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RESEARCH

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Can management buffer pasture loss and fragmentation for Sami reindeer herding in Sweden?

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Abstract

Today, climate change and competing land use practices are threatening rangelands around the world and the pastoral societies that rely on them. Reindeer husbandry practised by the indigenous Sami people is an example. In Sweden, approximately 70% of the most productive lichen pastures (important in winter) has been lost, either completely or because of a reduction in forage quality, as a result of competing land use (primarily commercial forestry). The remaining pastures are small and fragmented. Yet, the number of reindeer in Sweden shows no general decline. We investigated the strategies that have allowed reindeer herders to sustain their traditional livelihood despite a substantial loss of pastures and thus natural winter forage for their reindeer. Changes in harvest strategy and herd structure may partially explain the observed dynamics, and have increased herd productivity and income, but were not primarily adopted to counteract forage loss. The introduction of supplementary feeding, modern machinery, and equipment has assisted the herders to a certain extent. However, supplementary feeding and technology are expensive. In spite of governmental support and optimized herd productivity and income, increasing costs provide low economic return. We suggest that the increased economical and psychosocial costs caused by forage and pasture losses may have strong effects on the long-term sustainability of reindeer husbandry in Sweden.

Keywords: Adaptation, Pastoralism, *Rangifer tarandus*, Resilience, Reindeer husbandry, Winter grazing

Introduction

Rangelands, i.e. natural pastures, extend over larger areas than any other land type (see for instance Reid et al. 2014 and references therein). Rangelands are very important to food production in general and to pastoral societies in particular and share some basic features: they are exposed to harsh and unpredictable weather, have low productivity, are sparsely populated, and remote from markets, and they are mostly managed as commons in some form (Reid et al. 2014). Many pastoral systems are threatened, not least from climate change (e.g. Ims et al. 2013), but also from encroachment by other forms of land use (Galvin 2009; Dong et al. 2011; Lopez-i-Gelats et al. 2016). This tends to lead to loss and fragmentation of pastures, and thus forage loss, and causes major challenges as pastoral systems generally depend on animal movements or migrations to sustain the herds over the seasons (Naess 2013; Horstkotte et al. 2014). Some authors have suggested that institutional systems and lack of power may severely restrict the adaptive capacity of pastoralists (Löf 2014; Risvoll and Hovelsrud 2016), while others argue that pastoral systems are often very flexible and have been able to adapt to changes in the past (e.g. Galvin 2009; Moen et al. 2010). In any case, pastoralists must adopt strategies to adapt to changes that they cannot control.

In Sweden, reindeer husbandry is a form of pastoralism practised exclusively by the indigenous Sami people.

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It has centuries-old roots, still relies on natural pastures to a large extent to sustain the herds, and is of high cultural importance for the Sami people. Grazing rights are linked to the respective herding district and independent of land ownership (Swedish Reindeer Husbandry Act 1971: 437). During the last century, reindeer husbandry has been facing increasing encroachment from competing forms of land use, such as forestry, hydropower development, mining, and tourism (e.g. Moen 2006; Ims et al. 2013). Today, the incremental changes imposed by other land users create large cumulative impacts. For instance, an individual forest stand that is logged, an area covered by a mine, or a new railroad may occur in only a small portion of the range used by reindeer; however, taken together, these encroachments may have a substantial impact on the amount and availability of pastures (Pape and Löffler 2012; Kløcker Larsen et al. 2016). The gradual loss of land has also ramifications beyond that of the area lost itself; as the landscape becomes more and more fragmented and remaining pastures smaller and more isolated, use becomes much more difficult (Nellemann et al. 2003; Kivinen 2015; Kløcker Larsen et al. 2016), and resilience is lost from the system (Moen et al. 2010).

