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ORIGINAL ARTICLE

Compound hazards of climate change, forestry, and other encroachments on winter pasturelands: a storyline approach in a forest reindeer herding community in Northern Sweden

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Abstract
The impacts of climate change on rural cultures and livelihoods depend on how the resulting complex biophysical processes may transform people's land use practices. We argue that research can incorporate local concerns of compound hazards through deterministic rather than probabilistic approaches to better understand the multiple causations involved in such climate change impacts. We apply mixed methods within a storyline approach to examine how a forest reindeer herding community in Northern Sweden copes with and experiences basal ice formation on their winter pasturelands under the influence of climatic and environmental change. Our results show that the detrimental impact of basal ice formation on the availability of winter forage for reindeer is amplified by the directional effects of climate change and encroachments, especially particular forestry practices and their surrounding infrastructure. On the one hand, we show that policy action can address local concerns through ecological interventions that improve the amount and distribution of ground and pendulous lichens at the pastoral landscape scale. On the other hand, we show that policy inaction can threaten the community's desired experience of human-animal relations in their landscape, which was inextricably connected to ecological conditions for natural pasture-based reindeer pastoralism.

Keywords Reindeer husbandry · Snow conditions · Climate change · Encroachments · Compound events · Deterministic approaches

Introduction

Climate change has worsened the winter grazing conditions for reindeer pastoralism in Sweden (Rasmus et al. 2022)—an important cultural and livelihood practice among the indigenous Sámi people that is based on free-ranging animals that use natural pastures (Holand et al. 2022). Reindeer pastoralism produces food and provides multiple ecosystem services within its multi-purpose landscapes (Axelsson-Linkowski 2012), including climate warming mitigation as grazing supresses the greening of mountain ecosystems, counteracting albedo feedbacks (Skarin et al. 2020; te Beest et al. 2016). The land on which reindeer pastoralism is practiced also represents ancient cultural landscapes in which the Sámi people hold customary and indigenous rights to land, water, and natural resources and carry the collective experience of a colonial history (Bergman 2018; Östlund & Norstedt 2021).

In Sweden, reindeer pastoralism is organised in reindeer herding communities (RHCs), which "constitutes a geographic, economic, and legal entity" where members "are usually organised in winter groups (siida), which may consist of one or several reindeer herding enterprises" (Holand et al. 2022: p. 41). For RHCs, *winter pasturelands* refer to both seasonal pasturelands that are mostly located in boreal forests (that also include other values and ecosystem functions) as well as administrative areas in which RHCs have grazing

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rights between the 1st of October and the 30th of April (Holand et al. 2022). The pastoral winter season is a critical time in the annual herding cycle, wherein the accessibility of ground and pendulous lichens as forage is vital to the survival of the herd (Horstkotte and Djupström 2021; Harnesk 2022), although their food intake can consist of other grazing plants as well (Mathiesen et al. 2000). Decades of statements from reindeer pastoralist organisations and academic peer-reviewed research have discussed the importance of well-functioning boreal forest ecosystems for reindeer populations and highlighted their deteriorating ecological state as a result of the cumulative effects from encroachments and climate change (Horstkotte et al. 2022). Intensive forestry has (with significant spatial coverage) resulted in the loss, degradation, and fragmentation of lichen habitats, mainly due to forest densification and changes in forest age structure (Horstkotte & Djupström, 2021; Harnesk 2022). Here, Forest RHCs and Concession RHCs[1] are particularly affected as their herds are located within boreal forests for the entire year, in contrast to Mountain RHCs that "migrate between summer pastures in the mountains at the border to Norway and winter pastures in the lowland forest" (Holand et al. 2022: p. 41).

In rural areas, including land used by pastoral and indigenous communities, climate research is becoming increasingly influential in politics that affect landscapes and natural resources. We have argued elsewhere that probabilistic event attribution using risk-based and statistical analyses of extreme weather events and its connection to potential financial compensation under the loss and damage policy regime comes with ethical concerns, not least for reindeer pastoralists (Olsson et al. 2022). This is mainly related to how extremes are defined in policy, as well as data limitations related to statistical analysis, also in relation to multiple causation (Olsson et al. 2022). In this paper, we seek to understand the perspectives of reindeer pastoralists on the multiple factors that influence forage availability, including climate change, and interpret local concerns of compound hazards through a place-attachment lens. The results will contribute to ongoing debates in the science–policy interface on climate change and biodiversity.

We adopt a *storyline approach* (Lloyd & Shepherd 2020), which can be likened to a crime scene investigation in which multiple lines of circumstantial evidence are collected to determine the most likely perpetrator. It is primarily a deterministic rather than probabilistic approach, which we argue can better demonstrate causal factors that affect the level of impact that weather and climate events have on reindeer forage availability. We define a *hazard* according to the IPCC as a "natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources" (Möller et al. 2022: p. 2911). By *compound hazard*, we put emphasis on multivariate notions of causality, where impacts of hazards in specific locations are understood as arising through a combination of drivers, rather than primarily climate drivers of individual weather events (Zscheischler et al. 2020). In this case study, we focus on basal ice formation, specifically *botneskárta*[2] (Eira et al. 2013), which refers to basal ice, under snow, that is thick enough to coat forage resources at the ground vegetation layer with ice, making key forage resources inaccessible. Ground lichens in particular are critical to reindeer survival as they can make up to 70% of the reindeer's food intake during the pastoral winter season (Åhman and White 2018; Storeheier et al. 2003), making botneskárta one of the worst snow conditions for RHCs, with substantial associated costs and burdens.

Basal ice can be formed during unusually warm weather events during snow cover periods, when the snowpack receives sufficient liquid water amounts from snowmelt and rainfall to percolate through it (Rasmus et al. 2018). It then reaches the surface of the ground, where it may subsequently refreeze when air temperatures drop to below zero (Rasmus et al. 2018). A frozen ground contributes to basal ice formation by impeding the rain and meltwater from percolating through the soil column (Rasmus et al. 2018). Two types of weather events can create conditions for this to occur, rain-on-snow events and thaw-and-freeze events, both of which mostly occur between October and December (Rasmus et al. 2018; Pascual and Johansson 2022). The temporal scales of these events are short (hours to days), and they may appear as extreme warming and/or rainfall events (Rasmus et al. 2018). Even one single event can, under unfortunate conditions, generate basal ice formation (Rosqvist et al. 2021). These events must be followed by temperatures below 0 °C for the basal ice to remain (Rasmus et al. 2018). In cases of basal ice formation, ground lichens generally remain inaccessible to reindeer until the melt that occurs during the arrival of spring (Rasmus et al. 2018; Ryd and Rassa 2020). The spatial variability of basal ice formation is high because it depends on local snow conditions and the lateral redistribution of water, which in turn depend on, for example, local topographical and land cover factors, as well as the specific timing, duration, and intensity of rain-on-snow and thaw-and-freeze events (Rasmus et al. 2018).

