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Coping with difficult weather and snow conditions: Reindeer herders' views on climate change impacts and coping strategies

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ABSTRACT

Winter is a critical season for reindeer herding, with the amount and quality of snow being among the most important factors determining the condition of reindeer and the annual success of the livelihood. Our first aim was to model the future (2035–2064) snow conditions in northern Finland, especially the quantities related to ground ice and/or ice layers within the snow pack, exceptionally deep snow and late snow melt. Secondly, we studied the strategies by which herders cope with the impacts of difficult weather and snow conditions on herding by interviewing 21 herders. SNOWPACK simulations indicate that snow cover formation will be delayed by an average of 19 days and snow will melt 16 days earlier during the period 2035–2064 when compared to 1980–2009. There will be more frequent occurrence of ground ice that persists through the winter and the ice layers in open environments will be thicker in the future. The snow cover will be 26–40% thinner and snow in open environments will be denser. Variability between winters will grow. In interviews, herders indicated that a longer snowless season and thin snow cover would be advantageous for herding due to increased availability of forage, but more frequent icing conditions would cause problems. The most immediate reaction of reindeer to the decreased availability of forage caused by difficult snow conditions is to disperse. This effect is intensified when the lichen biomass on the pastures is low. To cope with the impacts of adverse climatic conditions, herders increase control over their herds, intensify the use of pasture diversity, take reindeer into enclosures and/or start or intensify supplementary feeding. The research also reveals that predators, competing land uses and the high prices of supplementary feed and fuel were the major threats to the herders' coping capacity. Coping capacity was facilitated by, among other factors, the herders' experience-based traditional knowledge (TK) and skills, a diversity of pasture environments and the use of seasonal pasture rotation. More often than before, herders combine their TK and skills with technical applications, which greatly facilitates herding. We

Abbreviations: ATV, all-terrain vehicle; DW, dry weight; LAI, leaf area index; MBE, mean bias error; RHA, Reindeer Herders' Association; RMSE, root mean square error; SWE, snow water equivalent; TK, traditional knowledge.

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conclude that the coping capacity of herders could be facilitated in the future not only by reorganizing the management systems and herding practices for sustainable use of pastures, but also by diversifying the livelihood, increasing its profitability and mitigating the adverse effects of climate change, predators and competing land uses.
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Introduction

The global mean temperature is expected to rise 1–5 °C by the end of the twenty-first century (IPCC, 2013; Stocker et al., 2013). In the reindeer management area of Finland (Fig. 1), it is projected that winter temperatures, the number of thaw days and winter precipitation will increase, while the occurrence of soil frost will decrease. It is likely that snow melt will occur, and the growing season start earlier than before. Summers will be warmer and periods of high temperatures become longer and still hotter than earlier. In autumn the first frosts will be delayed, and soil frost and snow cover will appear later than before. The effects of warming on the structural properties of snow are not well known, although it is probable that the proportion of dry frost snow will decrease and that of melting or icy snow increase (Rasmus et al., 2004; Jylhä et al., 2008; Räisänen and Eklund, 2012) (Table 1). Winter air temperatures have already increased during the past 30–50 years in several locations (Kivinen et al., 2012; Kivinen and Rasmus, 2015), and the snow season has become shorter (Rasmus et al., 2014).

In northern Finland, the reindeer herding year starts in May with calving (M1–19, F1–2, Nieminen, 2014; Helle, 2015). In free-ranging calving, semi-domesticated reindeer (*Rangifer tarandus tarandus*) give birth to their calves in their natural calving regions, for example, forested areas or the southern slopes of fells. Calving is followed by calf earmarking, which is carried out from midsummer onwards. Each reindeer must be marked with the owner's reindeer earmark (Reindeer Husbandry Act, 1990). In enclosure calving, pregnant hinds are separated into a section of their own within the enclosure from March–April until the end of May. In this practice, the calves are earmarked immediately after birth and hinds with a calf are let free thereafter. Herding work in the summer includes hay-making for possible supplementary feeding during the following winter. In autumn, herders start collecting their herds and moving them to the round-up sites either on foot or with the aid of ATVs (all-terrain vehicles), motorbikes, snowmobiles or helicopters. The work is facilitated by the rutting time, when male reindeer attract small herds of female reindeer around them. During round-ups the reindeer are counted, the animals to be left alive are separated from those to be slaughtered, and calves not marked in summer get their earmarks (M1–19, F1–2, Nieminen, 2014; Helle, 2015). The reindeer to be left alive also get medication against parasites. After the round-ups, reindeer are herded onto winter pastures and given supplementary feed in the field or in pens if needed, especially during difficult snow conditions. During the late winter, reindeer feed on arboreal lichens in old-growth forests where available, or on the fells, where snow conditions are more favorable for digging up terricolous lichens. A hard snow cover makes digging difficult but facilitates feeding on arboreal lichens by allowing reindeer to reach higher. Herders' annual work includes herding to protect reindeer from predators, searching for the remains of reindeer lost to predators, repair of fences, driving reindeer away from human settlements and fields, planning meetings and bookkeeping (M1–19, F1–2, Nieminen, 2014; Helle, 2015).

Reindeer herding is affected throughout the herding year by the local climate – either directly through the effects of weather events on the well-being of reindeer or on herding work, or indirectly through the impact of weather conditions on pastures (Tyler et al., 2007; Turunen et al., 2009; Furberg et al., 2011; Vuojala-Magga et al., 2011). Winter is a critical season for herding, because difficult snow conditions can radically decrease the availability of winter forage, mainly terricolous lichens (Kumpula et al., 2000; Kitti et al., 2006; Turunen et al., 2009; Heikkinen et al., 2012; Kivinen and Rasmus, 2015; RHA, 2015a). Deep snow or ice formation in the snow pack cause reindeer to expend more energy because they have to spend more time digging and walking (Fancy and White, 1985; Collins and Smith, 1991), and this can impair their condition (Helle and Kojola, 2008). Ice-locked pastures generated by warmer and wetter winters, have had a strong negative effect on the condition and productivity of reindeer populations. This effect has been documented in Northern Fennoscandia (Helle and Kojola, 2008; Tyler et al., 2007; Vuojala-Magga et al., 2011; Vikhamar-Schuler et al., 2013; Turunen and Vuojala-Magga, 2014), Svalbard (Chan et al., 2005; Hansen et al., 2011, 2014), Northern America (Barry et al., 2007; Miller and Barry, 2009) and Russia (Forbes and Stammler, 2009; Bulgarova, 2010; Stammler-Gossmann, 2010).

The adverse effects of winter weather are often combined with low lichen biomasses resulting from heavy grazing by high density reindeer populations. The large-scale deterioration of lichen pastures has been observed over past decades throughout the reindeer herding area of Finland (Kumpula et al., 2014; Pekkarinen et al., 2015). A recent analysis indicates that reindeer densities, grazing system, pasture type and several abiotic factors have contributed to the reduction in lichen biomass (Kumpula et al., 2014). In many herding co-operatives, this deterioration stems from cascading consequences of competing land uses combined with high reindeer densities, long-term grazing and a lack of or incomplete seasonal pasture rotation, which expose the remaining pastures to high grazing pressure. The consequences of difficult snow conditions can be critical in regions where lichen-dominated winter pastures, for example, old-growth forests rich in arboreal lichens, have become fragmented and have declined in number and quality (Helle and Jaakkola, 2008; Anttonen et al., 2011; Jaakkola et al., 2013; Kumpula et al., 2014; Pekkarinen et al., 2015).

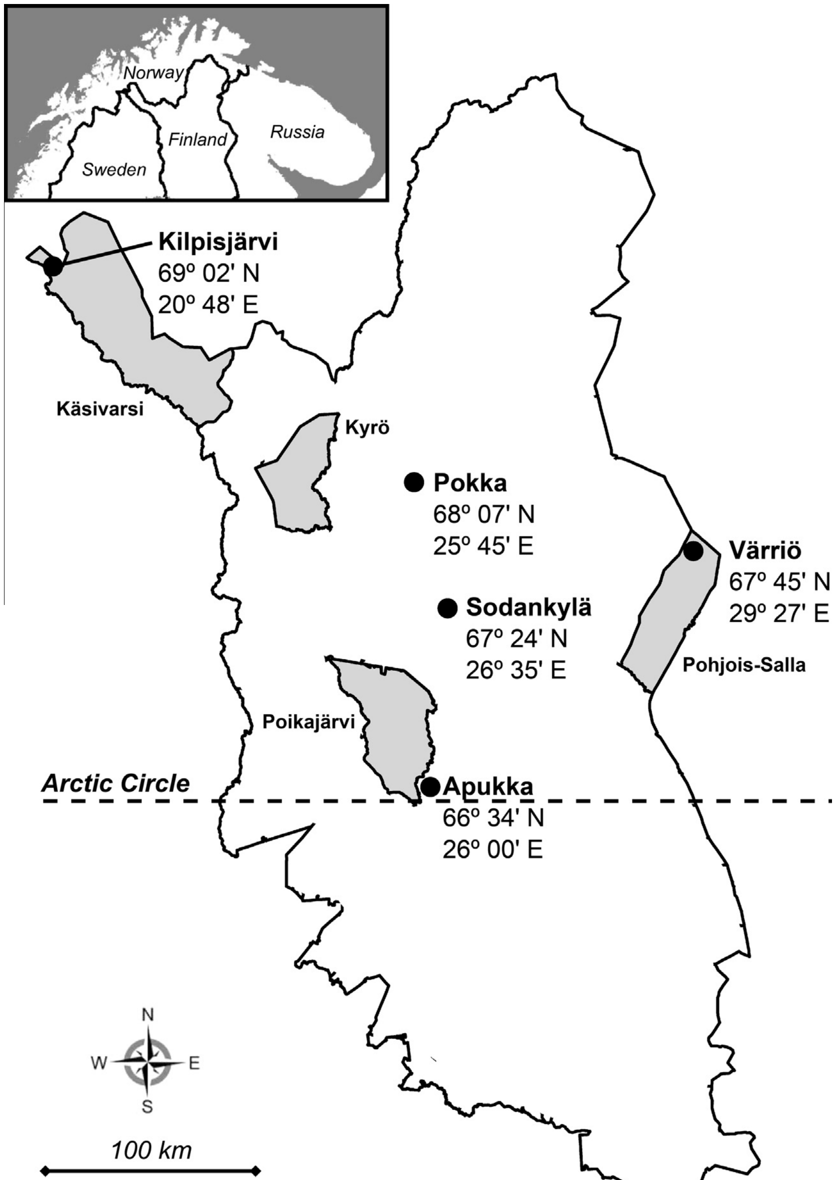

Fig. 1. Locations of the herding co-operatives and the weather stations.