Already in the 1960s, Skuncke (1969) stated that in the preceding century the settlement process of northern Sweden had caused substantial losses of valuable winter reindeer pastures. In particular, he referred to lichen pastures in the boreal forest, as lichens are usually a main food source for reindeer in winter (Heggberget et al. 2002), although other vegetation types (e.g. shrubs and graminoids) may also constitute a significant part of the diet (Åhman and White 2018). More recently, Sandström et al. (2016) demonstrated that from the 1950s to the 2010s, 71% of lichen-abundant forests, i.e. forests with > 50% of ground lichen cover, has been lost (i.e. their lichen cover is now < 50%). Additionally, from the 1950s to the 1990s, roughly 50% of those forests defined by the Swedish National Forest Inventory (NFI) as lichen-moderate, i.e. having 25–50% of ground lichen cover, was redefined as having less than 25% lichen cover (Sandström et al. 2016). This decline in lichen cover has become even more pronounced in recent years (Horstkotte and Moen 2019).

The large decline in ground lichen cover might be explained by the long-term effects of forestry on both the forest floor and the forest stand structure (see Forbes et al. 2006; Kivinen et al. 2010 for a detailed discussion). However, as those data are based on rather coarse forest classifications (> 50% lichen cover, 25–50% lichen cover, and < 25% lichen cover), converting those changes into actual lichen biomass or forage loss is challenging, since lichen biomass is determined by both lichen cover and lichen height (Uboni et al. 2019). It is important to understand that most of these forests are still available to the herders, albeit that logging residues or young, planted forests may restrict access to some extent (Kivinen et al. 2010). In addition, infrastructure development may have completely removed pasture areas or made them inaccessible in some cases (e.g. Össbo 2014; Axelsson Linkowski 2017). Reindeer herders consider pasture loss and fragmentation as a real and critical threat. For instance, interviews with old and young reindeer herders show that pastures that were not used by the older generation because they were considered as "low quality" are now considered by the younger generation as good, or at least acceptable (Axelsson Linkowski 2017). This suggests that the loss of land and forage has been so strong that, within only one generation, the herding communities have experienced a change in the perception of what constitutes a good pasture (sometimes referred to as a shifting baseline; e.g. Hilding-Rydevik et al. 2017). Herders also argue that today the winter pastures are so fragmented that they need to use up to four times as large an area as their father did for the same herd. The young herders state that they do not have alternative pastures to use, which destroys the rotational grazing scheme used by earlier generations (Axelsson Linkowski 2017).

However, in spite of the documented loss of productive winter pastures, the total reindeer population size in Sweden has not shown any long-term trend in the last century (Moen and Danell 2003). Bårdsen et al. (2017) showed that this pattern is also true for most of the 51 individual herding districts in Sweden, and they concluded by wondering why they did not detect "evidence of population declines when in fact the most apparent changes in the husbandry are expected to affect the number of reindeer negatively" (Bårdsen et al. 2017; 172). This can be seen as a paradox, i.e. a statement that runs contrary to one's expectation. Indeed, in ecological systems, the density of species that follow an ideal-free distribution (i.e. that are not territorial) should reflect their pasture quality (Morris 1994). The main question in this paper is then: how can this apparent paradox, where a long-term decline in pasture quality and quantity does not cause long-term declines in reindeer numbers, be explained? We addressed this question by using data from official statistics, focusing on the strategies that herders may have adopted for dealing with loss of forage. We hypothesize that the apparent paradox is due to several adaptations and responses by the herders, such as changes in herd structure, management, and use of the pastures.

Study site and system

We have focused on reindeer husbandry in Sweden, where there are no wild reindeer populations but all animals are privately owned and herded by Sami indigenous herders within 51 herding districts in northern Sweden (Fig. 1). The majority of reindeer migrate between summer pastures in the mountains in the west and winter pastures in the boreal forest at lower altitudes in the east. Winter forage is generally regarded as the bottleneck in the system, just as in many other northern pastoral systems (Skuncke 1969; Moen 2006; Sandström et al. 2006), although the relative importance of different seasonal pastures may differ regionally.

