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Human–animal agency in reindeer management: Sámi herders' perspectives on vegetation dynamics under climate change

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Abstract. Many primary livelihoods in Arctic and sub-Arctic regions experience accelerating effects of environmental change. The often close connection between indigenous peoples and their respective territories allows them to make detailed observations of how these changes transform the landscapes where they practice their daily activities. Here, we report Sámi reindeer herders' observations based on their long-term inhabitance and use of contrasting pastoral landscapes in northern Fennoscandia. In particular, we focus on the capacity for various herd management regimes to prevent a potential transformation of open tundra vegetation to shrubland or woodland. Sámi herders did not confirm a substantial, rapid, or large-scale transformation of treeless tundra areas into shrub- and/or woodlands. However, where they observe encroachment of open tundra landscapes, a range of factors was deemed responsible. These included abiotic conditions, anthropogenic influences, and the direct and indirect effects of reindeer. The advance of the mountain birch tree line was in some cases associated with reduced or discontinued grazing and firewood cutting, depending on the seasonal significance of these particular areas. Where the tree line has risen in elevation and/or latitude, herding practices have by necessity adapted to these changes. Exploiting the capacity of reindeer impacts on vegetation as a conservation tool offers time-tested adaptive strategies of ecosystem management to counteract a potential encroachment of the tundra by woody plants. However, novel solutions in environmental governance involve difficult trade-offs for ecologically sustainable, economically viable, and socially desirable management strategies.

Key words: adaptation strategies; climate change; *Rangifer tarandus;* reindeer husbandry; shrub encroachment; tree line.

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Introduction

A prolonged growing season and northward shift of species distribution patterns are among the ecosystem transformations that are reported in many parts of the Circumpolar North as a consequence of climate change (CAFF 2013, Larsen et al. 2014). Though highly variable across the Arctic in magnitude and direction, treeless tundra is becoming encroached by an increased abundance of erect woody plants, as well as by the latitudinal and altitudinal progression of the tree line (Xu et al. 2013, Myers-Smith et al. 2015).

The effects of such environmental processes threaten not only Arctic biodiversity, but also may affect the living conditions and livelihoods of both indigenous and non-indigenous residents (Krupnik and Jolly 2002, Larsen et al. 2014, Chapin et al. 2015). Through cultural interaction with the landscape, indigenous peoples in particular apply their own systems of observing and adapting to environmental change (Parlee and Manseau 2005). These practices often visibly shape the biophysical land into a cultural landscape (Berkes and Davidson-Hunt 2006, Tømmervik et al. 2010, Ruiz-Mallén and Corbera 2013), thus enhancing those ecosystem services deemed particularly important to the livelihood (Forbes 2013, Comberti et al. 2015). This includes the potential of pastoral people to realize their humanity through their animals (Cassidy 2012). In the Eurasian Arctic, reindeer husbandry is a widespread livelihood, with the reindeer (*Rangifer tarandus*) as an eminent cultural as well as ecological keystone species (Forbes and Kumpula 2009).

Reindeer husbandry in northern Fennoscandia is practiced by the indigenous Sámi people. Generally spoken, reindeer husbandry today is an extensive form of land use focused on meat production and dependent on access to large season-specific grazing grounds (Pape and Löffler 2012). Since its origin at latest in the 17th century, reindeer husbandry has been adapting and transforming in response to a variety of drivers, including ecological, socio-political, and technological changes to become today's rationalized commercial enterprise (Helle and Jaakkola 2008, Moen and Keskitalo 2010, Hausner et al. 2011).

In northern Fennoscandia, the tree line at the edge of treeless tundra is formed by mountain birch (*Betula pubescens* ssp. *czerepanovii*; Hämet-Ahti 1987). Using the landscapes above, at and below the tree line, reindeer herders and their animals had and have an impact in all these biotopes and on their constituent species (Suominen and Olofsson 2000, Staland et al. 2011, Biuw et al. 2014). However, it remains very difficult to generalize the impact of reindeer on vegetation cover and composition (Bernes et al. 2015). The magnitude of the impact that reindeer have on the tree line is debated, but their effect on creating mosaics of different vegetation types seems evident (Moen et al. 2008). Consequently, reindeer may alter the tree line relative to its potential position governed by abiotic conditions, as well as shifts of the tree line as a response to climate change (Moen et al. 2008, Hofgaard et al. 2013). Ellenberg (1988) therefore attributes an "anthropo-zoogenic" character to the forest–tundra ecotone.

Here lies the essence of individual and collective active participation of animals and people in shaping each other's life, including cultural and biophysical elements of the pastoral landscape. We define this shared life between co-participants (Ingold 2000, Anderson et al. 2017) who carry out actions together as "human–animal agency." This relationship is not of static character, but a compromise between the preferences of human and non-human actors (Sara 2011). By their practices, reindeer herders engage culturally with the landscape, creating via lived experiences their own moral codes of social–ecological relationships (Davidson-Hunt and Berkes 2003).

The reindeer herders' local observational knowledge is codified as qualitative language-based data, stemming from perpetual adaptation and co-evolution with their environment (Berkes 2012). Although the herders' qualitative descriptions of environmental processes differ from quantitative measurements, their strength lies in expanding observations derived from herbivore exclosures or similar experiments at comparatively low spatial and temporal levels (Olofsson et al. 2009, Biuw et al. 2014, Kaarlejärvi et al. 2015) to levels in space and time that are relevant for their daily practices.

We therefore aim at understanding, from the reindeer herders' own perspective, the consequences of the combined effects of people, animals, and climate change that shape their pastoral landscape in northern Fennoscandia as well as the herders' adaptive capacity to react to these changes by using their animals to modify the structure and function of the landscape.

Based on focus group interviews, we give an overview of (1) the impacts of weather and reindeer behavior on herding practices, followed by (2) the significance of the forest–tundra ecotone as grazing grounds during the herding year. We then report in detail (3) the herders' observations of the vegetation changes near the tree line and their drivers, as well as (4) the consequences thereof on the pastoral landscape. Based on this analysis, we discuss potential future adaptations to environmental change that could affirm Sámi reindeer husbandry as a viable livelihood and expression of Sámi values, with the options to cultivate and maintain the connection to the dynamic pastoral landscape. This includes implications that reindeer can have as ecosystem engineers (Jones et al. 1994) for conservation policies of their sub-arctic habitats.