The aim of the present investigation was to study reindeer herders' experience-based traditional knowledge (TK) about the impacts of weather and snow conditions on herding work over the past 30 years and to explore how herders cope at present and might cope in the future with varying conditions in four herding co-operatives (Käsivarsi, Kyrö, Pohjois-Salla and Poikajärvi) in northern Finland. "Coping strategy" is defined here as a specific response or effort that herders employ in their work to minimize the damage to their livelihood due to unfavorable weather and snow conditions, whereas "coping capacity" refers to the ability of herders to cope with the impacts and risks of difficult weather and snow conditions. Rasmus et al. (2015a) examined the annual management reports of the herding co-operatives studied (1981/1982–2010/2011) (RHA, 2015a) and found that there were three particular snow conditions that herders most often cited as difficult: formation of ground ice and ice layers within the snow pack, exceptionally deep snow and late snow melt. These were the conditions we focused on when we first modeled the snow conditions in the recent (1980–2009) and in the future climate (2035–2064). These simulations are particularly valuable, as data on future snow structure is limited. Second, we studied the perceptions of 21 herders by interviewing them about the impacts on their work of difficult weather and snow conditions and the changing climate, their strategies for coping in these situations and how their coping capacity is affected by different factors.

Table 1
Summary of the projected changes in seasonal conditions in northern Finland during the coming decades.

Season	Projection
Spring	• The last frosts in the spring will occur a few weeks earlier[4] • Snow will melt earlier, and snow-free sites will be formed earlier[1,2,4,5,6,9,10,11,13,14] • The growing season will start earlier[4] • The ice cover on the lakes and rivers will break up earlier[13] • Spring floods will decrease in volume and occur earlier[13]
Summer	• Summers will be warmer; periods of high temperatures will be longer and hotter [4] • Heavy rains will be stronger, but in summer and early autumn drought may be more common[4,8] • The growing season will be longer and warmer[4]
Autumn	• Precipitation will increase and the discharge of rivers will increase[4,13] • The first frosts will be delayed by several weeks[4] • The snow cover will form later[1,2,5,6,9,10,11,13,14] • Soil frost will appear later[5,14] • The ice cover on rivers and lakes will form later[13]
Winter	• Winter temperatures will increase[1,2,3,4,8,10,12] • The number of frost days will decrease by one-third[3,4,6] • The number of thaw days will increase, as will the number of days when the temperature is both below and above zero during the same day[3,4] • Rainfall will be more common[2,4,8,10,13] • Winters with scanty snow will become more common[1,2,5,6,9,10,11,13,14] • The proportion of dry frost snow will decrease and that of thaw-freeze/icy snow will increase[7] • Winter flooding of rivers will become more common[13] • Cloudiness will increase[8] • Soil frost will be more shallow than earlier[5,14]

[1] ACIA (2005).
[2] Eklund (2010).
[3] Jylhä et al. (2008).
[4] Jylhä et al. (2009).
[5] Kellomäki et al. (2010).
[6] Kivinen et al. (2012).
[7] Rasmus et al. (2004).
[8] Ruosteenoja et al. (2013b).
[9] Räisänen (2008).
[10] Räisänen and Eklund (2012).
[11] Räisänen et al. (2004).
[12] Stocker et al. (2013).
[13] Veijalainen et al. (2012).
[14] Venäläinen et al. (2001).

Materials and methods

Study sites

Our study sites were the herding co-operatives of Käsivarsi, Kyrö, Pohjois-Salla and Poikajärvi in northern Finland (Fig. 1). They were selected to represent the variation of climate, topography, vegetation and herding practices of the country's reindeer management area. The salient characteristics of the co-operatives are presented in Table 2. Reindeer densities in the herding co-operatives studied ranged from 1.7 to 2.6 animals per km^2 land area, with the lowest density in Poikajärvi and highest in Käsivarsi (Mattila, 2012; RHA, 2015b). During the pasture inventory period of 2005–2008 lichen biomasses of 150 kg DW ha^{-1} were measured in Käsivarsi (fell district), 128 kg DW ha^{-1} in Kyrö and 271 kg DW ha^{-1} in Pohjois-Salla (data not available for Poikajärvi) (Table 2) (Kumpula et al., 2014).

Of the study sites, Käsivarsi is one of the 13 Sámi herding co-operatives in Finland. In these co-operatives, herding is based on the *siida* system, whereby family and kinship play a key role in herding practices. A siida is an extended family or kin group consisting of economically independent households (Vuojala-Magga et al., 2011). Käsivarsi is the only "fell" herding co-operative; 21.4% of it is covered by open fells, whereas the corresponding figure for the other three "forest" co-operatives studied is less than 3% (Kumpula et al., 2009). Herding in Käsivarsi is organized in ten siidas in winter and four siidas in summer, with each having an independent seasonal pasture rotation system. One of the siidas uses large fenced-in enclosures for calving (approximately 50% of all the reindeer in the co-operative), while the others ear-mark their calves in the summer. Some of the siidas rely exclusively on natural pastures; others give supplementary feed to the reindeer. In Kyrö, winter and summer pastures are separated by a fence. In winter, all reindeer in the co-operative are gathered in the same area (collective herd). The animals are given supplementary feed in the forest and when the snow conditions are difficult, they are brought into enclosures. Calves are marked in the summer. In Pohjois-Salla, winter and summer pastures are separated by a fence, and all reindeer are herded together all year round. Winter feeding has been minimal. Reindeer are marked in the

Table 2
Characteristics of the co-operatives studied in northern Finland and metadata for the weather stations.

Characteristics	Herding co-operative			
	Käsivarsi	Kyrö	Pohjois-Salla	Poikajärvi
Total surface land area (km²)[5]	4567	1650	2130	2414
Phytogeographic region[1]	Fell lapland	Forest lapland	Forest lapland – North Ostrobothnia	North Ostrobothnia –Ostrobothnia
Largest permitted number of reindeer[8]	10,000	3500	4800	4600
Number of reindeer (2013–2014)[8]	11,795	3109	4682	4217
Reindeer/km² land area (2013–2014)[5,8]	2.6	1.9	2.2	1.7
Calf percentage (calves per 100 females at autumn roundup, 2013–2014)[8]	56	49	43	48
Number of reindeer killed by traffic (2013–2014)/% of reindeer[8]	93/1	45/1	8/<1	166/4
Number of reindeer killed by predators (2013–2014)/% of reindeer[8]	704/6	168/5	243/5	18/<1
Number of reindeer owners (2013–2014)[8]	177	100	103	103
Terricolous lichen pasture (ha/reindeer)[2,3]	11.3	6.48	9.23	Data not available
Arboreal lichen pasture (ha/reindeer)[2,3]	0.83	12.2	14.86	Data not available
Lichen biomass (2005–2008) (kg DW ha^{-1})[4]	150	128	271	Data not available
Shrub, deciduous and herb pasture (ha/reindeer)[2,3]	14.0	12.6	15.15	Data not available
Fells (ha/reindeer)[3]	21.4	0.6	2.3	Data not available
Peatland (ha/reindeer)[3]	10.1	18.6	7.52	Data not available
Area of infrastructure impact (% of the total land area)[3]	4.6	9.47	7.82	Data not available
	Weather station			
	Kilpisjärvi	Pokka	Värriö	Apukka
Coordinates of station	69.05°N 20.79°E	68.17°N 25.78°E	67.75°N 29.61°E	66.58°N 26.01°E
Elevation of station (m.a.s.l)	480	275	370	106
Mean annual temperature, 1981–2010 (°C)[6,9]	−1.9	−1.3	−0.5	0.4
Mean January temperature, 1981–2010 (°C)[6,9]	−12.9	−14.0	−11.4	−12.8
Mean July temperature, 1981–2010 (°C)[6,9]	11.2	13.3	13.1	15.1
Mean annual precipitation, 1981–2010 (mm)[6,9]	487	547	601	556
Mean maximum snow depth, 1981–2010 (cm)[6,9]	110	101	83	68
Mean snow melt date, 1981–2010 [9]	May 26	May 17	May 16	May 2
Mean mid-winter snow density, 1981–2010 (kg m^{-3})[6,7,10]	223	200	Data not available	207
Mean mid-winter thickness of ground ice, 1981–2010 (cm)[6,7,10]	4.9	1.4	Data not available	3.0

[1] Kalliola (1973).
[2] Kumpula et al. (1997).
[3] Kumpula et al. (2009).
[4] Kumpula et al. (2014).
[5] Mattila (2012).
[6] Pirinen et al. (2012).
[7] Rasmus et al. (2016).
[8] RHA (2015b).
[9] From a nearby FMI station.
[10] Simulated value representing the snow cover in an open area, based on weather data from a nearby FMI station.

summer. In Poikajärvi, which is located near the town of Rovaniemi, each herder herds his/her own reindeer (family herd). Due to nearby human settlements and road networks, which have fragmented the pastures, there is no clear pasture rotation. Supplementary winter feeding is practiced intensively both in the field and in enclosures.