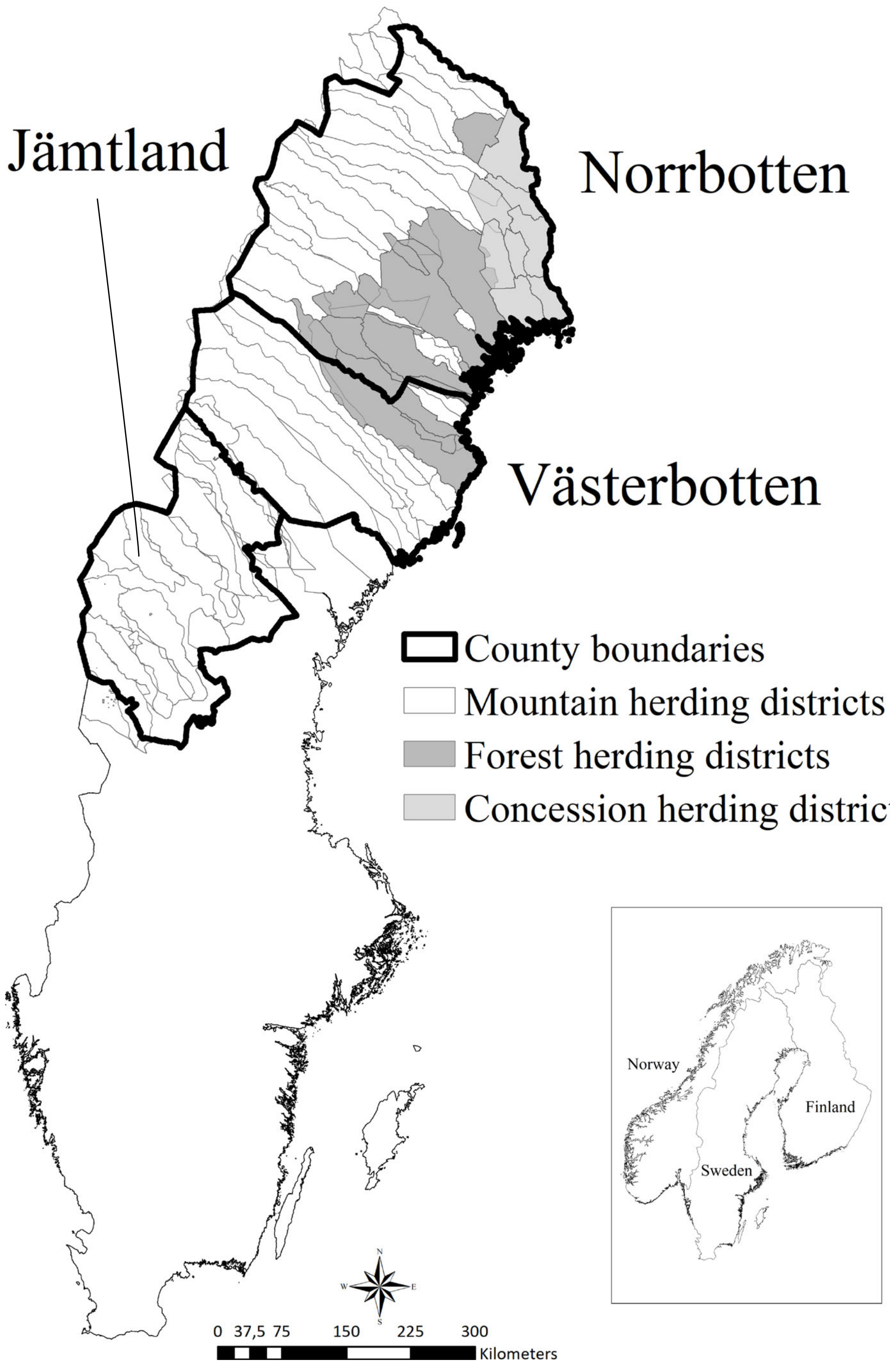

Fig. 1 Map of the Swedish reindeer herding area. Boundaries of the 51 Swedish reindeer herding districts. Reindeer belonging to the mountain herding districts migrate between winter pastures in the east, close to the Baltic coast, and summer pastures on the Scandinavian mountain chain in the west. Forest and concession herding districts remain in the boreal forest year around. The winter ranges of mountain districts partly overlap with land of the forest districts