We examine how members of a Forest RHC cope with and experience basal formation within their pastoral landscape under the influence of climatic and environmental change. This case study examines the Maskaure RHC, one

[1] Concession RHCs are located by the border of Finland and have another legal system based customary reindeer ownership among local farmers, effectively allowing non-Sámi ownership of reindeer.

[2] Northern Sámi language.

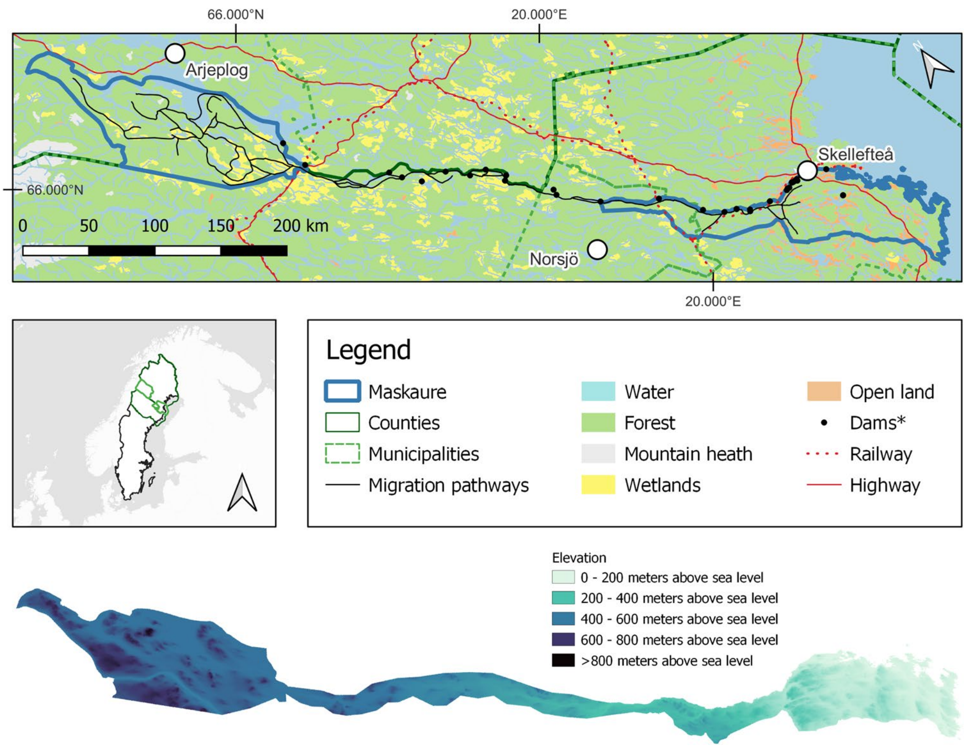

Fig. 1 Location of Maskaure's pasturelands and administrative borders for municipalities of Arjeplog, Norsjö, and Skellefteå, as well as the counties of Norrbotten, to the North, and Västerbotten, to the South (Lantmäteriet 2019, 2022a, b; Länsstyrelsernas geodatakatalog 2021). We will refer to Maskaure's areas to the west as their year-round lands and those to the east as their winter pasturelands, although both are administrateively categorised as winter pasturelands. *Hydropower–related dams on Maskaure's pasturelands and migration pathways

of the smallest in Sweden, currently with one winter group, *siida*,[3] coordinated by four full-time active pastoralists and a maximum allowed amount of 3000 reindeer in their winter herd. In collaboration with the RHC, we sought to answer two sets of research questions:

1. What are the causal factors leading to basal ice formation impacting forage availability? Has climate change already resulted in detectable changes to these factors, and how might climate change contribute to these factors in the future?
2. How does the RHC respond to basal ice formation? How would they prefer to respond to basal ice formation? How does place-attachment affect their experience of basal ice formation events?

Our goal is to better understand what constitutes ecological conditions conducive to natural pasture-based reindeer pastoralism on winter pasturelands in order to articulate and promote management and planning that better supports its continuation.

Study area

Maskaure is a Forest RHC with pasturelands in Northern Sweden located between ~ 66°00 and 64°40′N (Fig. 1). It contains a range of environments including mountainous forests and forested lowlands towards the Baltic coastline. Traditionally, the large-scale migration from autumn to winter pastures (from the west towards the east) occurs in November–December, and from winter to spring pastures (from the east towards the west) occurs in March–April. We focused on the winter pasturelands located in eastern inland and coastal Västerbotten County, because the hazard that we study mainly impacts grazing dynamics on those seasonal pasturelands.

The forests in our study area are located within the subartic middle boreal zone. They are dominated by Scots pine (*Pinus sylvetris*) on dry and oligotrophic heaths and Norwegian spruce (*Picea abies*) on moist sites (Esseen et al. 1997). The ground vegetation generally contains more bryophyte and lichen species than vascular plants, with lichens being particularly abundant on pine heaths and rocky ground (Esseen et al. 1997). The climate in the area is strongly influenced by the Atlantic Ocean, resulting in relatively deep snowpacks (> 30 cm) during winter (DJF)—with low frequency of extreme cold and warm spells and frequent shifts between cold and mild periods.

Within the Maskaure RHC, mean winter (DJF) air temperatures exhibit an east–west gradient, ranging from – 6 °C in the east to – 10 °C in the west (SMHI 2022). Precipitation decreases westwards due to the shadow effect caused by the Scandinavian Mountains and ranges from ~ 700 mm in the east to ~ 550 mm in the west (SMHI 2022). However, mean winter snow depths increase westwards, from ~ 30

[3] Northern Sámi language.

to > 50 cm, due to the longer cold seasons and the more sporadic occurrence of melt and/or rain events (SMHI 2022). The Maskaure RHC's land area has undergone rapid warming, most apparent in winter but discernible throughout the year: the mean annual air temperature for 2012–2021 was ~ 1.5 °C higher than that for 1971–2000 (SMHI 2022), while mean winter air temperature increased by ~ 3 °C (Bell et al. 2021). Other climate research comparing the time periods 1991–2018 with 1961–1990 also observed increases in air temperature and precipitation (SMHI 2021a) and in the number of zero-crossing days (SMHI 2021b) in the same areas.

