue to change over the next decades. Forecasting of catchment runoff and flooding scenarios, coupled with the changing river ice situation through improved hydraulic modelling based on future synoptic-scale climate scenarios, will be critical. Moreover, a pragmatic strategy might also consider observations from recent events and closely monitor and learn how system's forcing and response is changing in real-time.

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