Methods

To address our hypothesis, we collected data and official statistics describing the status of lichen pastures and reindeer husbandry in Sweden from 1945 until 2015; we then explored circumstances and strategies that may have enabled reindeer herders to adapt to and buffer the loss of productive winter pastures. In particular, we examined changes in reindeer herd structure, harvest strategies, and supplementary feeding, for which we had quantitative data. As the available data for these 70 years are of varying temporal and spatial scales and contain data gaps that did not match among datasets (see the "Data availability and sources" section below), we were not able to build a complete statistical model of drivers and responses to test our hypothesis. Instead, the statistical models we describe below were only intended to detect and describe temporal trends, and not to be seen as mechanistic models of drivers. We discuss the different adaptation strategies that we have identified and the possible relative role these may have in explaining the addressed paradox.

Data availability and sources

Data on forest classification based on ground lichen cover

Data on forest classification were produced by the NFI. The NFI staff classifies Swedish forests based on the cover of the species group dominating the ground layer (distinguishing between lichens, wet mosses, and dry mosses). This inventory started in 1953 and is carried out annually, but the classification categories and the sample plot size have changed through time. For a detailed description of how lichen-abundant and lichen-moderate forests have been classified, see Additional file 1.

Data on reindeer husbandry

Data related to reindeer husbandry in Sweden over the study period (1945–2015) are limited and partly scattered. The only data that have been continuously reported over the whole period are reindeer numbers (Additional file 1). Data until 1965 were available in a governmental report from the Swedish Ministry for Foreign Affairs (Kungliga utrikesdepartementet 1967). We found additional data in reports by the Swedish Agricultural Agency (Lantbruksstyrelsen/Rennäringsenheten 1985), Statistics Sweden (1999), the Swedish Agricultural Statistics Annual Reports 1976–2015, and the journal *Rennäringsnytt* ("Reindeer Husbandry News", 1967–1991, published by the Swedish Agricultural Agency). We obtained annual data on reindeer numbers in the winter herd after harvest, reindeer harvest, and income from slaughter from 1995 onwards as original data from the Sami Parliament in January 2016. These data were specified by animal category (calf, female > 1 year old, and male > 1 year old, respectively), owner, reindeer group (or enterprise), and herding district. Details on data and data sources are available in Additional file 2. A year was considered as beginning with July 1 and ending with June 30 the following year. Therefore, hereafter e.g. the year 1997 refers to the period July 1, 1996–June 30, 1997. We standardized all economic data to the year 2015 using the historical Cost-of-Living Index (CLI, retrieved on September 4, 2017, at www.scb.se), in order to be able to compare data referring to different years.

We used data on the amount of factory-made (grain-based) feed for reindeer sold per year to estimate to what extent the current level of feeding might replace natural pastures in a longer perspective. Data were provided for the period 1986–2015 by two main Swedish producers that prefer to remain anonymous. In some years, data were missing for either of the producers, so we calculated the production for those years based on the assumption that the production of one producer relative to the other had been the same during the whole period 1986–2015. Some factory-made feed is also bought from Finland, but the amounts are unknown. Other feeds, mainly hay and grass silage, are also used for feeding reindeer, even though in limited amounts, as herders find it difficult to get good enough forage for reindeer from farmers (Persson 2018), and since herders in Sweden do not usually own land for growing hay or silage.

In order to reveal how management methods and techniques used in reindeer husbandry have changed over time and may have affected the utilization of pastures, we searched for information in governmental reports and publications from the Swedish Agricultural Agency, including the periodical publication *Rennärings-nytt* (Reindeer Husbandry News) from the period 1967–1991 (see details in Additional file 3).