Climate data

Weather datasets representing the control period (1980–2009) and the projected future climate scenario (2035–2064) at Sodankylä (Fig. 1) were used to estimate changes in the structural properties of snow during warming winters. Sodankylä was used as an example site, as it is situated in the middle of the reindeer management area, and its winter climate and snow conditions are representative of the northern boreal forest conditions in northern Finland (Pirinen et al., 2012). Strong correlations were found between snow conditions in Sodankylä and several other locations around the reindeer management area by Rasmus et al. (2016). Sodankylä has a mean annual temperature of −0.4 °C, mean January temperature of −13.5 °C, mean July temperature of 14.5 °C, mean annual precipitation of 527 mm, mean maximum snow depth of 87 cm, mean snow melt date of May 3, mean mid-winter snow density of 205 kg m^{-3} and mean mid-winter thickness of ground ice of 2.5 cm (Table 2). The control dataset for weather is based on observations at the Sodankylä synoptic weather station operated by the Finnish Meteorological Institute (FMI) and comprises the following variables measured at hourly resolution: air temperature (°C), relative humidity (%), wind velocity (m s^{-1}), wind direction (°), precipitation (mm) and incoming shortwave radiation (W m^{-2}) (Fig. 1). The control dataset was transformed to represent future climate using a delta-change method, with the hourly values of the weather variables modified in accordance with relevant climate model projections. The transform method preserves daily weather variations and the dependencies that occur between the variables in the observational data. The differences between the observational and projected weather datasets in the basic statistics (e.g. mean temperature) depend on the climate model projection used. We used the means of the changes simulated by different global climate models (relative to the means for the control period 1980–2009) from the Coupled Model Intercomparison Project phase 3 data archive (Meehl et al., 2007). The projections were based on the A1B greenhouse scenario, according to which greenhouse gas emissions will increase at a medium rate during the 21st century (IPCC, 2000). The data and methods are presented in more detail in Ruosteenoja et al. (2013a) and Lehtonen et al. (2014).

Mean annual temperature during the control period was −0.4 °C and is projected to rise to 2.4 °C by the scenario period. Monthly temperature responses varied: for example, the mean January temperature rose more than four degrees, from −13.6 to −9.4 °C, whereas the mean July temperature increased only some two degrees, from 14.5 to 16.6 °C. The change in the annual sum of precipitation was more modest, from 522 mm for the control to 567 mm for the scenario period.

Snow cover simulations

The SNOWPACK model has been used to simulate the annual evolution of snow conditions (depth and structure) for recent (1980–2009) and future (2035–2064) conditions. SNOWPACK (Lehning et al., 1998; Bartelt and Lehning, 2002; Lehning et al., 2002a) is a physically based mass-and-energy-balance snow cover model originally developed for the Swiss operational avalanche service and thus has a strong focus on the development of snow pack structure and stability. It is able to simulate the detailed layered snow pack structure and the physical properties of the layers (Lundy et al., 2001). Because it is physically based, it does not require any calibration and has been used successfully in various climatic conditions, such as the Alps, Scandinavia, Russia, Canada, the USA, Japan and even Antarctica (Lehning et al., 1998; Lundy et al., 2001; Rasmus et al., 2004; Nishimura et al., 2005; Groot-Zwaaftink et al., 2013); it has proven to be reliable. Simulations of snow conditions relevant for reindeer herding have been published earlier for northern Norway (Vikhamar-Schuler et al., 2013) and for several locations in northern Finland (Rasmus et al., 2014, 2016). There is also a canopy module (Lehning et al., 2006) that simulates the impact of vegetation on snow cover and, more specifically, on the snow depth and structure below forest canopies. The canopy is described by its height, leaf area index (LAI) and canopy openness.

The SNOWPACK model must be forced with at least the following values: air temperature, relative humidity, wind velocity, incoming or reflected shortwave radiation and incoming longwave radiation. These meteorological parameters are required with a temporal resolution of at least a few hours. Since not all the required parameters were available or were not available at the proper temporal resolution, the preprocessing library MeteoIO, part of SNOWPACK, was configured as follows: the missing incoming longwave radiation (W m^{-2}) was supplied by a data generator based on Unsworth and Monteith (1975) for the all-sky conditions and Dilley and O'Brien (1998) for clear-sky conditions (if the cloudiness could not be computed). The daily sum of precipitation was distributed over the most probable time steps based on relative humidity and the difference between air temperature and surface temperature (Bavay and Egger, 2014). Finally, the simulation used a 16-meter-deep soil with a constant geothermal heat flux of 0.04 W m^{-2} (Steinkoglera et al., 2015).

Finnish reindeer regularly forage in coniferous forests. To compare the snow conditions in the open and forested environments, representative forest canopy estimates were needed. Canopy height estimates were derived from a dataset compiled by the Natural Resource Institute of Finland (http://kartta.metla.fi) and LAI from a countrywide LAI map (Heiskanen et al., 2011) for average-density and dense forests in the vicinity of Sodankylä. Canopy openness was estimated from LAI values using a function presented by Pomeroy et al. (2002). The respective LAI and canopy openness estimates for forests of average density were 1.69 and 0.30, and for dense forests 3.01 and 0.13. Simulations were performed for 29 winters during the control and scenario periods, with winter defined as starting on 1 September and ending on 30 June. Model output included time series for the mass and energy balance components of the snow cover, as well as graphical and numerical time series for the snow structure.

Model validation was performed using data from Sodankylä that included observations of open environments and simulations based solely on control-period data for open areas. Observations included FMI snow depth data for the whole study period, with this data used in validation when the observed snow depth exceeded 1 cm. Snow water equivalent (SWE) and mean snow density data were obtained from a permanent snow survey line monitored monthly near Sodankylä by the Finnish Environmental Institute (SYKE). The line is four kilometers long with 80 snow depth and eight to ten snow density measurement points and is designed to include the typical terrain and biotypes (open areas, forest openings, bogs and different forest types) of the region (Perälä and Reuna, 1990). More extensive snow depth data was available for shorter periods, as was some data on above snow cover radiation and snow temperature. The validation statistics include the mean bias error (MBE), the root mean square error (RMSE) and the strength and significance of correlation between the observed and simulated values (Table 3).

Table 3
Strength and significance of the correlation, mean bias error (MBE) and root mean square error (RMSE) between the observed values and SNOWPACK simulation output. Significance levels: *< 0.05; **< 0.01; ***< 0.001.

	Correlation	MBE	RMSE
Formation date, FMI (n = 29)	0.79***	2.72	7.97
Melt date, FMI (n = 29)	0.97***	2.28	3.25
Snow depth (cm), FMI (n = 45,603)	0.89***	−6.80	23.18
Snow depth (cm), snow pit (n = 137)	0.87***	−14.68	19.36
SWE (mm), SYKE (n = 92)	0.96***	−34.26	40.88
Bulk density (kg m^{-3}), SYKE (n = 85)	0.71***	33.36	71.07
Shortwave radiation out (W m^{-2}), FMI (n = 696)	0.94***	−27.62	52.47
Albedo, FMI (n = 469)	0.80***	0.21	−0.18
Longwave radiation in (W m^{-2}), FMI (n = 1004)	0.73***	56.75	136.84
Snow surface temperature (°C), FMI (n = 319)	0.63***	0.92	7.16
Snow surface temperature (°C), snow pit (n = 130)	0.75***	4.39	8.28
Ground surface temperature (°C), FMI (n = 18)	0.82***	−1.08	1.44
Ground surface temperature (°C), snow pit (n = 137)	0.16	−2.11	3.31

No numerical observation data was available for validation of snow cover structure (e.g. the presence of a ground ice layer). The annual management reports of the herding co-operatives around Sodankylä (Oraniemi, Pyhä-Kallio, Sattasniemi, Syväjärvi) were qualitatively reviewed, and the reports of icy snow/ground ice were compared to the output of graphical simulations of snow structure (simulation winters with a thick (>5 cm) ground ice layer during early and/or mid-winter). Seventy-eight per cent of the winters with icy conditions reported could be distinguished using this method. Winters with non-icy snow conditions could be detected with somewhat lower confidence: 62% of these "easy" winters were distinguished. The proportion of failed detections (ground ice reported but not simulated) was small, with only two events occurring during the study period. The efficiency of the model in capturing actual ground ice events in observational data was similar to that reported by Vikhamar-Schuler et al. (2013) in Kautokeino, Norway, and by Rasmus et al. (2014) in Muonio, Finland. The model performance is comparable to that in earlier studies. In a recent report the validation was extended across several sites in northern Finland, with results comparable to those presented here (Rasmus et al., 2016). The modeling approach can be said to reliably simulate the present-day snow climate in Sodankylä. The use of the model together with climate scenario data is justified by earlier experience of its robustness in studies on climate change impacts in Finland (Rasmus et al., 2004) and Switzerland (Bavay et al., 2013; Schmucki et al., 2014).