Materials and Methods

Study area

Sámi cultural practices, their historical contexts, and ecological conditions vary significantly across Sápmi, the traditional area of the Sámi (Valkonen and Valkonen 2014; Fig. 1). To cover this wide range of local conditions, we arranged workshops in six herding districts, two each in northern Finland, Norway, and Sweden (Fig. 1). We chose herding districts that differ distinctly in, for example, their environmental conditions or reindeer densities (Table 1). We established contact to the districts on either previous collaboration (Forbes et al. 2006) or personal contacts to the communities by two of the authors (T. Utsi and Å. Larsson-Blind). However, our aim is not to contrast the three countries in particular, but rather to draw comprehensive conclusions on causes and effects of observed vegetation change based on the knowledge and experiences of reindeer herders in the three countries.

Country-specific differences exist, for example, regarding herding practices and legislation. Reindeer husbandry is an exclusive right of the Sámi people in Norway and Sweden, while Finnish legislation grants the reindeer husbandry right to

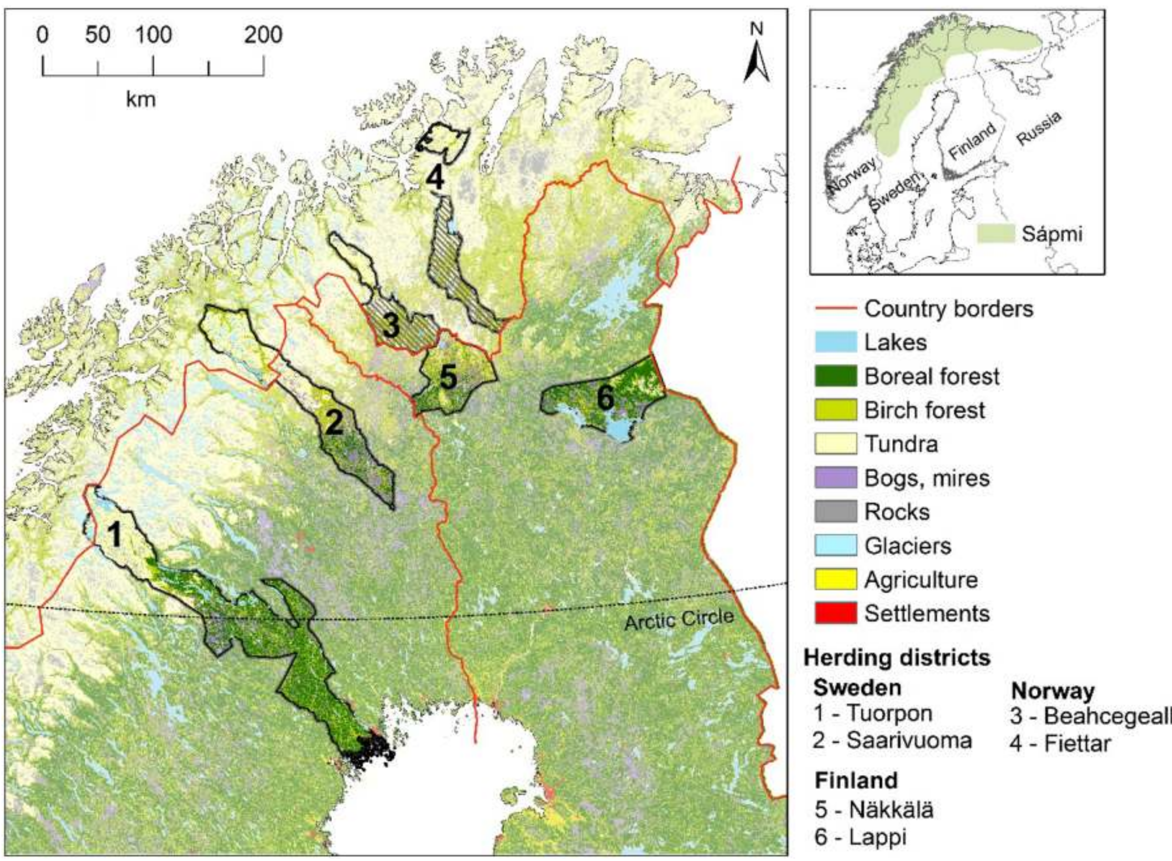

Fig. 1. Studied herding districts in Sweden, Norway, and Finland, showing also land cover classes. Hatched areas in Beahcegealli and Fiettar show winter, spring, and autumn pastures for several districts/herding groups (siidas). All groups in these areas have their specific pastures. The inset map illustrates Sápmi, the traditional area of the Sámi people.

Table 1. Distribution of major vegetation classes in km^2 and their relative amount (%) in the studied herding districts.

	Finland				Norway				Sweden			
	Lappi		Näkkälä†		Beahcegealli‡		Fiettar‡		Saarivuoma		Tuorpon	
Vegetation class	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Coniferous forest	2269	50	308	14	132	4	121	3	1203	18	5898	45
Birch forest	725	16	916	41	1046	33	907	26	1391	20	1346	10
Tundra vegetation	203	4	361	16	1267	41	1775	51	2320	34	2839	22
Bogs, mires	778	17	565	25	470	15	448	13	1397	20	1183	9
Bedrock outcrops, boulders	77	2	28	1	83	3	106	3	108	2	1004	8
Glaciers, snow fields	0	0	0	0	16	1	0	0	221	3	152	1
Settlements, infrastructure	2	0	4	0	0	0	0	0	9	0	150	1
Water	453	10	71	3	112	4	154	4	218	3	591	4
Total area (km^2)	4508		2252		3127		3512		6868		13,163	
Reindeer/km^2 (1995–2013)§	1.7		2.5		0.3		1.9		1.7		0.4	

Note: Based on the vegetation classification map by B. Johansen (*unpublished data*, plus Johansen 2009, Johansen et al. 2009).
† Statistics for the northern part of Näkkälä.
‡ Statistics for the grazing areas for Beahcegealli and Fiettar, with their particular summer grazing area and the winter, spring, and autumn pasture used by several districts/herding groups (siidas). See Fig. 1.
§ Data sources for reindeer numbers: Finland: Paliskuntain Yhdistys (www.paliskunnat.fi); Sweden: Sametinget (www.sametinget.se); Norway: Landbruksdepartementet (https://www.slf.dep.no/no/).

every citizen. In each country, reindeer husbandry uses roughly 50% of the land area. Although reindeer husbandry is the major source of income to only a relatively low percentage of the Sámi population, the livelihood continues to be of high cultural significance.