We focus on two key forage resources for reindeer on Maskaure's winter pasturelands: ground and pendulous lichens (Harnesk 2022). *Cladina* species represent the most common ground lichens for reindeer feed; however, these can only be effectively grazed when snow conditions allow reindeer to access them (Harnesk 2022). The most common pendulous lichens are *Bryoria* and *Alectoria* species and become important forage resources in winter pasturelands when snow conditions limit reindeer access to ground vegetation (Harnesk 2022). However, they are sensitive to air pollution and forest fragmentation (Esseen et al. 2016) and require forests that are older than 60 years to establish themselves and over 110 years to become plentiful (Dettki and Esseen 2003).

In the Västerbotten County, forest land with over 50% ground lichen cover has declined from 10% in 1955 to 3% in 2013 (Sandström et al. 2016). This habitat degradation has occurred mainly as a result of intensive forestry operations, especially clear-cutting, intensive soil preparation, and dense reforestation practices that remove lichens and limit their access to light, which promotes other competitors at the ground vegetation layer (Horstkotte and Moen 2019). As for pendulous lichens, in the Västerbotten County, the forest age structure has been reduced between 1955 and 2017, both in terms of the share of forest land with forests 60–120 years old (from 47 to 30%) and forests older than 120 years (from 20 to 15%) (Swedish National Forestry Inventory 2022). In the eastern inland and coastal zones of the Västerbotten County, old-growth forests are also increasingly fragmented, with the share of intact proxy continuity forest patches on forest land (i.e., forests not subjected to clear-cutting, a logging practice in which all or most trees in an area are removed at the same time) having declined from 75 and 84% in 1976 to 43 and 57% in 2013, respectively (Svensson et al. 2019). This development is also mostly due to intensive forestry operations, especially short rotation times, which has reduced the area of suitable habitats for pendulous lichens (Esseen et al. 2022, 2016).

Other land uses also affect Maskaure's reindeer pastoralism in the study area. Railway and road networks, mines and gravel pits, and an airport have contributed to landscape fragmentation. Migration pathways and the north border of the winter pasturelands follow the Skellefteå River, which on Maskaure's lands contains 13 hydropower production units and connected dams that affect mobility options. Grazing pressure is also affected by overlaps between the Malå and Maskaure RHCs west of the railway and that the Svaipa, Ran, and Gran RHCs have also occasionally had their reindeer grazing in the study area during winters in the past (SOU 2006).

Materials and methods

We adopt mixed methods within a *storyline approach* (Lloyd and Shepherd 2020), which entails approaching hazards in ways similar to forensics, starting from the impact of an event and tracing the causal factors that led to that outcome. Such an approach is well suited in situations where several contributing factors are at play in causing an impactful event. Such causal factors can either be independent of each other or linked as a cascading chain. This could render the use of resilience of coupled social-ecological systems appropriate, but we caution against this in situations where the stressors are increasingly human rather than environmental (Thorén and Olsson 2018). In order to get a broad overview of possible causal factors, we began by organising a workshop together with leading members of the Maskaure RHC and discussed what they perceived as concerns regarding the availability of forage during snow cover periods. We combined insights from this workshop with a literature review (Harnesk 2022) to design a storyline describing the impact that basal ice formation has on forage availability on the winter pasturelands of the Maskaure RHC. This *physical climate storyline* (Lloyd and Shepherd 2020) was revised throughout the research process and describes potential causal relationships in two interconnected analytical domains: the climate and weather domain and the environment and ecosystem domain.

In the *climate and weather domain*, we relied on quantitative analysis of climate data from weather stations located within reindeer pasturelands in Sweden, focusing on rain-on-snow events and thaw-and-freeze events (see Supplementary Material). Only four stations had sufficiently long (> 50 years) daily records of mean, maximum, and minimum air temperature; snow depth; and precipitation. Two of these stations were selected corresponding to elevation levels of Maskaure's winter pasturelands (Fig. 1): Malå (309 m above sea level) located within the Maskaure area and Forse (125 m above sea level) which despite laying ~ 2° south of the study area is the best available information source of past changes in the targeted weather events at similar elevations in the study area. We analysed the change in both frequency (i.e., number of occurrences) and intensity (i.e., amount of liquid water delivered to the bottom of the snowpack that may become basal ice) of different indicators associated with potential rain-on-snow events and thaw-and-freeze events during the "early snow cover period", which we defined as from the 1st of October until 31st of January. We focus on this period because the occurrence and intensity of the targeted weather events are higher during this period and because their negative effects on reindeer foraging can last longer and thus be more impactful. In the *environment and ecosystem domain*, we used spatial data on forest cover and forest operations to derive proxy data for continuity forests (PCF, forests likely older than 120 years) and degree of fragmentation in these patches (see Supplementary Material). We focus on such indices given the well-documented impact that intensive forestry operations have on lichen habitats.

In our qualitative research, we drew on our storyline and a *place-attachment lens* to construct and interpret *community narratives* based on biographical accounts collected through semi-structured interviews (Riessman 2008).

Building on Brännlund's (2019) research in the Sámi context, we understood place-attachment as a dynamic set of relationships between *identity*, *culture*, and *livelihood* within our informants' *landscapes* and land uses. We conceptualised place–people relations at the pastoral landscape scale and applied qualitative methods to study those relations. Thus, we are close to Ingold's (1993) view of landscapes as "constituted as an enduring record of—and testimony to—the lives and works of past generations who have dwelt within it, and in so doing, have left there something of themselves" (p. 152), but with an emphasis on our informants' perspectives and experiences of change processes in their landscapes. In turn, community narratives were derived qualitatively from the perspectives and experiences of our informants and reveal aspects of how they, at a community level in a particular moment in time, explain, understand, and logically connect different events and experiences (Riessman 2008). By focusing the interviews on personal oral histories and storytelling organised around consequential events, we sought to identify people's process of making sense of past events. For example, by asking questions such as what led up to that event, why did it unfold that way, then what happened, and how does this relate to their landscape.

We interviewed six male reindeer pastoralists in the Maskaure RHC selected by leading community members during the initial workshop: two young adult (20–35 years old, active), two middle-aged (35–60 years old, active), and two elders (over 60 years old, retired). The interviews were either held in the homes of the informants or at the Maskaure RHC's community house located by their winter pasturelands. On average, each interview lasted 2 h. Interviews included questions about their perspectives on and experiences of how different causal factors within our storyline had impacted forage availability on their winter pasturelands over time. We also asked them to exemplify their accounts with specific areas, which we recorded as GIS data. During the interviews, we also asked our informants about their relationship to the pastoral landscape of the Maskaure RHC, and why they think the landscape is important for Sámi culture. Three landscape transect drives were also conducted together, during which field notes were taken, serving as complementary data.