Calculations

For each winter, the following quantities were calculated from the simulation outputs, to be used in further analyses: snow cover formation and melt dates; maximum snow depth for the entire snow cover period; the mean values of mean snow density for early, mid and late winter (snow cover periods only); and the thickness of the layers at the bottom of the snow cover having a density more than 350 kg m^{-3} ("ground ice"). This density limit was found to be relevant for reindeer by Vikhamar-Schuler et al. (2013).

After consulting herders, three periods during the winter were distinguished as being approximately equal in length and representing times relevant for herding work. Early winter (Oct 1–Dec 15) is a period with significant weather variability and the time during which foraging conditions become easy or difficult. Mid-winter (Dec 16–Feb 28) is a time when snow conditions are normally stable and reindeer dig for forage as conditions allow. Late winter (Mar 1–May 15) is characterized by hardening of the snow cover, which prompts reindeer to use arboreal lichen pastures, if available. Spring means the approach of calving time.

The 29-winter mean, minimum, maximum, standard deviation and coefficient of variation for the entire snow cover period were calculated for each quantity listed above for both open areas and coniferous forests, with average and dense canopies examined separately in the latter case. The time series of the quantities studied were sorted in ascending order. The three smallest and largest values were defined as rare (corresponding to a frequency of occurrence of once in 10 winters); the absolutely smallest and largest values were defined as exceptional (corresponding to a frequency of occurrence of three times in 100 winters).

Interviews

The interview data consists of informal discussions and semi-structured and structured interviews. A total of 21 reindeer herders were interviewed in the period between November 2012 and January 2015 by Sirpa Rasmus and Minna Turunen. The informants were from Käsivarsi, Kyrö, Pohjois-Salla and Poikajärvi (Fig.1, Table 2). They were selected by the office manager of the Reindeer Herders' Association (Matti Särkelä) and managers of the herding co-operatives studied (Tuomas Palojärvi, Olli and Juuso Autto, Ensio Pirttilä, Veikko Heiskari, respectively), all of whom were informants as well. Nineteen males and two females ranging in age from 23 to 84 years were interviewed. Herding was or had been a full-time job for all the informants. One-third of those interviewed were retired but still actively participated in the herding work of their family members.

The interviews were conducted in Finnish, in groups and individually, either at the homes of the herders or in offices at the Arctic Centre or RHA in Rovaniemi. One-third of the informants were interviewed two or three times to get a more comprehensive view of their livelihood. The first discussions and interviews were conducted to gather knowledge about the co-operatives, pastures and herding practices, and these were tape-recorded, transcribed, analysed and coded (M1–19, F1–2) by Minna Turunen and Sirpa Rasmus. In the second and the third interviews, the herders were asked how the weather has impacted their work over the past 30 years and how they have coped to date during the difficult weather conditions in different seasons, with an emphasis on winter. We also used a structured questionnaire in which the herders were asked to describe their coping strategies under three types of difficult snow conditions – ground ice and/or ice layers in the snow pack, exceptionally deep snow and late snow melt (RHA, 2015a) – and how their coping capacity is affected by different factors (Table 4). Each informant was asked to evaluate the significance of 26 factors for his/her herding work on a scale from −5 to +5 (−5 very negatively, 0 not at all, +5 very positively). Average values and standard deviations were then calculated from this data. We also presented scientific information in popularized form about the expected changes in different seasons during the coming decades, with an emphasis on winter (Table 1). We asked how herders anticipate coping with the changes expected during the different seasons. In the discussions it was made clear that occurrence of certain difficult conditions may become rarer in the future (late snow melt, deep snow), whereas some may become more frequent (ground icing).

Results and discussion

Snow conditions in the future

Effect of warming on characteristics of snow

SNOWPACK simulations indicate that winters during the scenario period (2035–2064) in Sodankylä will be characterized by ephemeral snow cover formation and melting several times during the winter, a condition described by Sturm et al. (1995). Formation of a continuous snow cover may take several months, and some heavy snowfalls are experienced during the winters, with these often followed by melt events. This leads to a shallow but icy snow cover and frequent ground ice formation. The figures (Figs. 2 and 3) and tables (Tables 5–7) that follow present control and scenario projections for key quantities discussed with the herders.

Seasonal snow cover formation will be delayed in Sodankylä during the scenario period (2035–2064) by 19 days on average when compared to the control period (1980–2009); snow will melt 16 days earlier on average (Table 5). In open environments, the snow cover will be 26% thinner on average and in forests 40% thinner (Fig. 2a, Table 5). Snow will be denser (Fig. 2b, Table 6) and ground ice thicker (Fig. 2c, Table 7) in open environments. Variability between winters will be greater for all of the quantities studied.

According to the herders, the projected shortening of the snow period and thinner snow cover would both be favorable for reindeer herding due to the increased availability of forage such conditions would provide (Table 8, M1–19, F1–2). Due to the greater variability between the winters in the future (2035–2064), herders must also be prepared for thick snow cover and frost winters, although these will be less common than during the period 1980–2009.

Effect of the forest canopy on snow conditions

Comparison of the simulation outputs from open and forested environments with different canopy densities revealed the significance of pastureland diversity when considering the impact of warming winters on snow conditions. Simulated snow cover was thinner below forest canopies than in open areas during both the control (1980–2009) and scenario (2035–2064) periods. Variability between winters was greater in forested environments in both cases.

During the control period, snow density was higher in open environments than in forests during the early winter, and ground ice layers were thicker in open environments than in forests during the early and late winter. During the scenario period this was the case throughout the winter.

Even though snow density will increase in open environments, the snow cover in forests will be more porous during the scenario period. This holds for ground ice thickness as well; that is, an increase in ice thickness in open areas will be accompanied by a decrease in ice thickness in forests. To summarize, the conditions for reindeer herding will not deteriorate as much in forests as in open environments.

Icy conditions in the present and future climate

During the control period (1980–2009), simulations showed ground ice formation for approximately half of the winters. In many cases, it has been observed that the icy layer undergoes a softening over the course of the winter. Although this has been qualitatively observed, it has not yet been measured with reference to layer hardness. But snow grain metamorphosis is a well-known process produced by snow recrystallization, even within an icy layer (Domine et al., 2009) and it has been found to be able to transform an icy melt-freeze layer into depth hoar (a layer formed of coarse crystals that are only loosely bonded together) (Pinzer et al., 2012). As recrystallization is governed by the temperature gradient in the snow cover, it is especially efficient during the periods with low air temperatures and relatively thin snow cover and therefore especially

Table 4
Description of the three difficult snow conditions and the questions asked of the herders.

Difficult snow condition	Description
1. Formation of ground ice and/or ice layers in the snow pack	The weather is unstable during the early winter, and wet snow freezes on the pastures; or a thick icy layer is formed during the winter when the temperature falls after a rain-on-snow event or a thaw during a warm spell
2. Exceptionally deep snow	Heavy and frequent snowfalls cause snow to accumulate throughout the winter; a deep snow cover is formed
3. Late snow melt	Snow melts late, formation of snow-free sites takes time and the beginning of the growing season is delayed

Questions referring to difficult snow conditions 1–3.
How do you cope with the situation?
What other strategies are you familiar with?
What is the impact of different factors on how you cope with the situation?
(26 factors to be evaluated on a scale from −5 to +5) (Table 9)
What sources of data do you use when you decide on which strategy to use?

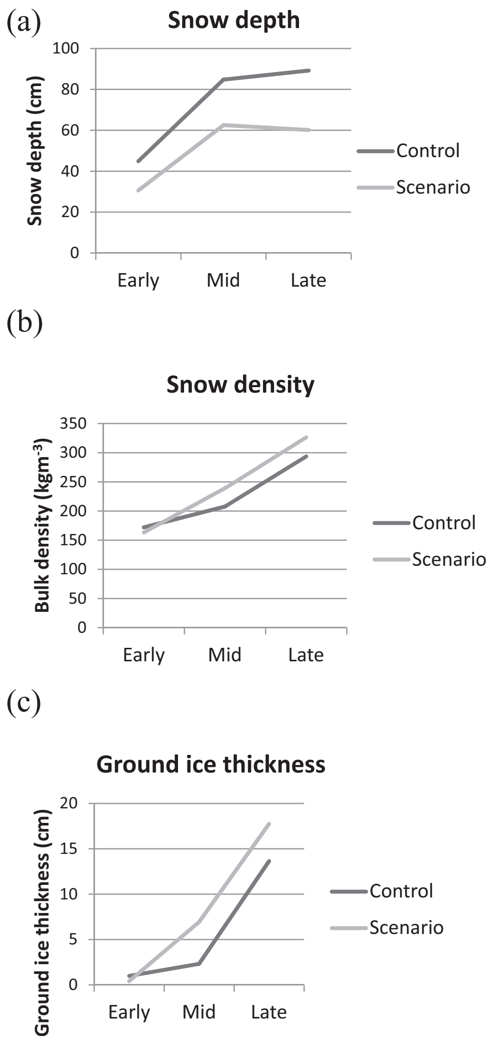

Fig. 2. Mean maximum snow depth (a), snow bulk density (b) and thickness of ground ice (c) for open environments during the control (1980–2009) and scenario (2035–2064) periods in Sodankylä. Early, mid- and late winter refer to the periods Oct 1–Dec 15, Dec 16–Feb 28 and Mar 1–May 15, respectively.

relevant to the areas under consideration. Owing to this process, ground ice did not persist through the winter very frequently in the simulations: 9 (31%), 6 (21%) and 9 (31%) cases in open environments, in forests with average canopy density and in dense forests, respectively.