Populations of semi-domesticated reindeer in Fennoscandia fluctuate in response to climatic drivers and management strategies, with a historic low in the 1940s and a maximum in the 1990s (Uboni et al. 2016). In the last 10 yr, the number of semi-domesticated reindeer in Fennoscandia has fluctuated between 200,000 and 250,000 in each country (Bernes et al. 2015). Each country is thereby home to approximately 10% of the world's semi-domesticated reindeer population (CAFF 2013). The average reindeer density during the period 1995–2013 ranges between 0–3 and 2–5 reindeer/km^2 in the studied herding districts (Table 1).

*Climate.—*Mean annual temperature in northern Fennoscandia ranges between 0°C in the boreal inland and −4°C in the Scandinavian mountain chain. However, the northern Norwegian coast is considerably warmer with a mean annual temperature of +2°C (Seppälä 2005). The vegetation period (i.e., daily average >+5°C) decreases with increasing altitude and latitude, spanning between 140 d in the boreal forest and 80 d in the Scandic mountains (Karlsen et al. 2008). Corresponding to the decrease in oceanity toward the east, mean annual precipitation decreases from 800 mm at the west coast to 400 mm in inner Finnmark (Lehtonen et al. 2013). Winter conditions (i.e., daily average <0°C) prevail from early November until late April/early May, so that snow cover lasts from 180 d in the southern parts of the study area to 210 d in the north and in the mountains (Lehtonen et al. 2013). During the period 1982–2011, both precipitation and temperatures increased in northern Fennoscandia, while there was no significant trend observed in the start of the growing season (Høgda et al. 2013).

*Phytogeography characterization.—*Open, treeless tundra vegetation characterizes the northernmost parts of the study area, in particular Norway's Finnmark, as well as the Scandinavian mountain chain along the border between Sweden and Norway (Ahti et al. 1968). The most dominant vegetation types of the tundra include snow patch vegetation, dwarf shrub heath (e.g., *Empetrum nigrum*, *Vaccinium* spp., *Betula nana*), and mountain meadows with a varied species composition of forbs and graminoids (Virtanen et al. 2016). The tree line is formed by mountain birch (*Betula pubescens* ssp. *czerepanovii*), while willows (*Salix* spp.) predominate in wetlands and riparian sites (Pajunen et al. 2010). Toward the inland, vegetation is composed of northern boreal species. Scots pine (*Pinus sylvestris*) dominate the tree layer on peat lands or xeric soils, and Norwegian spruce (*Picea abies*) on mesic soils (Esseen et al. 1997). Lichen heaths with lichen species such as *Cetraria* spp. and *Cladonia* spp. are important grazing grounds for reindeer especially during late winter, and dominate on unproductive soils above and below the tree line (Tømmervik et al. 2009). The herding districts in this study differ significantly in their respective environmental diversity, depending on their geographical location and extent (Table 1). The major vegetation classes have been derived from Landsat TM/ETM+ data analyses, with a spatial resolution of 100 m in the final map product (B. Johansen, *unpublished data*; see also Johansen 2009, Johansen et al. 2009).

Seasonal habitat selection and rotation of grazing grounds.—Reindeer generally migrate between different habitats in response to the pronounced seasonality in northern Fennoscandia and the associated availability of forage resources. The general migratory pattern leads from continental winter grazing areas, dominated by lichen-rich heaths in boreal or mountain birch forests, mountainous or tundra areas, to oceanic summer pastures rich in grasses.

The practices, extent, and direction of seasonal migrations differ between the three countries (Pape and Löffler 2012). Swedish herding districts are oriented in a northwest–southeast direction, with summer grazing in the mountains at the border to Norway and winter grazing in the boreal forest lowlands (Fig. 1). Reindeer in Saarivuoma herding district cross the border to Norway for spring and summer grazing, while Norwegian herders may use that area during winter (Fig. 1). In Norwegian Finnmark, reindeer migrate between winter grazing grounds in the heather-dominated mountain birch forest at the border to Finland, and summer grazing grounds toward the North Atlantic Coast. In the winter grazing area, acquired rights and internal rules regulate the access to and rotation of pastures between the districts and smaller groups, often based on kinship (*siidas*) within the district. Contrastingly, herding districts in Finland are of a more compact shape, covering comparatively smaller environmental gradients. No extensive seasonal migrations are taking place, though reindeer exploit the available environmental variability of their district, such as riparian habitats, tundra heaths, or coniferous forest. In Näkkälä, only the northern part of the district was considered in the workshop.

Focus groups and their analysis

We held one focus group in each district, based on semi-structured interviews with multiple respondents with a set of particular questions (Cox 2015), between October 2014 and June 2015 (Appendix S1). We invited all members of the districts to join the focus groups to ensure unbiased attendance. The participants, all active to a varying degree in reindeer husbandry or retired practitioners, discussed observations of vegetation change in their respective herding areas and the potential consequences thereof. The focus lay on the environmental drivers of change, but participants were given time to expand on other topics they considered significant for their district. Focus groups lasted between 4 and 6 h and consisted of five to eleven participants. For Fiettar district however, we were unable to gather participants in a larger group due to pending herding activities. We therefore conducted three individual interviews with male herders. In total, 38 participants took part in the focus groups, whereof six (15%) were women. Age cohorts were mixed, though elderly males frequently dominated the groups.