We used narrative analysis at the community level to identify shared narratives under coding themes provided by our physical climate storyline as well as an additional coding theme of desirable and undesirable responses to basal ice formation. To illustrate these narratives by situating them in geographical space, we created *narrative clusters* from our GIS-coded interview data. We also interpreted local concerns and examined how our informants experience the impact of basal ice formation by applying our conceptualization of place–people relations at the pastoral landscape scale to their biographical accounts of their relationships to their landscape when coding transcripts.

Physical climate storyline and narratives

In the winter of 2016/2017, the members of the Maskaure RHC experienced the worst winter in 30 years. There was substantial snow by mid-December, after which rain melted parts of the snowpack; forming basal ice that was reportedly about 20-cm thick. Ground lichens became inaccessible as forage, and the chair of the RHC told Sámi news media:

> Supplementary feeding is the only solution, but it is not economically possible, yet one cannot let the reindeer starve to death either.

Our physical climate storyline and narratives will describe this event sequence as a part of larger processes of climatic and environmental change. To do this, we first adopt an appropriate geographical perspective, while maintaining our focus on basal ice formation as a compound hazard that impacts forage availability. Our storyline takes place within a Sámi pastoral landscape, "where land uses are organised after historical seasonal migration patterns, and specific areas represent different and multiple functions for each of the eight Sámi pastoral seasons" (Harnesk 2022: p. 3; see also Horstkotte et al. 2017). The causal factors that shape these practices are dynamic, captured in the Sámi concept of *jahkodat*,[4] which highlights "the distinctiveness of any given year, not as a mutually interchangeable unit of time, but as a particular and unique succession of specific conditions, with variable and cumulative effects" (Benjaminsen et al. 2015: p. 226). We focus on the narrow, yet important, set of

[4] Northern Sámi language.

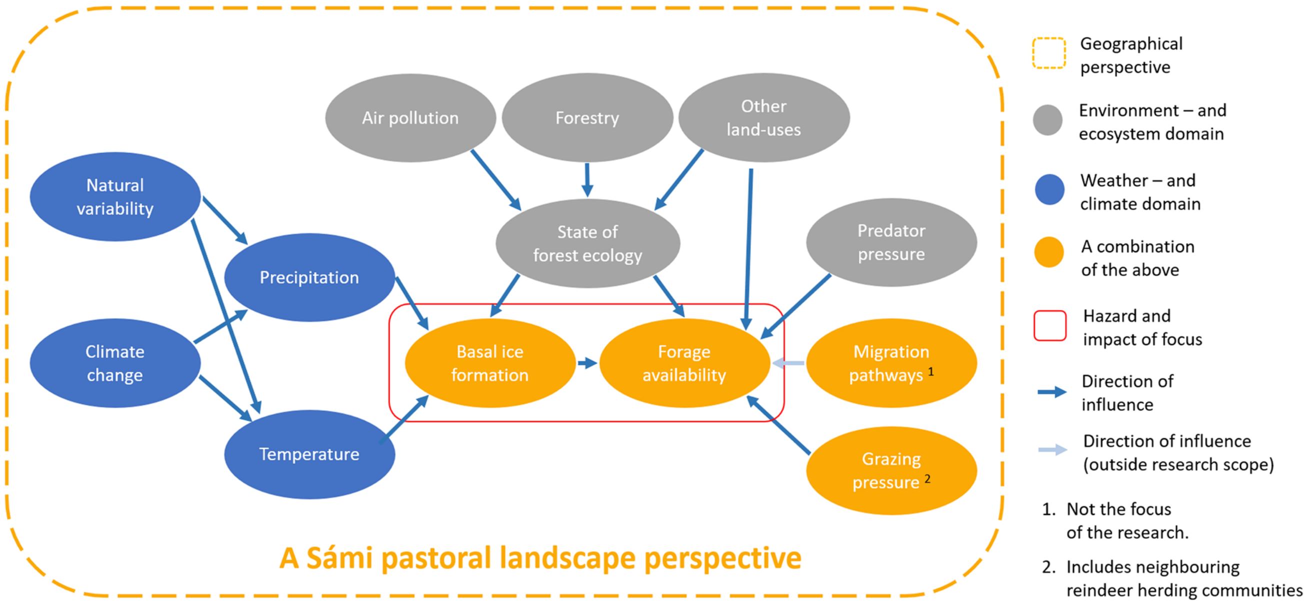

Fig. 2 Heuristic causal network for discussing the impact of basal ice formation on reindeer forage availability. Arrows indicate direction of causal influence but can include the effects of feedbacks. Note that migration pathways are generally outside of our research scope and that they, in reality, are also affected by factors such as the state of forest ecology. The blue shading indicates elements whose causality lies in the weather and climate domain, the grey shading those in the environment and ecosystem domain, and the orange shading indicates a combination of the two

causal factors that shape forage availability on winter pasturelands, which in the pastoral landscape perspective refers to the period from ground lichen grazing until preparations for spring migration (see Länsstyrelsernas geodatakatalog 2021). It should be acknowledged that these causal factors are also affected by the biophysical features of the pastoral landscape elsewhere, as well as the behaviour of reindeer and the decisions made by reindeer pastoralists (Holand et al. 2022).

From this geographical perspective, we have identified and discussed several causal factors (Fig. 2), asking whether they played any role in the 2016/2017 event, and if so, whether there was any plausible link with the anthropogenic climate change. In the sub-sections below, we present our findings within the weather and climate domain and the environment and ecosystem domain as well as under the theme of desirable and undesirable responses.

Weather and climate domain

Four narratives emerged from our interviews. The first is that basal ice formation had become more common because of an increase of days with rain-on-snow and thaw-and-freeze events, such as "thaw days" and "zero-crossing days" between pastoral autumn to early winter seasons. Early winters of the past were clear and cold, in contrast to the current mild and wet conditions. Moreover, past winters started with a period of cold air temperature before the snow came, whereas current early winter temperatures are close to zero degrees.

The second narrative is that basal ice formation occurs in specific parts of landscapes. When there was basal ice on flat pine heaths, the conditions could be better in mountains as a result of runoff. When there was basal ice on large clear-cut forests, the conditions would be worse for grazing, as the lack of canopy cover allowed wind and other weather conditions to pack the snow more densely.

The third narrative is about increased variation within and between winters. Abrupt changes in air temperature and precipitation have increased within a single winter. Recent instances of extreme precipitation causing exceptionally deep snow accumulating within a week were mentioned. Weather was described as "up and down by default", but this pendulum has increased in frequency and intensity making coordination and planning more difficult. Consequently, the variations between winters were also considered to have increased.