Data on lichen conditions

The lichen biomass available to reindeer as winter forage can be quantified by estimating cover and measuring height of mat-forming lichens (Uboni et al. 2019). We measured the thickness of the lichen mat (i.e. lichen height, methods described in Uboni et al. 2019) in optimal reindeer winter pastures, i.e. lichen-abundant forests with > 50% ground lichen cover as defined by the NFI, spread across the winter range of the Swedish reindeer herding area (Additional file 1, Fig. A1.1). We focused on five species: *Cladonia arbuscula*, *C. mitis*, *C. rangiferina*, *C. stellaris*, and *Cetraria islandica*, which are the mat-forming lichen species dominating reindeer diet in winter (Andreyev 1954). In summer 2015, we visited 73 forest stands in the boreal forest zone of Västernorrland, Västerbotten, and Norrbotten Counties, which had been sampled by the NFI in the period 2010–2014. These stands constituted a subsample of the stands visited by Uboni et al. (2019), created by removing the sample plots that turned out to have a lichen cover < 50%. In 2016, we visited 21 additional forest stands that had been sampled by the NFI between 2000 and 2012 in two areas of Norrbotten County, which were underrepresented in the 2015 dataset. The stands represent winter ranges for 21 reindeer herding districts, holding about half of the total reindeer population in Sweden.

Data analysis

Trends in reindeer numbers and lichen-dominated forests

Previous research analysing the NFI data on forest classification either did not separate the data based on the changes in sampling design that occurred in 1973 (Sandström et al. 2016) or did not evaluate the decline in lichen-dominated forests quantitatively (Sandström et al. 2006). Similarly, Moen and Danell (2003) did not analyze quantitatively the trend in the Swedish reindeer population. Therefore, we analysed the long-term temporal trends in reindeer numbers and in lichen-abundant and lichen-moderate forests by running regression models on the data on reindeer population size in Sweden and the forest data collected by the NFI (Additional file 1). For the latter analysis, we kept the periods 1953–1972 and 1973–2010 separate. Each regression model had either reindeer numbers, percentage of lichen-abundant forest plots, or percentage of lichen-moderate forest plots as the response variable and year as the predictor variable. We evaluated the need for a temporal autocorrelation structure added to the model residuals first by inspecting visually an autocorrelation function (ACF) plot of the residuals using the *acf* function in R (R Core Team 2019) and subsequently by comparing the Akaike information criterion (AIC, Burnham and Anderson 2002) of the linear regression models with corresponding generalized least squares models (GLS) with an AR1 temporal autocorrelation structure (Additional file 1, Table A1.3). We also scrutinized all models for violations of regression assumptions (heteroscedasticity and non-normality of the residuals).

Trends in the number of harvested reindeer and sale of factory-made reindeer feed

We analysed the long-term temporal trend in the number of harvested reindeer by running regression models with those data as the response variable and year as the predictor variable. We evaluated the need for a temporal autocorrelation structure added to the model residuals by inspecting visually an ACF plot. Since an autocorrelation structure seemed to be necessary, we additionally compared the AIC of the linear regression model with the corresponding GLS model with an AR1 temporal autocorrelation structure (Additional file 2, Table A2.1). The models did not suffer from heteroscedasticity or non-normality of the residuals.

We ran the same analysis on the quantity of reindeer feed sold by two Swedish producers. Here, an autocorrelation structure was not required. However, since a visual inspection suggested that the model residuals of the linear regression model suffered from lack of normality, we applied a square root transformation to the response variable. The model did not suffer from heteroscedasticity.

Results: Untangling the paradox

Our analyses of trends in reindeer numbers and lichen-rich forests confirmed our preunderstanding of an apparent paradox. The reindeer numbers showed no significant trend during the study period (Fig. 2; GLS model with AR1 temporal autocorrelation structure: $\beta = -0.45$, SE = 1.54, p value = 0.7701). At the same time, the percentage of lichen-abundant plots declined significantly (Fig. 2; period 1953–1972, linear regression model: $\beta = -0.21$, SE = 0.04, p value = 0.0002; period 1973–2010, GLS model with AR1 temporal autocorrelation structure: $\beta = -0.16$, SE = 0.03, p value < 0.0001). Lichen-moderate plots slightly declined from 1973 to 2010, even though that decline was only close to statistical significance (Fig. 2; GLS model with AR1 temporal autocorrelation structure: $\beta = -0.06$, SE = 0.03, p value = 0.0564).