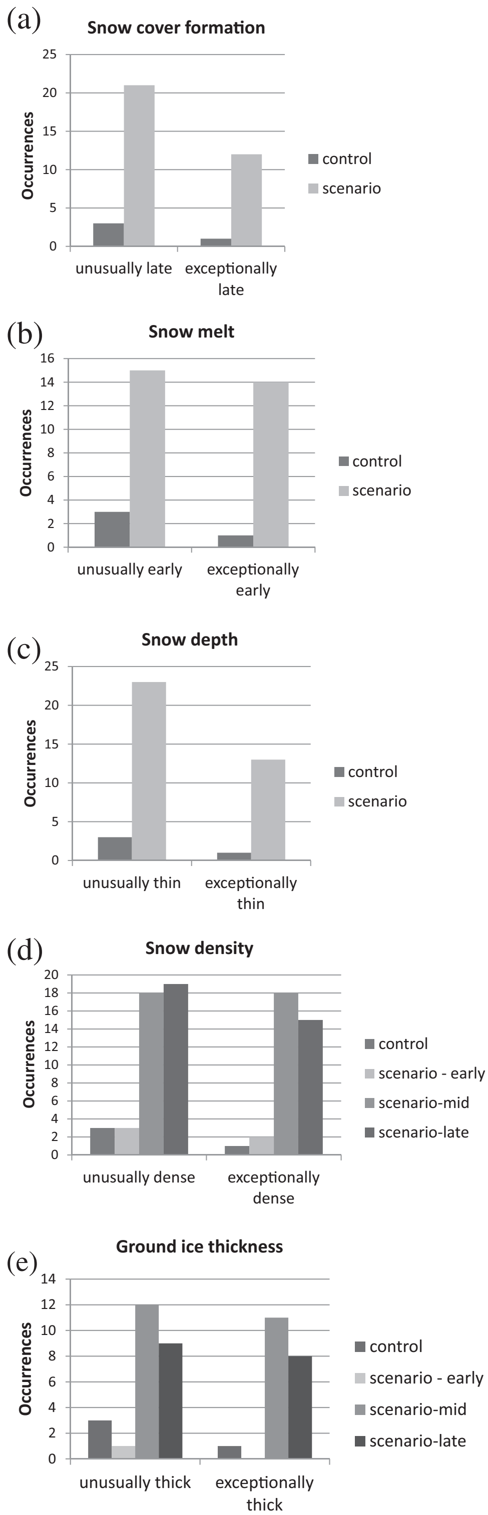

Fig. 3. Occurrence of unusually and exceptionally late snow cover formation (a), early snow melt (b), thin snow cover (c), dense snow cover (d) and thick ground ice layers (e) during the control (1980–2009) and scenario (2035–2064) periods in open environments in Sodankylä. "Unusual" means once in 10 winters, and "exceptional" three times in 100 winters in the control-period climate. Early, mid-, and late winter are treated separately in panels d and e. Early, mid- and late winter refer to the time periods Oct 1–Dec 15, Dec 16–Feb 28 and Mar 1–May 15, respectively.

Table 5
Statistics on snow cover formation and melt dates for the control (1980–2009) and scenario (2035–2064) periods at Sodankylä. Mean values and coefficients of variation are bolded.

	Control **Mean** (range) Standard deviation/**coefficient of variation**	Scenario **Mean** (range) Standard deviation/**coefficient of variation**
Formation date	**24.10** (27.9–19.11) 12.0	**12.11** (8.10–26.12) 17.9
Melt date	**11.5** (21.4–29.5) 8.8	**25.4** (6.2–14.5) 19.2
Max snow depth, open (cm)	**91** (54–126) 16/**0.2**	**67** (43–98) 15/**0.2**
Max snow depth, forest, mean (cm)	**60** (35–92) 13/**0.2**	**36** (18–59) 13/**0.4**
Max snow depth, forest, dense (cm)	**50** (30–83) 13/**0.3**	**30** (15–52) 11/**0.4**

During the scenario period (2035–2064), simulations showed frequent ground ice formation. As weather conditions allowing efficient snow grain metamorphism (long periods with low temperatures) become rarer, softening of the icy layer will not often be seen during the scenario period. Even if some cases of the icy layer melting are taken into account, ground ice will persist through the winter significantly more frequently during the scenario period: 23 (79%), 16 (55%) and 15 (52%) cases in open environments, in forests with mean canopy density and in dense forests, respectively.

Increase in the frequency of anomalous snow conditions

A clear increase was seen during the scenario period in the occurrence of snow formation dates that are considered unusually late (an occurrence of once in 10 winters) or exceptionally late (occurrence three times in 100 winters) during the control period climate (Fig. 3). An increase was also seen in the occurrence of unusually or exceptionally early snow melt dates and thin snow depths in open areas. Correspondingly, unusually or exceptionally early snow formations, late snow melts and thick snow cover are essentially lacking during the scenario period (1, 0 and 0 occurrences, respectively).

An increase in the occurrence of snow bulk densities (again, in open environments) during the scenario period that are considered unusually or exceptionally high during the control period is most significant in mid- and late winter, as is the case with the occurrence of an unusually or exceptionally thick ground ice layer (Fig. 3). No significant changes are seen in the frequency of an unusually or exceptionally porous snow cover or thin ground ice thicknesses.

Herding work in changing weather, snow and climate conditions

Early winter

Herders reported a late or unsynchronized start of rutting among the reindeer in recent autumns (M12, 16–19) (Table 8). Although photoperiod and body condition have been considered the primary drivers of the timing of rut in reindeer (Eloranta et al., 1992; Stokkan et al., 2007), the implication of delayed frost and snow cover formation in the timing of rut merits further study, as predictions indicate such conditions will become more common in the future (Jylhä et al., 2008; Räisänen and Eklund, 2012) (Fig. 3a). A late rut, the absence of snow (under which condition reindeer are not focused on digging for lichens through the snow cover), increased availability of mushrooms, mould formation on vegetation due to snow accumulation on unfrozen soil or the formation of ground ice – all combined with low lichen biomasses on the pastures (Table 2) (Kumpula et al., 2000, 2014; Turunen et al., 2009) can cause herds to disperse over a wide area ("break loose"), which can make it difficult to gather and move them to the round-up sites. Abundant mushroom crops mean that reindeer will be quite fit in the early winter, but it is a factor causing dispersal of herds (M1–19). As a herder from Käsivarsi noted: "*Reindeer will disperse and an animal will take off if it does not get forage from pastures; a reindeer will go quite a long way to get mushrooms*" (M1).

Dispersal of herds delays round-ups and the slaughter. Where this occurs, herders end up with less meat for sale, since calves will be lighter (Heikkinen et al., 2012); calves start losing weight rapidly after frosts come and a snow cover forms, particularly if the herding is based exclusively on natural pastures (M1, 2). A late, thin and/or non-uniform snow cover is a challenge for herders, because it is not favorable for the use of snowmobiles or ATVs. Late and weak ice formation on waterbodies can make the gathering of reindeer even more difficult because the risk of animals drowning is increased (M1–8). On the other hand, late ice formation can facilitate herding, because open waterbodies can provide more effective barriers to reindeer than frozen ones (M12) (Table 8).

Table 6
Statistics for snow bulk densities for the control (1980–2009) and scenario (2035–2064) periods. Early, mid- and late winter refer to the periods Oct 1–Dec 15, Dec 16–Feb 28, and Mar 1–May 15, respectively. Mean values and coefficients of variation are bolded.

	Early winter		Mid-winter		Late winter	
	Control **Mean** (range) Standard deviation/ **coefficient of variation**	Scenario **Mean** (range) Standard deviation/ **coefficient of variation**	Control **Mean** (range) Standard deviation/ **coefficient of variation**	Scenario **Mean** (range) Standard deviation/ **coefficient of variation**	Control **Mean** (range) Standard deviation/ **coefficient of variation**	Scenario **Mean** (range) Standard deviation/ **coefficient of variation**
Open	**172** (120–243) 30/**0.18**	**163** (109–236) 31/**0.19**	**208** (163–246) 20/**0.096**	**239** (121–324) 46/**0.19**	**294** (263–339) 22/**0.076**	**326** (111–396) 60/**0.18**
Forest, mean	**157** (110–212) 30/**0.19**	**141** (77–231) 33/**0.23**	**211** (140–301) 42/**0.20**	**193** (103–283) 54/**0.28**	**294** (228–376) 34/**0.11**	**231** (101–370) 67/**0.29**
Forest, dense	**156** (110–211) 31/**0.20**	**143** (84–222) 34/**0.23**	**212** (128–325) 50/**0.24**	**185** (102–308) 54/**0.29**	**298** (236–383) 39/**0.13**	**212** (95–376) 67/**0.32**

Table 7
Statistics for ground ice thickness (cm) for the control (1980–2009) and scenario (2035–2064) periods. Early, mid- and late winter refer to the periods Oct 1–Dec 15, Dec 16–Feb 28 and Mar 1–May 15, respectively. Mean values and coefficients of variation are bolded.