The fourth narrative was an overall increase of winters with bad grazing conditions, *goavvi*.[5] Even if there were bad winters in the past, it has become "easier to count the good ones nowadays" (because they are so few). Young pastoralists had almost never experienced a "good winter", or "how a winter should be", and that the grazing conditions

[5] Northern Sámi language.

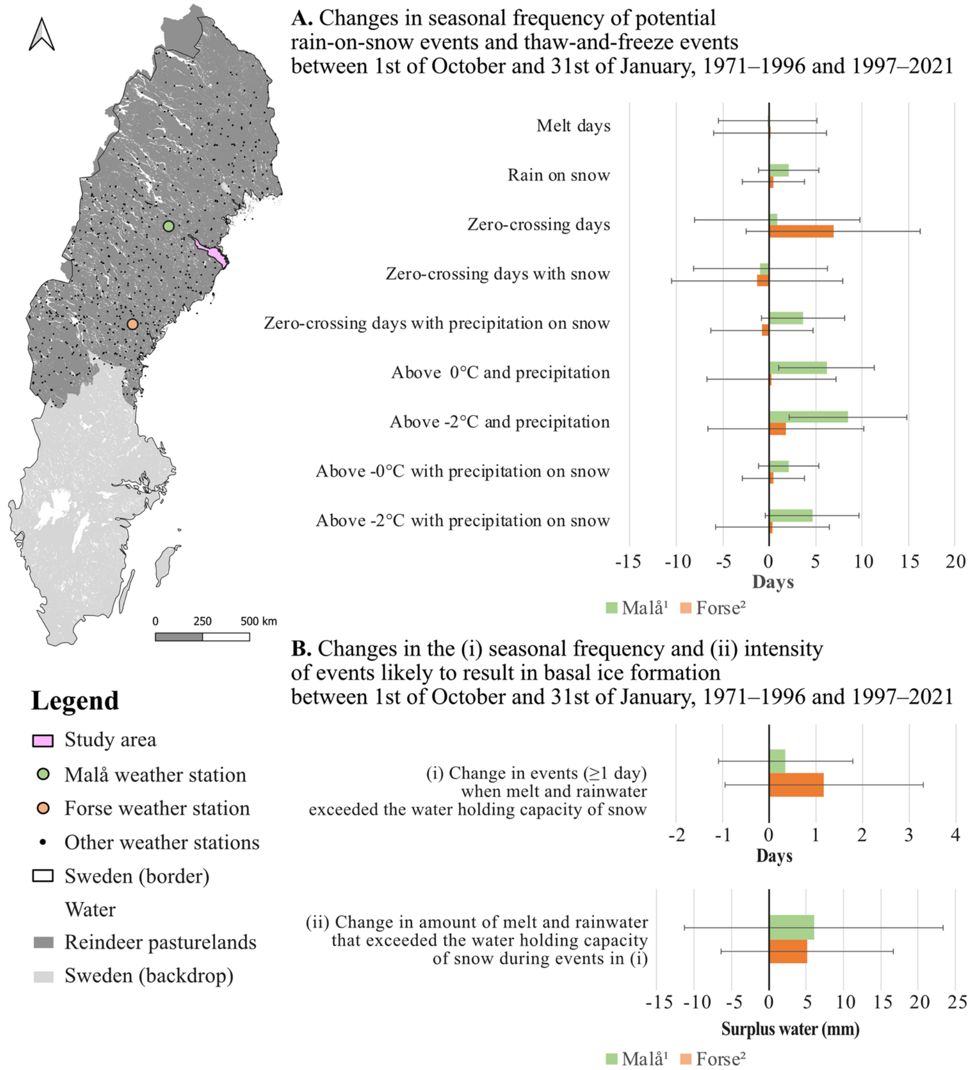

Fig. 3 Changes in seasonal (from 1st of October to 31st of January) frequencies and intensity of selected indices between 1971–1996 and 1997–2021 for the two selected weather stations. [1]Data for year 1986/1987 and 1992/1993 are missing. [2]Data for year 1997/1998 are missing

of a good winter "sounded like the world of fables". However, the reasons were also connected to the larger narrative of there being poorer forage resources in the landscape. To quote one informant:

> I think a lot is connected to the fact that there are so much less pastures. Because many times, before, if it became like that, then one could take the reindeer up to the mountains. Now you almost have no alternatives to work with. Now you must find *any* pastures.

Quantitative analysis

Proceeding from our theoretical understanding of basal ice formation and informed by these narratives, we were also interested in quantitative analysis of changes in the frequency and intensity of weather events that could potentially be connected to basal ice formation.

As presented earlier, Maskaure's lands have experienced an increasing trend of precipitation, air temperature, and number of zero-crossing days in the last 30 years (SMHI 2021b). The number of rain-on-snow and thaw-and-freeze events has also increased for the two selected stations (Fig. 3A). We also estimated the amount of liquid water that a given snowpack can hold before water starts to accumulate at its base, the accumulated rain and meltwater during ≥ 1 consecutive days of melt and rain, and the accumulation of liquid water at the base of the snowpack during these events (see Supplementary Material). The conditions for basal ice formation (rain + meltwater > water holding capacity of snowpack) were found to have increased considerably in the latest 25-year period (Fig. 3B). The intensity of such events has also increased, as suggested by the larger amounts of liquid water potentially reaching the snowpack base during the latest 25-year period (Fig. 3B).

It should be noted, however, that this quantitative analysis is subject to various limitations. These include the high