In a pastoral system that is highly dependent on natural pastures, the lack of long-term trends in animal numbers during a time of pasture loss may be linked to ecological as well as management factors. From an ecological point of view, loss of land and forage is expected to reduce animal body conditions, and thereby recruitment rate and weight gain (Åhman and White 2018). However, in a managed system, like reindeer herding, this primarily limits the number of animals that can be harvested, and their carcass weights, rather than herd size. There is also a “highest reindeer number”, decided for each herding district by the County Administrative Boards, which the herders have to adapt to, although this is not a dynamic management tool that can adjust to changes in forage resources. From a management point of view, herders may adopt strategies to overcome the consequences of decreases in pasture quality and quantity, for example changes in herd composition, supplementary feeding, or altered pasture use, which in turn can be supported by the use of new technologies and management practices.

Ecological consequences of loss of food resources

The goal of any pastoral system is to provide subsistence and market products through the conversion of forage into animal products. Loss of food resources is expected

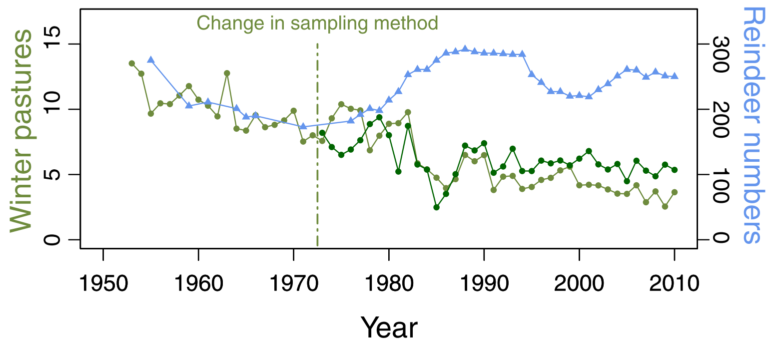

Fig. 2 Change in winter pasture and reindeer numbers in Sweden from 1953 to 2010. Time series of the percentage of Swedish National Forest Inventory (NFI) plots classified as lichen-abundant (light green dots) or lichen-moderate (dark green dots), and of the number of reindeer in the winter herd (after harvest), expressed in thousands of animals (blue triangles). The vertical, green dashed line indicates that NFI data for the period 1953–1972 are not directly comparable to data from 1973 to 2010. For a description of data sources and methods used to derive this figure, see Additional file 1

to result in reduced reproduction (fewer offspring) and an increase in the number of animals suffering of, or lost to, malnutrition (Gaillard et al. 2000), which should translate into lower harvest rates and reduced weights of the harvested animals. However, in Sweden, the number of harvested animals did not show any significant long-term trend from the 1970s (data on annual harvest are not available for earlier years) to the 2010s (GLS model with AR1 temporal autocorrelation structure: $\beta = 627.45$, SE = 1740.41, p value = 0.7205), despite a peak at the beginning of the 1990s mimicked by harvest rate (Fig. 3), following an increase in reindeer numbers during the 1980s (Fig. 2).

The herd structure and harvest strategy within reindeer husbandry, however, have changed substantially during the study period, improving the productivity of the herd. In the period 1951–1960, the winter herds were composed on average by 51% females, 19% males, and 30% calves (Additional file 2, Table A2.2), and Skuncke (1969) reported an even higher proportion of males, i.e. 29%, for the northern regions. Instead, in the period 2006–2015, the herd was on average composed by 67% females, 9% males, and 24% calves. A larger proportion of females will evidently increase calf production and thereby the productivity of the reindeer herd. At the same time, a change in harvest strategy towards more calf slaughter has further improved herd productivity. According to Kungliga utrikesdepartementet (1967: 276), calves were only a minor part of the slaughter during the 1950s (e.g. 3–4% in Västerbotten County in 1959/1960). Since the 1970s, calf slaughter gradually became more common, starting in the southern reindeer herding districts (Holand 2007). From 1993 and onwards, calf harvest was encouraged by the Swedish authorities by giving a higher subsidy for calf meat than for adult reindeer meat (www.sametinget.se). The shift occurred at