Interviews were supported by maps of the respective district, providing detailed information about, for example, vegetation communities at 100 × 100 m resolution (map produced by B. Johansen, *unpublished data*). These enabled participants to point out in detail where they had observed changes in the landscape, encroachment of grazing grounds as a result of diverse factors, or other information they considered significant. Focus groups were held in Sámi or the national language, with an interpreter present to facilitate between participants and researchers. With the participants' consent, we recorded the interviews and transcribed them verbatim. Participants received a summary of each interview for approval prior to in-depth analysis of the recorded material.

From the transcribed interviews, we extracted emerging themes after several careful readings. We coded text passages depending on the research objectives and topics that emerged inductively from each focus group, using the OpenCode software (ICT Services and System

Development and Division of Epidemiology and Global Health 2011). These codes were assigned to text passages containing keywords, sentences, or paragraphs that captured the main argument or observation (Coffey and Atkinson 1996). To explore and synthesize the data, we systematically grouped codes related to each other by their content and context into broader categories (*axial coding*, Corbin and Strauss 2008). Based on these categories verified by the participants' experiences, our particular aim was to identify patterns related to geographical or historical factors that explain the participants' observations. For comparative analysis of codes and categories within and between the districts, we arranged them into tables to facilitate comparison and synthesis. The results present common observations from the participants by selected quotes, while detailed responses are available in Appendix S2: Table S1. All research follows the ethical guidelines for handling traditional knowledge by the International Arctic Social Science Association (http://iassa.org/about-iassa/research-principles) and the International Centre for Reindeer Husbandry (http://reindeerherding.org).

Results

Weather and reindeer behavior influence herding practices

In their daily reality of herding practices, participants emphasized the need to "cooperate with the weather" (Saarivuoma, P8). Reindeer respond to variable weather and habitat conditions in "select[ing] what lands to use" (Saarivuoma, P2) in order to maximize their foraging efficiency. Consequently, herding strategies need to embrace weather and reindeer behavior to the degree that reindeer herders "must carry out [their] work according to the reindeer" (Saarivuoma, P4).

Due to these dynamics, "[n]o year is like another" (Saarivuoma, P2), and it is difficult to plan ahead (Tuorpon, P1). This is especially true, as the herders perceive weather patterns having become less predictable and more variable during all seasons in recent years. Examples include warmer winters with a later arrival of snow (Näkkälä, P2/Lappi, P8/Tuorpon, P4) and longer and more intensive warm spells (Tuorpon, P4), resulting in more frequent rain-on-snow (Tuorpon, P1). Winds have become stronger (Lappi, P5/Tuorpon, P4) and summers getting warmer than ever remembered (Näkkälä, P1/Saarivuoma, P8).

Significance of vegetation zones as grazing grounds in different seasons

Several tree and shrub species fulfill different functions in the pastoral system. Besides mountain birch trees, these include dwarf birch (*Betula nana*), willows (*Salix* spp.), and pine (*Pinus sylvestris*). The significance and function of these species as either forage resources, influencing reindeer behavior, or grazing conditions differ between seasons (Table 2).

In spring, young leaves of birches and willow, as well as dwarf birch, are preferred forage (Fiettar, P3). However, the long time for deep snow in birch forests to melt away can delay their suitability for grazing in late spring. Once the snow has disappeared, these forests offer abundant freshly emerged vegetation, such as grasses (Fiettar, P2). Birch forests defoliated by autumnal moths (*Epirrita autumnata*) are a valuable grazing habitat due to increased growth of grasses relative to vegetation composition in the understory before moth attacks. However, reindeer do not select trees themselves for browsing (Fiettar, P2). Mountain birch forests may also offer shelter from avian predators or cold and windy weather (Fiettar, P2).

In summer, reindeer graze freely in open tundra or mountainous areas, selecting for forbs and grasses. In late summer, places with willows might be "a very good place to graze" (Saarivuoma, P2). Mushrooms in birch forests are considered an essential resource for reindeer, so they "are in good condition for the winter" (Näkkälä, P5).

During winter, the effects of trees on snow depend on tree species and size (Table 2) and "vary from winter to winter" (Fiettar, P1). Snow remains loose inside the mountain birch forest during early winter, but after accumulation up to 2 m and wind compaction, reindeer prefer open tundra areas with less snow (Beahcegealli, P3/Tuorpon, P1/Fiettar, P1/Lappi, P5). However, also on the tundra, snow tends to become compacted by winds and may become an obstacle to reindeer foraging.

During winter, old birch trees may offer "a lot of forage for the reindeer..., [but] not the new trees" (Beahcegealli, P3) in the form of foliose lichens growing on their bark—a critical

Table 2. Function of woody plants at the tree line and open tundra vegetation on reindeer behavior and grazing conditions in different seasons.

Season	Species	Effects on grazing conditions and reindeer behavior	Herding district
Spring	Mountain birch, dwarf birch, willows	Young, fresh leaves as forage resource during early growing season	All
		Long duration of snow melt due to hard and deep snow in dense forest	Fiettar, Norway
Summer	Mountain birch forest	Protection from predators and unfavorable weather conditions	Fiettar, Norway
	Willows	Important browsing resource in riparian areas and wetlands	Lappi, Näkkälä, Finland Saarivuoma, Sweden
	Open tundra vegetation	Important foraging habitat, insect relief	All
Autumn	Mountain birch forest	Habitat for mushrooms as forage resource	All
	Willows	Antler rubbing	Beahcegealli, Fiettar, Norway
Winter	Mountain birch, willows	Protection from unfavorable weather conditions	Beahcegealli, Fiettar, Norway
		Increased snow depth can reduce forage accessibility	Saarivuoma, Sweden Beahcegealli, Fiettar, Norway
		Loose snow can increase forage accessibility	Saarivuoma, Sweden Beahcegealli, Fiettar, Norway
		Old trees offer bark lichens as forage resource	Beahcegealli, Norway
	Open tundra vegetation	Hard snow can reduce forage accessibility	All
		High variability in snow cover characteristics can increase forage accessibility	All
	Pine	Low snow cover compared to birch trees/open areas	Saarivuoma, Sweden

resource, if grazing grounds in the tundra are locked by hard snow or ice. Therefore, one potential strategy to buffer adverse grazing conditions in terms of snow depth and hardness in open fells or tundra is to let the reindeer loose in the forest—trading off the risk of less herd control against the risk of their starvation (Fiettar, P1). Old forests also are shelter from strong winds or cold during winter (Beahcegealli, P3). Birch forests can thus be both "good and bad" (Fiettar, P1) during winter.