	Early winter		Mid-winter		Late winter	
	Control **Mean** (range) Standard deviation/ **coefficient of variation**	Scenario **Mean** (range) Standard deviation/ **coefficient of variation**	Control **Mean** (range) Standard deviation/ **coefficient of variation**	Scenario **Mean** (range) Standard deviation/ **coefficient of variation**	Control **Mean** (range) Standard deviation/ **coefficient of variation**	Scenario **Mean** (range) Standard deviation/ **coefficient of variation**
Open	**1.0** (0–5.4) 1.7/**1.7**	**0.4** (0–4.0) 0.9/**2.1**	**2.3** (0–9.2) 3.0/**1.3**	**6.9** (0–23.2) 5.9/**0.8**	**13.6** (4.2–33.6) 7.3/**0.5**	**17.8** (0–39.1) 9.7/**0.6**
Forest, mean	**0.3** (0–2.2) 0.6/**2.2**	**0.1** (0–2.2) 0.4/**3.1**	**2.5** (0–14.5) 3.9/**1.6**	**2.2** (0–10.8) 3.1/**1.4**	**9.6** (0.5–27.2) 7.3/**0.8**	**3.2** (0–21.7) 5.2/**1.6**
Forest, dense	**0.2** (0–2.0) 0.5/**2.2**	**0.1** (0–1.9) 0.4/**3.0**	**2.7** (0–13.7) 3.9/**1.5**	**2.0** (0–14.8) 3.6/**1.8**	**8.6** (0.7–28.0) 6.7/**0.8**	**2.5** (0–19.3) 5.2/**2.1**

Table 8
Impacts of changing climate and difficult weather and snow conditions on herding, and the strategies applied by herders to cope with them during the herding year at present and in the future.

Weather/nature condition	Impact on reindeer/reindeer herding	Coping strategy
Autumn		
Warm autumn. Late appearance of soil frost and late formation of snow and ice cover	• Late rut, not synchronized among reindeer • Difficult to gather and move herds to the round-up sites • Increased working hours and transportation expenses • Decreased calf weight due to delayed round-ups, less meat for sale • Increased probability of animals drowning	• Increased control over herds • Use of helicopters in gathering reindeer • Avoidance of weak ice
Abundant mushroom crops	• Reindeer fit, but herds "break loose" to feed on mushrooms • Difficult to gather and move herds to the round-up sites • Increased working hours and transportation expenses	• Increased control over herds
Mould formation on vegetation	• Herds "break loose" to seek higher-quality forage • Deaths of reindeer due to mould (mycotoxins)	• Increased control over herds • Intensified utilization of pasture diversity • Supplementary feeding
Winter		
Ice formation on the ground and in the snow pack	• Herds "break loose" to find higher availability of forage • Increased working hours and transportation expenses	• Increased control over herds • Intensified utilization of pasture diversity • Supplementary feeding • Reindeer taken into enclosures
Deep snow	• Moving and digging deplete energy stores of reindeer	• Increased control over herds (also decreases vulnerability to predators)
Deep and soft snow	• Moving by snowmobile difficult • Increased vulnerability of reindeer to predators	• Intensified utilization of pasture diversity • Supplementary feeding • Track making for reindeer by snowmobile
Long periods of extremely low temperatures	• Energy storages of reindeer depleted faster	
Strong winds, storms	• Herds "break loose" to feed on arboreal lichens that have fallen on snow from trees ("lichen rain")	• Supplementary feeding
Long snowless period	• Increased availability of forage, improved growth of reindeer • Less need for supplementary feeding • Fewer expenses from due to feeding	• Utilization of natural forage • Increased control over herds • Utilization of natural forage
Warmer winter	• Increased insect harassment, parasites and diseases • Less birch leaves, but more graminoids and herbaceous plants as summer forage • Improved visibility due to destruction of birch forest by geometrid moths	• Anti-parasite medication • Repellents • Changed pasture rotation due to destruction of birch forest by geometrid moths
Spring		
Early snow melt	• Increased availability of fresh forage, improved condition and growth of reindeer	• Utilization of fresh forage
Late snow melt	• Energy stores of pregnant hinds in particular are depleted • Decreased availability of fresh forage • Perishment of new-born calves in deep and soft snow • Calves born on snow vulnerable to predators	• Calving in enclosures • Herding pregnant hinds to snow-free sites
Summer		
Long hot periods	• Reindeer, particularly calves, suffer from heat and insects, especially during calf- marking	• Avoidance of hot periods in marking calves • Rescheduling of calf-marking
Long-lasting heavy rains	• Calves suffer, growth retarded	
Warmer and longer growing seasons	• Tundra and lichen dominating mountain birch forests replaced by conifer forests • Less winter forage and/or it has changed species composition • Weaker visibility due to denser forests	• Changes in the herding practices due to expansion of forests

Mid-winter

In the future, ground ice that persists through the winter will become more common (Fig. 3e) and the layers of ice in open environments will become thicker (Fig. 2c), whereas the incidence of exceptionally deep snow (Fig. 2a, Table 5) and late snow melt (Table 5) will decrease. The most immediate reaction of reindeer to the decreased availability of forage caused by these conditions is "breaking loose" (M1–19, F1–2) (Table 8). Formation of ground ice was felt to be the most critical factor, since even an exceptionally deep snow cover is manageable for reindeer if they have access to ground vegetation (M1, 9–15). In Kyrö, however, deep snow was found to be the most serious problem: "*The worst period is when snow is deep* *and soft, it [a reindeer] cannot move or reach the ground by digging... and it cannot get anything from the trees either if they are covered by heavy snow loads*" (M7). In Poikajärvi, herders did not feel that deep snow (max snow depth during 1981–2010 was 68 cm) hampered their work (M16–19), whereas in Käsivarsi and Kyrö (max snow depth 110 cm and 101 cm respectively) (Table 2) deep snow was found to be challenging (M1, M3–8).

Dispersal of herds can also be caused by a sudden increase in the availability of forage, for example, as a result of "lichen rain"; this refers to lichen falling on the snow cover from trees due to winter storms or strong winds (M16–19), which herders have reported as being more common today than earlier (M1, Vuojala-Magga et al., 2011). Dispersal of reindeer causes more expense for herders, as it requires increased use of snowmobiles (or ATVs) in gathering and moving the animals; this is even more the case in a herding system based on tight control of the animals rather than free grazing (e.g. in Pohjois-Salla).

Late winter and spring

Herders pointed out that warming winters with longer snowless periods (Table 5) and thinner snow cover (Fig. 2a, Table 5) would provide better opportunities for herding (M1–19, F1–2). In the case of early snow melt (Fig. 3b, Table 5), the availability of fresh, green, soft forage increases, which is favorable for lactating reindeer and their new-born calves, as discussed in Mårell et al. (2006), Turunen et al. (2009) and Tveraa et al. (2013). Late snow melt can greatly decrease the availability of forage for pregnant or lactating reindeer, and be fatal for new-born calves, which can perish in deep and soft snow or be easily caught by predators (M1–19, F1–2, Vuojala-Magga et al., 2011).

Summer

Although winter is a critical season for herding, herders reported unanimously that the winter survival, condition and productivity of reindeer depend on the cumulative impacts of the weather during the entire reindeer-herding year (Table 8). For example, an early spring and favorable conditions in summer can help reindeer to recover from stresses caused by a difficult winter. During the calf markings in June–July, young calves may suffer from long periods of hot weather and insect harassment or, alternatively, from cold and heavy rains (M3–8, 16–19) (Table 8). Insect harassment, which is dependent on the summer temperature and windiness, has an impact on the weight, reproduction and mortality of reindeer, because stressed reindeer spend less time on grazing and their energy expenditure increases (Helle and Tarvainen, 1984; Hagemoen and Reimers, 2002; Weladji et al., 2003). In the future, longer periods of heat and increased insect harassment may increase calf mortality and decrease slaughter weights: reindeer are well adapted to cold and snow, but not to heat, for example because they lack sweat glands (Soppela et al., 1986; Nieminen, 2014). An unfit reindeer may have difficulties surviving during the upcoming winter. As a herder from Kyrö said: "*One can see from the weight of a calf what the summer was like*" (M5).

It is projected that by the middle of the century the thermal growing season in northern Finland will lengthen by about one month and the effective temperature sum increase by 300–500 degree days (Ruosteenoja et al., 2015). Forests will be denser and expand northward and upward. The biomass of reindeer summer forage will increase but its quality may deteriorate. The plant species composition of reindeer pastures will gradually change. Lichen-dominated mountain heaths will be replaced by forest vegetation and the biomass of reindeer summer forage will increase. Terricolous lichens, the animals' preferred winter forage, will be gradually replaced by shrubs and graminoids in lower-altitude subarctic and mid-arctic ecosystems (Turunen et al., 2009) (Table 8).

Herders' coping strategies

To cope with difficult winter weather and snow conditions, herders reorganize their herding practices. This includes increasing control over their herds, intensifying the use of the diversity of pastureland – for example, using a seasonal pasture rotation or reserve land – bringing reindeer into enclosures and/or starting or intensifying supplementary feeding of the animals (M1–19, F1–2) (Table 8).

Increased control over herds means that reindeer which have "broken loose" are gathered and kept together by driving around the herd more frequently on snowmobile or ATV than earlier, which also provides protection against predators (M1–19). Technical applications, for example, collars equipped with a global positioning system (GPS), are used for monitoring the herds in all of the co-operatives studied (M1–19, F1–2), and in Pohjois-Salla (M9–15) helicopters have proved to be an effective tool in monitoring and gathering herds as well.