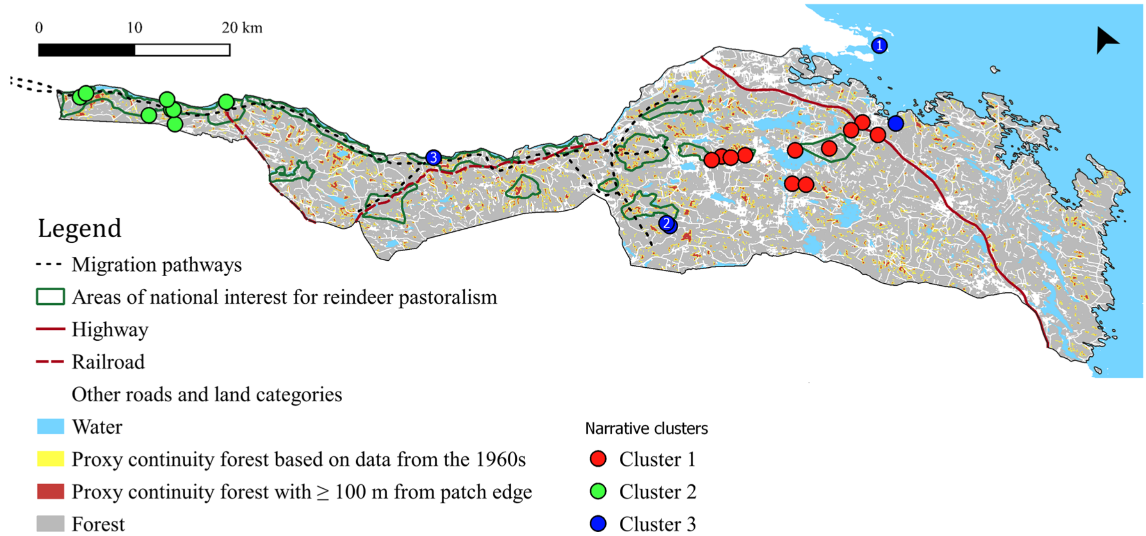

Fig. 4 Map over the amount and distribution of forest, proxy continuity forest, and proxy continuity forest patches with 100-m distance from patch edge. The map also shows migration pathways and areas categorised as national interest for reindeer pastoralism based on accounts from the Maskaure reindeer herding community. The map also shows highways, railroads, and water, as well as other roads and land categories. The map also illustrates the location of the narrative clusters. See Supplementary Material for more information

spatial heterogeneity of basal ice formation, the observed delays in cold and snow cover conditions leading to misleading declines in several indices and, most significantly, the lack of long-term, spatially-dense climatic and environmental records relevant to the hazard, which illustrates our argument about data injustice in climate research (see Olsson et al. 2022).

Ecosystem and environment domain and narratives

Four narratives emerged from our interviews. The first narrative was in relation to a general reduction, degradation, and fragmentation of ground lichens on winter pasturelands.[6] This included the well-established effects of clear-cutting, intense site preparation, dense reforestation, short rotation cycles, and encroachments from other competing land uses (see Harnesk 2022). This narrative is illustrated by a geographical cluster (Fig. 4, cluster 1) that was said to be “the finest pine heaths that Maskaure had”, but where intensive forestry alongside other land uses (gravel pits, roads, and an airport) had “torn the land to pieces to an incredible degree”. The overarching narrative of environmental change effectively shapes all other narratives we identified in our study and can be considered a master narrative.

[6] Although predator pressure and human activity, such as recreational activities, were part of our physical climate storyline, our informants did not emphasise these in their explanations of winter pastureland dynamics.

The second narrative is that forage in some areas had been severely degraded but had recently shown some indications of recovery. In addition to the first narrative, this one also included examples of grazing pressure in two ways. First, the Maskaure herd started to spend more time grazing on their pasturelands as the RHC began to use trucks to transport reindeer from their year-round lands to their winter pasturelands in the late 1970s and early 1980s. Second, there were instances in which neighbouring RHCs would graze on Maskaure’s winter pasturelands; however, in this narrative, the grazing pressure from neighbouring RHCs had been reduced, and some informants spoke about observable improvements in the amount of forage in the area (Fig. 4, Cluster 2). This narrative indicates the possibility of ecosystem-based improvements to forage availability.

The third narrative relates to a total lack of pendulous lichen forests suitable for traditional adaptive responses to poor winter grazing conditions, explained by air pollution from the Rönnskär Smelter (Fig. 4, cluster 3, point 1). Although our informants understood the absence of pendulous lichens as generally caused by a decreased age structure and continuity of forests, they linked the absence of pendulous lichens on their winter pasturelands to the smelter. Although foraging on pendulous lichens is a traditional adaptive response to poor winter grazing conditions, the extent to which pendulous lichens were absent from the winter pasturelands was so impactful that this narrative rejected that response as an option. While pendulous lichens had recovered somewhat, they were not considered suitable as pastures during basal ice formation due to the degree of fragmentation of their habitats. This narrative illustrates that

Table 1 The largest and mean patch sizes of proxy continuity forest and the percentage of functional core area relative to total forest land area for the proxy continuity forest patches ≥ 1 ha and for the proxy continuity forest patches ≥ 1 ha with reduced patch area 100-m distance from patch edge. See Supplementary Material for more information

	Number of patches	Largest patch (ha)	Mean patch size (ha)	Median patch size (ha)	Total area (ha)	Share of total forest land (%)
Proxy continuity forest	1246	208.6	8.37	5.23	10,424	9.6
Proxy continuity forest with ≥ 100 m from patch edge	554	63.17	4.25	2.35	2356	2.2

polluting industries can impact reindeer pastoralism through environmental change.

The fourth narrative is related to the notion that a larger land area of the winter pasturelands must be used now than in the past due to the cumulative effects of forestry, other competing land uses, and changing snow conditions—and with this comes the use of new and different pastures. Even areas close to the Baltic coast are now used—to quote an informant:

> Two years ago it was really, really bad. […] Then we took the reindeer, and we were by the coast, the ocean coast. There we could find a one-two kilometres wide stretch where it had thawed away. You know, the ocean was open. We could manage by basically following the coast. […] But this comes with other problems. We are talking about long distances, and it gets costly in other ways. A real hassle.

This narrative is intertwined with shifting migration strategies in two ways. First, the introduction of truck transports during winter migration resulted in increased grazing pressure because of the herd spending more time on the winter pasturelands. Here, it should be mentioned that the shifting migration strategies were partly due to the building of hydropower along the Skellefteå River. Second, mobility options are affected by encroachments, as is the case with a new railway, planned to start development in 2026, about 4 km west of the highway on the Maskaure winter pasturelands. This project would render approximately 18,500 ha largely unusable for reindeer pastoralism between the railway and the highway and with barrier effects and impacts on mobility options east of the highway. This narrative illustrates that as more land becomes subject to encroachments, more land may become used by reindeer pastoralists more often, which adds new challenges to their migration strategies.

Quantitative analysis

The theoretical and narrative understanding of ecological conditions conducive to ground—and pendulous lichen growth and sustenance (in relation to forestry) was corroborated by a quantitative analysis.