Where available, pine forests may increase accessibility to terrestrial lichens during winter, as "there is less snow under them" (Saarivuoma, P2). Participants stressed that the "mountains have been the rescue, irrespective of whether it is locked pastures [in the forest] or lots of snow" (Saarivuoma, P2). For that reason, mountain pastures are often saved for as long as possible as grazing grounds for early spring (Saarivuoma, P7).

Observed vegetation changes in the pastoral landscape and their drivers

Observed shifts of the tree line and tree growth.— Though the reindeer density differed between the districts (Table 1), the observations of direct and indirect impacts of reindeer on the vegetation were very similar. Reindeer herders in all districts observe an increase in abundance and growth of trees and shrubs, but to varying degrees (Table 3). Species mentioned in particular include mountain birch, willows, pine, and juniper (*Juniperus communis*). Participants had observed the progression of trees into formerly treeless areas and that "the trees have started to grow so much, especially in recent times. You can say in a 20-yr time span" (Beahcegealli, P3). Individual birch trees are establishing at mountains well above the tree line (Tuorpon, P1). Also in coastal areas, birch trees establish locally "in the mountains where they have never been before" (Fiettar, P2). In other herding districts, herders had not noticed forest moving up into the tundra (Fiettar, P1/Näkkälä, P2, P5). Spatial variability of shifting tree lines was also noted, as the tree line seemed to move upward in coastal areas, yet this was not observed inland (Fiettar, P2).

Where a progression of the tree line or increased tree growth is observed, participants highlighted the connection to favorable abiotic conditions. In particular, soil thickness and its

Table 3. Observed vegetation changes in the herding districts.

Country	District	Mountain birch and willow	Coniferous species
Norway	Beahcegealli	Rapid growth and increased abundance within past 20 yr, but without much progress into tundra areas	
		Increased abundance in abandoned corrals and in areas with decreased human activity, such as woodcutting and fire	
	Fiettar	Progression of tree line observed in coastal areas, but not in inland areas	
		Inland forests have not increased much, but trees get bigger	
		Increased abundance in areas with decreased human activity, such as woodcutting and fire	
Finland	Lappi	Progression into open areas not observed	Rapid growth of pine in forest lowlands
			Increased abundance of pine in abandoned corrals
	Näkkälä	Not much progression into open areas observed	Increased abundance and rapid growth of pine in tundra areas
		Increased abundance in areas with decreased human activity, such as woodcutting and fire	
Sweden	Saarivuoma	Rapid growth and increased abundance	Increased abundance of pines in the mountains
		Birch trees moving higher up the mountains	Rapid growth of juniper
		Increased abundance in abandoned corrals	
	Tuorpon	Rapid growth and increased abundance	Spruce observed at the tree line
		Birch and willow moving higher up the mountains	

effect on water availability are important (Lappi, P5/Beahcegealli, P1). Thin soils in the tundra are unlikely to retain enough moisture for tree growth (Beahcegealli, P3). In addition, higher elevations are often rocky places, where "trees cannot develop roots" (Fiettar, P2). Due to these limitations, new trees grow "where there are already trees" (Beahcegealli, P3). Previously established trees "create protection [from harsh climate] for others that are coming" (Fiettar, P2). In one particular area, new trees grow densely on areas that had been burned in the 1970s (Fiettar, P1).

Further changes at the tree line and above include the species composition. More pines grow in the mountains, reported to have "grown in a relatively short time... they can be all over the place" (Näkkälä, P5). It was also observed that "spruce has come to the birch forests" (Tuorpon, P1).

Changed human land use affects tree growth and recovery.—Increased growth of trees can result from the regeneration of trees where earlier land use by people, including husbandry practices, has changed or ceased (Table 3). Today, where people use fuel-heated cabins instead of tents (*lavvo*), they cut trees less and less for firewood (Beahcegealli, P3/Tuorpon, P3). Consequently, rapid growth of willows was noticed "[e]specially in the old places where people lived ... Our parents used to cut them down. It's more like what you did there not whether it was warmer by some degrees" (Näkkälä, P2). However, participants also observed that the "forest is growing where there hasn't been a lavvo" (Fiettar, P2). In addition, other grazing practices disappeared, such as outfield grazing by cattle (Saarivuoma, P6). Local effects that facilitate forest establishment are the disposal of slaughter waste, including reindeer intestines containing tree seeds and organic materials. Combined with fertilization by feces from nearby corrals, new forests may establish from these seeds (Fiettar, P2).

Abandonment of reindeer corrals may set vegetation succession on a new trajectory, and trees might flourish at these sites (Lappi, P6/Beahcegealli, P1). However, how exactly an abandoned corral develops depends on its former use and location (Fiettar, P1). For example, at higher elevation, woody plants do not overgrow very old milking meadows (Tuorpon, P1).

Can herbivores affect the expansion of woody vegetation?—Though fresh vegetation is important for reindeer "to gain enough of energy" (Fiettar, P3), participants discussed how much trees actually form a vital resource. Reindeer select for fresh leaves of young willow and birch early in the growing season (Beahcegealli, P1/ Fiettar, P2), but "the larger willows they don't care too much about" (Beahcegealli, P3). Therefore, reindeer browse trees and shrubs only a "very short period" (Fiettar, P2). Forests are not a very attractive habitat for foraging during summer, before the mushrooms season (Fiettar, P2).