In the interviews, the herders indicated that *utilization of the diversity of pasture* – variations in topography and vegetation – plays a critical role in their capacity to cope with difficult snow conditions (M1–19, F1–2) (Table 9); this finding is in agreement with earlier studies (Tyler et al., 2007; Riseth et al., 2010). Based on model simulations, ground ice is not commonly formed simultaneously both in open environments and below forest canopies, and there is a great deal of small-scale spatial variability in snow depth and quality within forests of different densities (Rasmus et al., 2011, 2016). In Pohjois-Salla, the reindeer herding system in itself is an example of a strategy for coping with the prevailing conditions: all the reindeer are herded in the same area and allowed to scatter, and herders are confident that the animals will find forage on diverse pastures under almost any conditions. In this region, pastures include fell slopes with a thin snow cover, gorges with steep drops, pine-dominated xeric and sub-xeric heath forests and spruce-dominated heaths with an abundance of arboreal lichens (M9–15). Due to the interaction of wind, vegetation and topography, reindeer find their way to habitats where the snow conditions are most favorable: "*The wind always exposes at least one of the habitats [where the availability of forage is greater]*" (M4).

Table 9
Impact of the evaluated factors on the ability of herders to cope with impacts and risks of difficult snow conditions. Each herder interviewed was asked to evaluate the significance of 26 factors for his/her herding work on a scale from −5 to +5 (−5 – hampers coping very much, 0 – no influence, +5 – facilitates coping very much). The table includes the average values with standard deviations (std) calculated from the responses from herders (n = 15–18).

Facilitating factor	Average	Std	*n*
Knowledge of/skills in handling reindeer	3.94	1.16	17
Regard for reindeer herding as a livelihood (own)	3.88	1.18	17
Diversity of pastures	3.78	0.92	18
Use of pasture rotation	3.56	1.74	18
Use of technical devices	3.55	1.53	18
Condition of reindeer	3.17	2.85	18
Supplementary feeding	3.00	1.28	17
Herding tradition	2.78	1.69	18
Support provided by herding co-operative	2.28	1.69	18
Amount of arboreal lichen pasture	1.90	3.1	17
Support provided by society at large	1.83	1.95	18
Regard for the livelihood (others)	1.69	2.39	16
Extent of own hay fields	1.56	2.56	18
Part-/full-time employment of herders	1.41	2.55	17
Quality of weather forecast	1.33	1.45	18
Amount of labor	1.22	2.72	18
Support provided by own village/siida	0.93	1.48	15
Uncertainty of the continuation of reindeer herding as a livelihood	0.53	3.09	17
Own financial situation	0.25	3.38	16
Hampering factor			
Occurrence of predators	−4.33	0.75	18
Other land use	−3.83	0.76	18
Price of reindeer feeds	−3.23	0.80	17
Price of fuel	−2.94	1.96	18
Uncertainty about future land use	−2.65	1.64	17
Disturbance caused by human activity	−2.33	1.37	18
Factors related to legislation	−1.29	1.93	17

Most of the herding co-operatives in Finland still lack an appropriate seasonal pasture rotation system in which winter and summer pastures are separated with a fence, and therefore it is difficult to avoid continuous deterioration of lichen pastures (Kumpula et al., 2011, 2014). All the co-operatives studied here except Poikajärvi (due to its location near a town and road networks) employ *pasture rotation* between winter and summer pastures. This prevents summer-time trampling of winter pastures (Kumpula et al., 2011, 2014). In Käsivarsi, each siida uses pasture rotation in its own area. The use of pastureland has been intensified by using reserve pastures, where reindeer are herded only during the most difficult snow conditions. For example, when the snow is deep, reindeer are taken to the tops of fells, where wind-whipped snow areas (deflation areas) provide thinner snow cover and thus better availability of forage (M1–3, 9–15).

Supplementary feeding of reindeer started in Finland in the late 1960s. It was a response to decreased availability of winter forage resulting from the fragmentation of and decline in pastures due to forestry, overgrazing caused by high reindeer densities and lacking or incomplete pasture rotation. It was also an acute response to ground icing and deep snow, often combined with mouldy vegetation (Helle and Jaakkola, 2008; Turunen and Vuojala-Magga, 2014). As well as preventing losses of animals, supplementary feeding helps herders to achieve or maintain an adequate level of nutrition for the herd over the winter and to produce bigger calves for slaughter (Helle and Jaakkola, 2008; Turunen et al., 2013; Turunen and Vuojala-Magga, 2014). Winter feeding has been most common in Poikajärvi, where it is primarily a strategy to offset the negative impacts of other land uses in the region (M16–19). By contrast, in Pohjois-Salla only a small proportion of the herds have been given supplementary fodder (M9–15), and in Käsivarsi there are still siidas which rely exclusively on natural pastures (M1–3).

Feeding can be intensified in a number of ways. One is to either extend the period during which herds are fed or feed them on more days. Another is to increase the ratio of enclosure feeding to field feeding. A herder from Kyrö remembered the impacts of difficult snow conditions on herding in 1996–1997: "*In 1996 we knew that it would be a hard winter, because it rained the whole autumn; the rain became snow, but it did not get cold at all*...". "*In January–February 1997 it snowed 40 cm within a couple of nights; the reindeer went swimming through the snow... we couldn't get anywhere – even with snowmobiles... the tops of birches were bent down into the snow pack and you couldn't get anywhere with a snowmobile in birch forests*...". "*We made a big fuss to the state administration, as it was possible to get compensation in the case of reindeer losses; afterwards, we applied for subsidies for supplementary feeding, because in the beginning of March 1997 we had to take all the [reindeer] home [into enclosures]; it snowed so much that the border fences [between co-operatives] were covered by snow – and they're two meters high*" (M5).

Supplementary feeding has been criticized by both herders and researchers because of the increased costs it involves, the changes it causes in the animals' behavior (M1, M3–8, Turunen and Vuojala-Magga, 2014), the heightened risk of diseases it entails (M1, Aschfalk et al., 2003; Halvorsen, 2012) and the harmful impacts it has on ecosystems (Turunen et al., 2013). A herder from Käsivarsi pointed out that feeding also attracts predators: "*there are many factors, not only how reindeer live and what the situation is; there are also the predators, which discover that masses of reindeer are fed in one place; so a predator sees that it is easy to go there and always catch at least one*" (M1). He continued that if the Finnish government is to mitigate the negative impacts of climate change on herding, support directed to seasonal pasture rotation would be a far more resilient strategy than supplementary feeding. The same herder went on to remark: "*...herding rather than feeding reindeer should be supported in one way or another. I think that it is not right [to support feeding].... Reindeer will change [due to feeding]; they won't know enough to dig [for lichens] although they could get forage that way; and to the extent I have been in Käsivarsi, [I can say] the pastures are not poor in lichens; there are good places, rich in lichens, but one has to control where the animals go, so that in summer you do not let them go onto the lichen-rich pastures, so they won't spoil the lichens by trampling*" (M1).

During the critical calving time there is not much that can be done if the snow happens to melt too late. A herder noted in this regard, "*We can only cross our fingers and hope for the best*". Some herders reported that they had tried to herd pregnant hinds to a region with snow-free sites. In the co-operatives studied, only herders from one siida in Käsivarsi have used large calving enclosures. Use of enclosures not only enables immediate earmarking of a calf, but it also facilitates the feeding of pregnant hinds and their protection from predators. It has also prevented perishment of new-born calves on the snow and in waterholes during springs with late snow melt (Vuojala-Magga et al., 2011; Turunen and Vuojala-Magga, 2014). The practice is expensive due to the costs of building fences and feeding, and the risk of diseases may increase (M1, Aschfalk et al., 2003; Halvorsen, 2012).

The herders reported that in June–July the adaptation options for long periods of heat have included discontinuing calf-marking and/or rescheduling it for cooler weather, or for the autumn in conjunction with round-ups (M3–19) (Table 8). A herder from Pohjois-Salla noted: "*When it is too hot, there are problems, like in 1972, when the reindeer had to be released from the enclosure, it was too hard... maybe they were stressed or whatever, since they started to collapse...*". "*They couldn't stand the procedure; we had to stop the work [ear-marking] and release them from the enclosure*" (M11).

How do reindeer herders make their decisions when selecting coping strategies to mitigate the negative impacts of difficult weather and snow conditions? According to the herders interviewed, decision making in a particular situation is mostly based on herders' own experience-based knowledge, skills and observations, which comprise, for example, studying the quality of snow by digging a hole in the snow pack or monitoring the behavior of herds using GPS collars. Discussions with the other members of one's siida, family, relatives or closest herder colleagues and/or the board and manager of the co-operative are also important M1–19, F1–2). Some of the herders (M16–19) remarked that individual decision making by the herders and subunits of the co-operatives regarding, for example, whether, when and which proportion of the herds are fed in enclosures due to difficult weather and snow conditions has partly replaced the collective decision making used in past years.

Factors affecting coping capacity

Coping in the present day-climate

The coping capacity of herders in difficult winter weather and snow conditions (deep snow, late melt and ground icing) was affected most negatively by the presence of predators. This was the most widely held opinion, with the smallest standard deviation (Table 9). Difficult snow conditions as such are problematic for reindeer, and consequently to herding. Reindeer will move more, disperse, and their body condition will be worse due to low food availability. A high incidence of predators means that dispersed reindeer will be easy prey. Poor body condition also favors predators. Tablado et al. (2014) have reported how snow conditions in Central Norway affected the predator–prey interaction. Deep snow and icy conditions on high-elevation pastures forced reindeer to lowland forests. This led to low calf survival, mostly due to elevated lynx predation rates. Herders reported that a snow cover that carries the animals' weight when they walk on it, but not when they run, creates especially favorable conditions for predators: a large reindeer trying to flee easily sinks into the snow (M1–19, F1–2). If the surface of the snow cover hardens, it improves the situation.