We examined the number of PCF patches within the study area and found that less than 10% of the forest land could be categorised as PCF and only 2.2% as large PCF patches with more than 100 m distance to their edge (Fig. 4, Table 1). This underlines two points. First, that at least 90% of the forest land in the study area is subject to intensive forestry operations, which in its current form reduces the amount of ground and pendulous lichens. Second, that even if pendulous lichens were present, their possible habitats would be highly fragmented, making such areas less suitable as pasturelands. Concerning air pollution, the Rönnskär Smelter operated since the late 1920s without any air pollution control until the 1970s, during which it annually emitted up to 130 000 t SO_2 and hundreds of tonnes of lead, zinc, copper, and arsenic (Bergqvist 2007: pp. 48–50). It is also specifically named in an international, quantitative study on air pollution, where it was referred to as one of the most impactful sources of air pollution in Sweden (Rühling 1994).

Responses to basal ice formation—a scenario exercise

We conducted a scenario exercise with our informants to get a better understanding of how they would respond to basal ice formation under different ecosystem and environmental circumstances. The first scenario was based on the event description presented in the beginning of the "Physical climate storyline and narratives" section and asked how they would respond within the current landscape if their herd was already located on the winter pasturelands. In the second scenario, participants were asked to describe the biophysical features of the landscape that they thought would provide optimal conditions for responding to basal ice formation, and what their response would be. We also asked, in these two scenarios, how government agencies and civil society organisations could support them. From this exercise, we identified narratives on desirable and undesirable responses to basal ice formation, presented below.

Within the current landscape, our informants' response to basal ice formation is *emergency feeding*, which involves gathering the reindeer, either in a corral or preferably free ranging and provide them with supplementary feed; both of which require different logistical measures to be taken (see Åhman et al. 2022). In the first scenario—a "nightmare scenario" according to one of our informants—these logistical measures entail gathering the reindeer in a corral, which depending on circumstance may entail transporting feed to strategic locations and using this to gather most of the reindeer in one spot, to then either build a temporary corral, or move the reindeer to one that already has been built. These measures must also be conducted quickly as during such ice-layer formation events; the snow can be dense enough to carry the weight of reindeer, making it easier for them to travel, with risks of losing control of the herd. Over time, reindeer must be moved elsewhere to avoid the spread of diseases within the herd. Some years prior to our interviews, the RHC had invested in two feed silos, a truck, and a tractor, which they can use during emergency feeding. Maskaure's reindeer were also accustomed to feed, although the RHC does everything they can to avoid using it. For the most part, the pastoralists of the Maskaure RHC are well-prepared and well-equipped to perform emergency feeding within the current landscape.

The emergency feeding described in the narrative comes with costs and burdens. It is both labor and capital intensive. It increases the need for money to buy feed, fuel, and infrastructure, which makes reindeer pastoralism more susceptible to price fluctuations and other domestic and international perturbations such as inflation and the war in Ukraine. The grazing strategy of utilising larger areas is also connected to these added costs and burdens. Although the responses captured in the narrative were considered necessary to avoid reindeer mortality, it was generally viewed as an undesirable development. Preferred options that were discussed included more financial support from the existing catastrophe compensation scheme, which can cover up to 50% of costs associated with emergency feeding (based on an assessment of pasture availability by the government authority, see Sametinget 2022) or other forms of economic redistribution to improve the amount and distribution of lichens. The latter may include companies covering costs of labour and input to transplant ground lichens on land areas that have recently been logged.

The narrative around desirable responses, i.e., a landscape that would provide the RHC with optimal conditions to deal with basal ice formation, covered traditional natural pasture-based responses under two themes. The first theme was the existence of continuous old-growth forests with pendulous lichens, as their availability is significantly less affected by basal ice formation. The second theme was greater coverage of ground lichens, as less intensively grazed lichen areas have higher lichen height and more biomass, which increases the likelihood of available forage existing at least somewhere in the landscape. The RHC desired this because it lined up with ecological conditions conducive to natural pasture-based practices, which was considered as promoting the well-being of the reindeer and as connected to Sámi culture more broadly. To realize such a landscape would require ecosystem interventions, such as less intensive soil preparation, lichen transplantation (i.e., artificial spread), vigorous thinning, longer rotation time in the forestry regime (Horstkotte and Djupström 2021; Eggers et al. 2023), which our informants would welcome, but would also affect non-pastoralist land users and their land use practices, such as cuts to profits and wood production in forestry (Harnesk 2022).

Place-attachment and local concerns

Our informants were attached to place at the landscape scale in several ways, with the relations between their families and reindeer within that landscape being tightly intertwined. Our informants included both those who had longer connections to the past siidas of the Maskaure RHC and those who had moved their reindeer to Maskaure from other RHCs after the 1990s. The various bonds to the Maskaure landscape and land uses can be demonstrated by their ability to identify and describe specific locations in detail. Their descriptions of the locations included not only their names, but also their multiple functions, not only in terms of forage availability, but also the availability of fish and animals to hunt, which is connected to the broader cultural and livelihood practices of RHCs.

Place at the landscape scale represented a *livelihood* for our informants. That said, most have, or have had, jobs on the side, and they all made it clear that money was not their reason for being reindeer pastoralists. Many expressed that they felt a responsibility for the well-being of the reindeer, and many were stressed and worried about how they, or future generations, could continue given the current condition of the landscape. They valued the freedom that came with reindeer pastoralism and valued being outdoors with the reindeer within the pastoral landscape. When the RHC experiences hardships, such as basal ice formation, they deal with it collectively, at times involving broader networks of family and friends.

Place at the landscape scale represented an *identity* for our informants. When migrating with the reindeer between different seasonal pasturelands, they said that they think about the generations before, how the landscape used to look, and about the conditions that will be handed over to future generations. During certain activities—such as calf marking and separations of herds based on ownership—family and friends (with other jobs) would participate, which they thought positively about. Although some expressed that they felt more at home around the Arjeplog area, some were more transhumant in the sense that they felt at home in a range of locations in their landscape. Their commitment to the well-being of their reindeer was clear, regardless of they or their reindeer were located. As one informant put it, reindeer pastoralism is “a privilege and a responsibility”.

Place at the landscape scale represented a central component of Sámi *culture*. Informants considered a landscape that supports natural pasture-based reindeer pastoralism as a cornerstone for Sámi culture. Much of the material and immaterial practices of Sámi culture were related to the well-being of the reindeer, and this, in turn, was dependent on well-functioning and multi-purpose pastoral landscapes—especially, good pasturelands. Even if emergency feeding was considered positive in the sense that it helps save reindeer from starvation during poor winter conditions, increased reliance on supplementary feed was considered negatively, not only for financial reasons, but also for its implications for their desired way of life, as it represented a break away from reindeer pastoralism based on natural pastures towards more stationary practices that depend on capital input.