The perception of the reindeers' influence on the establishment of trees and shrubs was highly diverse (Table 3). At places where reindeer do not graze, the tree lines may move upward on mountain slopes (Saarivuoma, P2). Some participants from Finland without extensive seasonal movements observed that "[i]n the summer areas, we don't get these thickets and birches, the reindeer control it" (Lappi, P4), while elsewhere there was more uncertainty as "we can't be sure what effect now the reindeer will have" (Näkkälä, P5). Participants in districts with clearer separation between summer and winter grazing grounds stated they "don't think the reindeer herders will be able to keep the bushes from growing" (Tuorpon, P1), an opinion shared in other migratory districts as well (Fiettar, P1/ P3). Apart from grazing pressure, the direct impacts of reindeer on vegetation include trampling and the rubbing of velvet antlers, causing damages to the trees, preferably willow (Fiettar, P1/P2). One reason discussed why reindeer were not able to control the potential expansion of trees was that "you'd need huge herds to achieve that. The thing limiting the size of the herds is the winter" (Tuorpon, P1); that is, the availability and abundance of winter resources does not allow these numbers of animals.

Other herbivores influencing tree line dynamics are autumnal moths (*E. autumnata*). In years with mass outbreaks, their larvae defoliate vast areas and may cause tree mortality, resulting in open landscapes abundant in grasses (Fiettar, P1/ Saarivuoma, P2). In these areas, it "takes lots of years until the trees are coming back" (Saarivuoma, P8).

Increased tree growth changes the pastoral landscape

Participants characterized reindeer as "animals that you work together with" (Lappi, P1). Therefore, reindeer herders need to adjust their herding strategies to the behavior of their reindeer toward increased abundance of woody vegetation. There was an amplifying feedback observed between the growth of trees and adverse snow conditions for grazing during winter. Reindeer avoided areas that had become unsuitable as grazing grounds, which favored the further growth of trees (Saarivuoma, P4). These dynamics depend on a "change in the climate, wind, and ice [that] made it impossible to use this area" (Saarivuoma, P4). Losing open areas would therefore entail less landscape variability to adapt to changing grazing conditions (Beahcegealli, P3). Therefore, participants had a strong opinion that "trees should grow in the forest, not in the mountains" (Saarivuoma, P2). Increased shrub growth might have a detrimental effect on seasonal grazing rotation, as shrubs "will wreck the whole system. It would make [the mountains] a summer pasture and now it is a winter pasture" (Lappi, P6). However, where there is a comparatively high abundance of open areas, there is a feeling that "more forest can come without problems" (Fiettar, P2).

During summer, increased growth of willows leads to a higher abundance of harassing insects. To avoid these insects, reindeer move higher up to more open and windy places (Tuorpon, P1). Consequently, reindeer herders need to relocate their activities, such as calf marking, further away from their traditional summer settlements. The coupling between factors influencing vegetation dynamics, their consequences on reindeer behavior, and herding practices is therefore tight (Fig. 2).

On nutrient-poor soils in the continental parts of the study area, increased growth of birch trees may favor winter forage, that is, terrestrial lichens, as "the lichen grows better if it is where the birches are" (Näkkälä, P5). However, "too many trees [. . .] can destroy the lichen" (Beahcegealli, P3). Increased abundance of woody vegetation also leads to a more frequent presence of moose (*Alces alces*), grouses (Capercaillie, *Tetrao urogallus*; Fiettar P1/Saarivuoma P2/Tuorpon, P1), and bears (*Ursus arctos*; Fiettar P1, P2/Tuorpon, P1).

Discussion

Importance of habitat heterogeneity

Reindeer herders, who act across the landscape on which their livelihood depends,

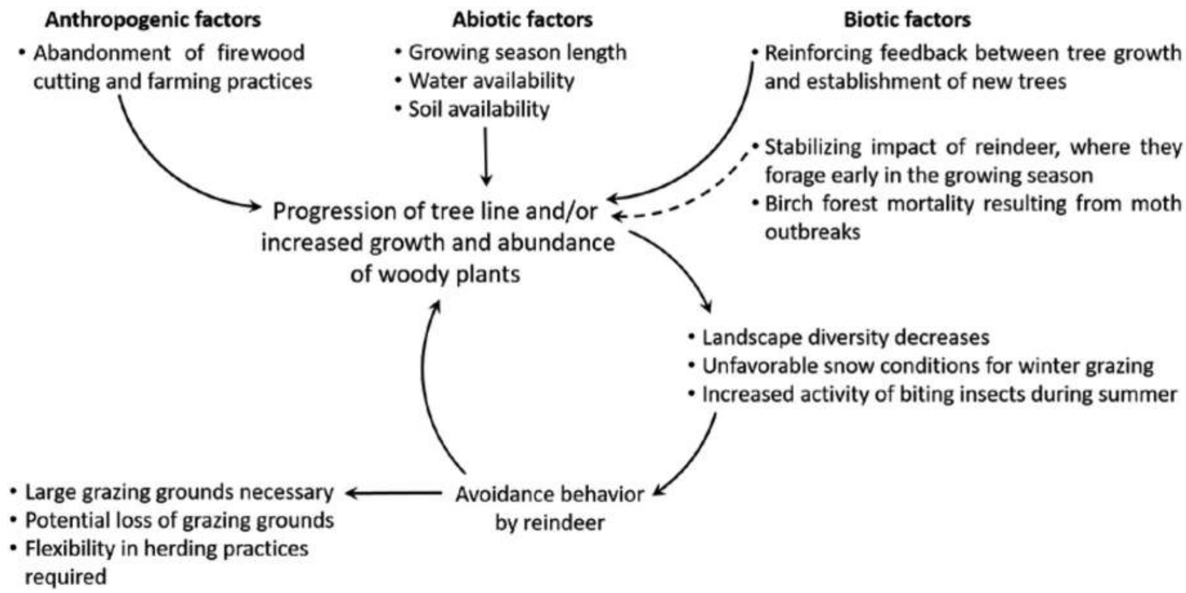

Fig. 2. Main factors influencing the vegetation dynamics at the tree line and the resulting consequences. The dashed arrow indicates stabilizing impacts on woody plant growth; the full arrows indicate enhancing relationships.

observed a high variability in the magnitude of tree line advances, depending on site conditions, reindeer grazing, and anthropogenic impact. They emphasized in particular the strong controls at the local level that shape this variability by abiotic and biotic conditions, as well as human land use activities, including herding practices that create different patterns in the spatial and temporal grazing pressure (Table 3). Their observations confirm earlier work reporting highly diverse tree line dynamics, ranging from progression to stagnation (Tømmervik et al. 2009, Van Bogaert et al. 2011, Hofgaard et al. 2013, Vuorinen et al. 2017), but interrelate these phenomena to the direct impact on their livelihood (Fig. 2).