In Finland the number of reindeer killed by predators (wolverine, wolf, bear, lynx and eagles) and for which herders received compensation in 2013–14 was 4162 (RHA, 2015b); the figures for the co-operatives studied here ranged between 18 and 704 animals, being lowest in Poikajärvi and highest in Käsivarsi (RHA, 2015b) (Table 2). The state pays compensation for reindeer killed by wolverine, wolf and lynx directly to herders, but compensation for losses caused by golden eagles is paid to co-operatives. The herders were not completely satisfied with the current predator policy, including the documentation requirements and the late payment of the compensations. The state motivates young people to take up herding by providing subsidies for the purpose, but higher predator populations are making the livelihood unprofitable, particularly in the eastern and south–eastern parts of the management area. Herders agreed that the predator compensation system should be a compromise between the viewpoint of herders and Finland's commitment to international agreements (e.g. CITES, 1976; Bern Convention, 1986; Council Directive 92/43/EEC, 1992; CBD, 1994).

Competing land uses, including forestry, tourism, human settlement and road networks, were the second important factor cited by herders as degrading their coping capacity. Other land use greatly decreases the pasture area and the option of using the diversity of pastureland. The greatest uncertainty regarding future land use stemmed from the plans and test-drilling of the mining industry, especially in Pohjois-Salla, Kyrö and Käsivarsi. As a herder from Kyrö noted: "*This herding co-operative will not be able to cope with a mine here*" (M4). Herders pointed out that different land use activities increase the pressure on herding in protected areas. Protected areas – especially those in the region of Kyrö (Pallas-Yllästunturi

National park, 1020 km^2; Pulju Wilderness Area, 614 km^2) and Pohjois-Salla (Natura 2000 sites), which feature old-growth spruce forests rich in arboreal lichens – have secured the late winter pastures for reindeer, but do not provide suitable calving areas due to disturbances caused by late-winter tourism (skiing, snowmobiling, dog sledges etc.). The herders emphasized the need for true participation of herders at all stages of land-use planning as an adaptation strategy, because to date their participation has remained mostly a formality (M1–19, F1–2).

Among the other major threats to the coping capacity of herders were the high prices of commercial reindeer feeds, grass and fuel. The costs arising from supplementary feeding, motorization, fuel and information and communications technology devices decrease the profitability of the livelihood (Forbes et al., 2006; Heikkinen et al., 2012; Turunen and Vuojala-Magga, 2014). The government has directed its support towards bigger herds, pursuant to the EU regulations that have come into force since 1995, when Finland joined the EU (Saarni and Nieminen, 2011). The regulations have their origin in agricultural policies and aim at lowering production costs but do not take into account the interests of herders with smaller herds and reindeer herding's special character as a subsistence livelihood. As a consequence of the current support instruments (e.g., animal-based subsidy), the profitability of herding has remained low: production costs are high and the number of reindeer available for slaughter has decreased. Despite its complications, however, the current support instrument has also had a positive influence on reindeer husbandry in maintaining reindeer meat production at a high level and, as a consequence, benefiting the processing industry and tourism (Saarni and Nieminen, 2011).

Herders' high regard for their livelihood was of utmost importance for their capacity to cope in difficult weather and snow conditions. In addition to using diversity of pastures and seasonal pasture rotation (see in Section "Herders' coping strategies" Herders' coping strategies), herders' ability to cope with the impacts and risks of difficult winters was facilitated by traditional knowledge (TK) and their experience-based skills related to the vegetation and topography of pastureland as well as to weather, snow, the behavior of reindeer and herding practices (Tyler et al., 2007; Riseth et al., 2010; Vuojala-Magga et al., 2011, Vuojala-Magga and Turunen, 2015) (Table 9). TK is transferred from generation to generation through practice and oral transmission (Berkes, 1999). For example, the transfer from older to younger generations of knowledge about the locations which have easier snow conditions for reindeer was found to be important in all the co-operatives studied (M1–19). In the Sámi region, TK (or IK, indigenous knowledge) is closely connected to the siida system, a self-created organization of herders and their extended families that increases flexibility in herding work due to the dynamic interaction of many generations.

Coping in the future climate

The applicability of TK in new situations may be challenged in the future for a number of reasons: the weather patterns and timing of snow and ice extent and stability will become harder to predict; variability between years will increase and what were previously rare or exceptional weather and snow conditions will become more frequent. There will be pressure due to predators and competing land uses. These developments, together with the relatively highly degree of motorization in herding work (e.g. ATVs, snowmobiles and helicopters), may lead to heightened safety concerns, one being a potential increase in the incidence of accidents.

The herders reported that although the continuity of herding as a livelihood is secure due to children and young herders in their co-operatives (Table 9), herding work is undermined by the lack of skilled employees (M1–19, F1–2). Most of the herders need to have one or more supplementary jobs to make a decent living. The shortage of workers can be partly overcome by technical applications, which herders combine with their TK and skills more often than earlier. For example, GPS collars combined with tablet computers or mobile phones have replaced the traditional bells on the lead reindeer in monitoring the movements of the animals (M1–19). Technical devices such as mobile phones and GPS improve workplace safety and make herding more effective. They reduce the time spent in the field but, then again, also the time spent with other herders and the elders, who are the main holders of TK. This raises the question whether the transfer of TK from older to younger generations is diminishing. The inter-generational link is crucial for the continued preservation and transfer of TK (Berkes, 1999). Some herders noticed that the generations do not meet each other as often as earlier. A herder from Käsivarsi remarked: "*Yes, they now go [herding] from home, you see that snowmobiles have developed, ATVs have appeared*. . .. *When I started, it was not possible to go home for the night; three weeks was the longest time that I did not have a chance to go home*" (M1).

Adaptation of reindeer herding to climate change takes place in a context of multiple factors. Climate change is one of these, and represents a driver that interacts with several environmental, societal, economic and political drivers in society at large. Sustainable use of lichen pastures is a key issue in adaptation of reindeer herding to the cumulative impacts of these drivers. In the interviews, the amount of lichen on pastures was judged as insufficient for some districts and sufficient for others with regard to present reindeer numbers (M1–19, F1–2). In the all herding co-operatives studied, the lichen biomasses on the pastures were very low: all values were far below 1000 kg DW ha^{-1}, which can be considered good in a woodland lichen pasture for secure winter nutrition of reindeer (Kumpula, 2001; Kumpula et al., 2014). A recent study indicated that a considerable reduction in grazing pressure is needed before the recovery process in pastures with low lichen biomasses can start (Kumpula et al., 2014; Pekkarinen et al., 2015). Carefully adjusted reindeer numbers for each district would most probably improve the profitability of the livelihood in the long term. Reduced grazing pressure would also minimize many of the negative impacts caused by climate change, such as expenses from gathering, moving and feeding the animals.

A need for a separate adaptation strategy in reindeer herding for climate change has been recognized in Finland, and planning has been started by the actors within the livelihood (MAF, 2005, 2013, 2014). In our opinion, an effective adaptation strategy for reindeer herding would require not only modifications of herding practices, as discussed in the present study, but also policies for increased profitability and diversification of the livelihood. This would include such measures as strengthening the direct sale of meat and supporting its processing into further products by herders themselves, as well as developing reindeer-based tourism services and the production of handicrafts. It would also be of vital importance to minimize the adverse effects of competing land uses and climate change through, among other things, truly participatory planning processes (MAF, 2005, 2013, 2014).

Conclusions

We estimated the snow conditions that would prevail in the future climate, taking as an example the town of Sodankylä, which is located in the middle of the Finnish reindeer management area. These estimates we obtained cannot be simply extrapolated to different latitudes, elevations, topographic details and vegetation patterns within the area, and it is clear that future warming will manifest itself differently in different locations. It can be assumed, however, that our simulations on snow depth, density and ground icing represent the probable average trend in northern boreal snow conditions. The interviews of reindeer herders indicate that a longer snowless season – particularly early snow melt and thin snow cover, which will become more common, will be advantageous for reindeer herding due to increased availability of forage and improved growth of reindeer. Late snowmelt and deep snow will become less frequent, whereas ice formation on the ground or within the snow cover and dense snow cover will be more common. These trends place additional demands on herders to develop successful coping strategies. Herders have managed with the difficult weather and snow conditions through the ages by using their TK and skills related to reindeer, pastureland and herding practices, although difficult conditions led to reindeer losses more often than today. Utilizing the diversity of pasture environment and herding practices like the use of seasonal pasture rotation have been and will be important facilitating factors in herders' coping capacity. The greatest threats to the coping capacity of herding are predators and the resources required by conflicting land uses, for example, mining. New threats to herding can arise in the form of diseases, parasites and insect harassment caused by rising temperatures and/or the use of reindeer enclosures (pen feeding, calving enclosures). It is projected that the predictability of weather patterns and of the timing of snow and ice extent and stability will decrease, variability between the years increase, and what were previously rare or exceptional weather and snow conditions become more frequent. All this will challenge the applicability of herders' TK as a coping strategy in the future. Development of adaptation strategies for reindeer herding in particular could support both the economic and cultural viability of the livelihood, especially if the efforts to that end involve active participation of herders. The adaptation strategy adopted should include not only reorganization of the management systems and herding practices for the more sustainable use of pastures, but also policies that will enhance the profitability and diversification of the livelihood and mitigate the adverse effects of climate change, increased predator populations and competing land uses.

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