From our landscape-based place-attachment lens, basal ice formation as a compound hazard can be understood as a threat to the natural pasture-based reindeer pastoralism that is deeply intertwined with the Sámi identity, culture, and livelihood. This desired way of life requires the maintenance of particular human-animal relations at the Sámi pastoral landscape scale. For these local concerns to be addressed, financial compensation to cover the costs of feed and fuel is insufficient and at worst represents a regime shift away from reindeer pastoralism based on natural pastures to being based on supplementary feed or ranching models (see Moen et al. 2022), which we have shown represent undesirable set of experiences for Maskaure’s members in terms of human-animal relations and within their landscape.

Discussion

Weather and climate domain

We initially consider the weather and climate domain, in which it is known that the Arctic region is warming 3–4 times faster than the rest of the world (Previdi et al. 2021). Along with these long-term changes, weather extremes, such as winter warm spells, are also expected to increase in intensity in high latitudes in the future (AMAP 2021). Consequently, we expect a temperature-induced shift from a snow-dominated to rain-dominated precipitation regime, which will occur progressively along a latitudinal gradient (from south to north) and an altitudinal gradient (from coast to inland). We also expect an increased amount of precipitation during the winter and more frequent high-intensity precipitation events (Pithan and Jung 2021). These climatic changes pose a greater risk for further increases in the frequency and amount of basal ice formation in the future. However, further reductions in the snow cover period or the complete melt out of the winter snowpack during extreme winter warming events (Pascual and Johansson 2022) could contribute to less impactful basal ice events. These snow-related changes are likely to emerge earlier and be more prominent in the milder southern and coastal areas. Future changes to basal ice formation will thus depend on the balance between the more frequent and intense weather events causing basal ice formation and the climate-induced changes in snow cover dynamics. The length and rapidity of these climatic and snow cover changes will depend on future greenhouse gas emission trajectories and on regional and local processes, such as the Arctic amplification, which are beyond the scope of our study.

Ecosystem and environment domain

We also consider the ecosystem and environment domain, relating our findings to scenario analysis literature on ground lichens and pendulous lichens. On the one hand, ground and pendulous lichens are likely to be reduced further if current forestry operations endure. Based on data from the National Forest Inventory and multiple models, one study expected a 40–60% decrease of “areas with potential for ground lichens on productive forest land within land designated as national interest for reindeer pastoralism” and projected that forests older than 120 years on productive forest land will continue to decrease by 2050 (Swedish Forestry Agency 2022). The occurrence of *Alectoria* spp. is estimated to decrease due to their poor suitability for long-distance dispersal being unfavourable for the younger and fragmented forest landscapes produced by intensive forestry operations (Esseen et al. 2022). The occurrence of *Bryoria* spp. is also expected to decrease as they are adapted to cooler and drier climates, but warmer and wetter winters are expected (Esseen et al. 2022). On the other hand, other studies suggest it is possible to achieve a 22% point increase of the proportion of forest area with potential for ground lichens by 2035 compared with 2020 with adapted forestry practices (Eggers et al. 2023). For pendulous lichens, the long-standing argument on altering the trajectory is that forestry “must apply a broad spectrum of methods, including uneven-aged continuous cover forestry and retention of large patches, to secure the ecosystem functions of these important canopy components under future climates” (Esseen et al. 2022: p. 3293).

Policy implications

Our research suggests that there is a high degree of stress on Maskaure’s pastoral landscape and that weather events can lead to major impacts on pasture availability, especially due to changes to the forest ecology brought on by encroachments, most extensively intensive forestry operations. This has been observed in national assessments and case studies of other RHCs as well (Horstkotte et al. 2022; Harnesk 2022). Our analysis showed that the increased frequency of years with poor winter grazing conditions represented a threat to the human-animal relations that our informants found desirable in their landscape and that increased dependency on supplementary feed represented a threat to their desired way of life. This would suggest that there are connections between local concerns based on people's relation to place and particular ecological conditions that relate to specific cultural and livelihood practices within those people–place relations.

Improved ecological conditions for the Maskaure RHC (and others) would require changes in both forestry and infrastructure management and planning so that they incorporate a Sámi pastoral landscape perspective into decision-making processes. In terms of policy goals, interventions should be directed towards improving and maintaining ecological conditions for reindeer pastoralism based on natural pastures at the landscape scale. As indicated above, research has suggested several ways that forest management and planning could be altered to support habitat formation and sustenance for ground and pendulous lichens. For ground lichens, concrete measures include reduced soil disturbance and more vigorous thinning throughout a longer rotation cycle, increased removal of logging residues, no fertilisation, more extensive burning, and possibly ground lichen transplantations where necessary (Horstkotte and Djupström 2021; Horstkotte and Moen 2019; Horstkotte et al. 2016; Eggers et al. 2023). For pendulous lichens, concrete measures include the retention of old-growth forests, increasing the area with pendulous lichens and the connectivity of such areas at the landscape scale (while considering the negative effects of edge influence from, e.g., larger openings), increasing the length of the rotation cycle, and saving large and old trees in continuous cover forestry practices (Esseen et al. 2022; Esseen 2019; Esseen et al. 2016; Esseen and Renhorn 1998; Rikkonen et al. 2023). Effective planning of these measures would also warrant meaningful incorporation of RHCs into such decision-making processes, as they collectively carry the best available knowledge of the highly variable grazing dynamics that exist in their pastoral landscapes (Harnesk 2022).

Conclusion

Our storyline approach demonstrates the multiple causation and compound hazards involved in the impact of basal ice formation on pasture availability for reindeer pastoralism. Combining theoretical understanding, qualitative interpretations, and quantitative observations within the weather and climate domain and ecosystem and environment domain, we argue that land use change was a more significant causal factor than climate change in reducing the availability of winter pastures for the Maskaure RHC. However, continued and accelerating climate change combined with continued intensive forestry operations will likely increase the tension between forestry and reindeer pastoralism—to the detriment of the latter. If not explicitly and profoundly accounted for, this tension is rendering event attribution increasingly problematic in this specific policy space. Our case also highlights the limitations of probabilistic event attribution and the strengths of the storyline approach, which feeds into discussions in the science–policy interface around climate change and biodiversity loss.

Our place-attachment lens showed that local concerns can be connected to human-animal relations within a particular geographical perspective (such as place–people relations at the pastoral landscape scale) and that people's subjective experiences of climate-related hazards may be shaped by such connections. It also showed that people may prefer certain ecological conditions over others and that these preferences may be associated with the livelihoods, identities, and cultures of people within their specific landscapes and land uses (such as landscapes conducive to reindeer pastoralism based on natural pastures over being based on supplementary feeding). Attempts to address such local concerns may warrant ecological interventions, but such interventions may come into conflict with other, more influential economic and political interests.

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