Herders described their human–animal agency as an instrument to shape the structure, function, and cultural relevance of the pastoral landscape—a process reported from many human–reindeer livelihoods across the circumpolar North (Castro et al. 2016, Stépanoff 2017). The current form of this relationship rests upon the herders' knowledge of the behavioral patterns and seasonal habitat selection of their reindeer (Table 2), as well as of the diverse landscape functions in relation to, for example, weather and snow conditions that generally fluctuate widely in the sub-Arctic within and between years (Bokhorst et al. 2016, Rasmus et al. 2016). However, the increased unpredictability and occurrence of extreme events experienced by the herders threatens to alienate the human–animal agency in its current form from their environment. The continued disruption of familiar climate patterns enhances the dependency on grazing grounds suitable for reindeer foraging under any weather conditions.

The frequency and duration of weather events that cause unfavorable conditions for reindeer grazing govern when and where there are the most functional grazing grounds. In consequence, spatial variability of forage resources may buffer reindeer against climatic variation and explains their seasonal grazing patterns, both within and between seasons (Hobbs and Gordon 2010). For that reason, participants did not assign an unambiguous role to different habitats for reindeer grazing or herding practices: Their suitability depends on the spatial composition of the surrounding landscape (i.e., habitat heterogeneity) and temporal variability (i.e., weather conditions). Where only one vegetation type is available, participants feel their flexibility to respond to changes in grazing conditions to be limited (see also Turunen et al. 2016). At the tree line, forests interweave closely with open areas, each with particular advantages or disadvantages for reindeer foraging or herding practices. This variability of structural and functional attributes at relatively low spatial levels allows reindeer to forage during many different conditions of forage accessibility (Table 2), given their ability to move freely to exploit the available habitats.

However, reindeer herders perceive a potential threat by increased abundance of woody plants in a homogenization or loss of landscape heterogeneity. This would entail the loss of open areas favored by reindeer during summer not only due to the high abundance of high-quality forage, but also because they offer relief from insects and facilitate thermoregulation (Table 2; Moen 2008). Regarding winter, reindeer herders characterized these open areas as "rescue" pastures during difficult grazing conditions (Table 2). As potential consequence of diminished habitat heterogeneity, competition for limited space may lead to increased grazing or trampling pressure on many, if not all, types of pasture vegetation (Skarin and Åhman 2014).

Feedback loops on plant community composition and forage availability

Although increased grazing or trampling pressure can have detrimental consequences for pasture vegetation, participants emphasized the need of sustained grazing pressure by reindeer to keep their grazing areas functional at the local level. The reinforcing feedback loop between too low or ceased grazing pressure and increasing abundance of shrubs may create snow conditions unfavorable for grazing or increases insect activity during summer, furthering the avoidance by reindeer of these areas (Fig. 2). Reindeer grazing thus sustains the vital landscape heterogeneity to offer flexibility under different grazing conditions, a process that simultaneously preserves unique arctic vegetation from encroachment by trees and shrubs (CAFF 2013). Also experimentally, the capacity of reindeer to prevent the invasion of boreal species into tundra habitats has been demonstrated (Olofsson et al. 2009, Kaarlejärvi and Olofsson 2014), thus acting as source of resilience of tundra ecosystems to environmental change (Kaarlejärvi et al. 2015). According to participants, reindeer grazing also may remove the shading effect of birch trees that slows down lichen growth—yet another process with favorable consequences for future grazing. Similar reinforcing impacts on forage availability by reindeer grazing and trampling have been reported from West Siberia (Forbes et al. 2009), where reindeer grazing increased the abundance of palatable vegetation rich in nutrients, in turn increasing the habitat use of these grazing lawns at the local level.

Additionally, the spatial variation in climatic components governs the response of tree species to recent trends in growing conditions. Where maritime influence is high, herders reported a progression of the birch tree line, such as in the mountain areas of Saarivuoma and Tuorpon, as well as in coastal areas of Fiettar (Table 3). At these sites, protective snow cover during winter and high soil moisture availability during the growing period favor the advance of birch trees (Anschlag et al. 2008, Öberg and Kullman 2012). Contrastingly, herders from districts at the more continental edge of the continuum, in particular Näkkälä and Lappi, reported increased growth of pine rather than a pronounced progression of willow or birch (Table 3). In these continental areas, pine as drought-resistant species might benefit more from recent trends toward warmer summers than mountain birch (Kullman and Öberg 2009). Though reindeer do not browse pine, their antler rubbing creates a high mortality risk of pines <150 cm in size (Holtmeier 2011), as similarly confirmed by herders in this study for willow (Table 2). However, moose do browse on pine and thus contribute to the dynamic of pine establishment (Callaghan et al. 2013, Kullman 2015). Corresponding to observations by reindeer herders in this study, moose are currently expanding their range also in other parts of the Arctic in response to increased abundance of forage, with consequences for the structure and function of these high-latitude ecosystems (Tape et al. 2016).

In coniferous forests, pines grow increasingly in areas heavily grazed and trampled by reindeer, in particular abandoned corrals (Table 3). The positive effect of reindeer on pine growth in these forests can partly be attributed to increased nutrient availability via feces and in particular lichen removal, as warmer soils in lichen-free areas enhance pine growth compared to soils with thick, isolative lichen mats (Macias Fauria et al. 2008). This interaction demonstrates that high levels of direct and indirect impacts by reindeer may have desired outcomes given particular aims in, for example, forest management.

The herders observe different tree species advancing in dependence on regional oceanity, which coincides with contrasting grazing regimes (Table 3). Maritime influence is higher in districts with pasture rotation in Sweden and Norway, compared to the districts in Finland where reindeer are more restricted in their movements between season-specific grazing grounds. The observed successful establishment of grazing-sensitive birch might therefore result from the combination of favorable maritime climate and distinct seasonal pasture rotation, that is, the distribution of the presence and grazing pressure of reindeer in space and time (Kumpula et al. 2011, Biuw et al. 2014).

Reindeer husbandry as an actor in shaping vegetation trajectories

Despite the emphasis of habitat heterogeneity as source of resilience for the livelihood, reindeer herders did not generally see increased abundance of erect woody plants as a major threat. Rather, the consequences depend on temporal and spatial context of their herding activities. Between the participants, no consensus emerged on the magnitude of reindeer impacts on tree line dynamics. One reason for this high variation seen in the animals' direct and indirect impacts on birch forests and associated woody vegetation lies in the different practices and spatial distribution of vegetation types with regard to seasonal forage selection by reindeer between the herding districts (Table 2). The magnitude by which reindeer do affect the tree line and shrub species depends on their seasonal migration pattern, that is, the position of the reindeer at the time of the emergence of fresh and maximally nutritious leaves (Table 2). Therefore, a strong interaction exists between grazing pressure and abiotic effects on plant community transition during environmental change (Van der Wal 2006, Saccone et al. 2014).

Participants saw options to shape these interactions by the use of their reindeer, thus pushing back invading woody vegetation, or at least modifying the shrubification of tundra areas. Though potentially limited in its effect at a broad Fennoscandian level, the human–animal agency of reindeer husbandry evidently has the capacity to keep the tundra free from woody vegetation at local levels. Although participants did not explicitly describe deliberate direction of their animals to specific places in order to realize these effects, they noted a tipping point in landscape function where reindeer have been absent for several years or where trees already present enhance further tree growth or facilitate establishment of new trees (Fig. 2). Reindeer grazing therefore may act as a process of "ecosystem engineering." Implemented at different intensities in space and time, it has the capacity to affect the structure and function of key components of the tundra biome and its various ecotones (Biuw et al. 2014). By adaptively shaping the interaction between vegetation and the climate system, diverse grazing patterns and intensities across the tundra landscape potentially can navigate the trajectories of climate change effects also at the regional level (Cohen et al. 2013, Te Beest et al. 2016). The significance of herbivores, therefore, lies in breaking a potential reinforcing feedback between regional climate change and increasing shrubification: Encroachment of previously open vegetation contributes to a lower reflectance of solar radiation, and may lead to an increased regional energy balance, furthering the advance of shrubs (Loranty et al. 2011, Myers-Smith et al. 2011).

Furthermore, increasing abundance of trees depends on the cessation of human land use activities (Table 3). Such increases are rather a local regeneration of the potential forest, than a true expansion at the cost of primary open tundra habitat (Aiko and Müller-Wille 2005, Van Bogaert et al. 2011), but might occur at strategic places where open areas would be preferred. Contrastingly, the combined effects of moth and reindeer herbivory may create open landscapes by causing birch mortality and preventing forest regeneration through birch seedlings (Holtmeier and Broll 2005). This interaction can be regarded as an environmental problem of overgrazing, or as a desirable outcome when preserving open habitats.

Adaptation challenges of reindeer husbandry to environmental change

Reindeer herders assigned particular functions for reindeer foraging and herding practices to all available vegetation types in their respective herding districts. Encroaching trees therefore change the landscape function (Fig. 2) and may break the cyclic pattern of mutual behavioral adaptation between reindeer and herders (Istomin and Dwyer 2010). Innovative ways of adaption become necessary, potentially including changed grazing rotation, establishment of new sites for animal handling, and trends to more rationalized herding practices. Reindeer herders do not necessarily consider these as ideal strategies due to cultural and financial concerns (Löf 2014), so that the human–animal agency shifts toward a new identity. How adaptations and involved trade-offs to rapidly changing environmental conditions can maintain cultural preferences and values therefore requires more research (Ford et al. 2015). In the present system, the impact of reindeer grazing involves inevitable trade-offs between the effects on different forage items. For example, reindeer herders noted the capacity of reindeer to control birch expansion where seasonal pasture rotation is not practiced extensively (Table 3). However, the year-round presence of reindeer damages the lichen cover due to trampling and thus reduces the quality of the winter grazing grounds (Kumpula et al. 2014).

Consequently, there is a need to closely observe current ecosystem transformations in the Arctic and their consequences for resident people. Any potential policy involving reindeer grazing for ecosystem engineering to halt a progress of encroachment of the tundra involves value-laden and context-specific concepts, depending on management objectives, time frame, and different knowledge types. This includes the local ecological knowledge and local observations of Sámi herders about reindeer behavior, vegetation dynamics, and other environmental variables, their abilities, and capacities, as well as scientific knowledge derived from historical observations and the current and projected dynamics of tundra ecosystems. To connect these diverse, equally important knowledge systems is an essential requirement for flexible and learning-based collaborations and decision-making in adaptive governance of rapidly changing social–ecological systems (Tengö et al. 2014, Schultz et al. 2015).

To understand how and why transformations of reindeer grazing grounds via woody vegetation encroachment occur, the interaction between these ecological processes and anthropogenic impacts that act on the landscape needs to be taken into account. For reindeer herders in northern Fennoscandia, the cumulative effects of other forms of land use, resource exploitation, or increasing carnivore populations require communication and governance between different stakeholders across diverse spatial, temporal, and administrative levels (Keskitalo et al. 2016, Larsen et al. 2017). Therefore, normative factors and complex power relations between stakeholders need to be addressed explicitly (Plummer and Armitage 2007). It is essential that the Sámi livelihood remains independent of its rights, self-determination, and cultural integrity from benefits that serve a mainstream purpose. Policies for conservation of arctic vegetation therefore need to prohibit colonial influences on ethical ways by which indigenous livelihoods engage with their social–ecological system, for example, by fragmenting their culture and knowledge (Kovach 2010, Ford et al. 2016). This demonstrates the place-specific significance of reindeer herders' accumulated knowledge about long-term vegetation trajectories and the diverse effects of grazing impacts to sustain their cultural as well as the ecological diversity of their environment and to keep their livelihood resilient to consequences of climate change, increased plant productivity, and species shifts.

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