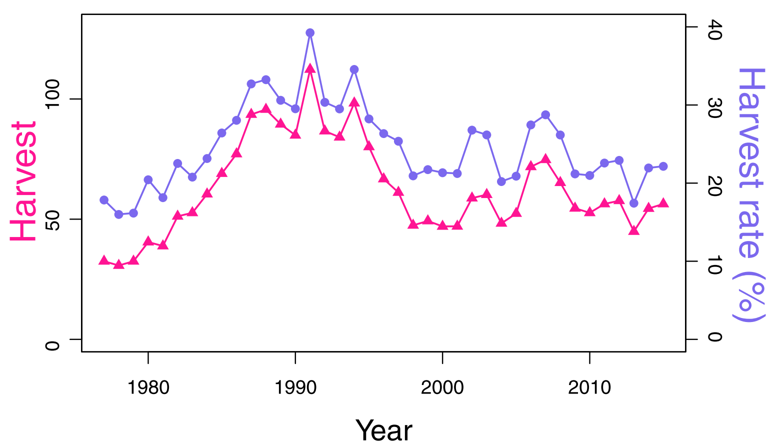

Fig. 3 Reindeer harvest in Sweden 1977–2015. Time series of the number of reindeer harvested in Sweden (left *y*-axis and pink triangles) and harvest rate (right *y*-axis and violet dots). The number of harvested reindeer was calculated as the percentage of harvested reindeer out of the total number of animals in the previous-year herd

different times and rates in different regions of the reindeer herding area, but was still apparent in the last decades when the harvest of calves increased (at least until 2012), representing now around 70%, while the share of harvested adults, both females and males, decreased (Additional file 2, Fig. A2.1). Since calves are at higher risk of mortality due to poor winter grazing conditions and predation, compared to adult reindeer (Saether 1997; Nybakk et al. 2002; Mattisson et al. 2014), this strategy reduces winter losses and thus increases the room for harvest. On the other hand, large males can dig through harder and thicker snow cover (Marin et al. 2020) and thus be a benefit for the herd during tough winters.

Despite the loss of land and pasture quality, reindeer body conditions in Sweden have not deteriorated from the 1960s to the present day, as indicated by a lack of trend in the average carcass weights of harvested reindeer (Table 1). Likewise, during the period 1996–2015, autumn carcass weights of calves (a suggested indicator of general body condition in the reindeer herd, Olofsson et al. 2011) have not declined (Additional file 2, Fig. A2.2). Autumn body mass largely depends on grazing conditions during the preceding summer (Tveraa et al. 2013). Nevertheless, food limitation in winter may have long-term effects on general body mass in the reindeer herd, through cohort effects (Ballesteros et al. 2013), and by affecting timing of calving (Paoli et al. 2018), birth weights, and lactation (Rognmo et al. 1983). Thus, the question remains: how has reindeer husbandry in Sweden been able to sustain not only reindeer numbers, but also animal body conditions and herd productivity in spite of large losses of good winter pastures?

Management strategies

Strategy 1—Changes in herd structure

Reindeer numbers may show a weaker response to forage loss if the proportion of females to males in the herd is increased, since females are smaller and require less energy than males, in spite of the extra energy needed for gestation (Åhman and White 2018). Given the same level of resources, a switch to a higher female to male ratio would increase the number of animals that the resources can support. As described above, a change in herd structure has indeed happened in Sweden, reducing the number of large reindeer (males) in favour of smaller reindeer (females).

To evaluate the possible impact of this change in herd structure on the apparent paradox, we calculated the effect of a change in herd structure on the body mass of an average sized reindeer and hence the effect on energy demand (Additional file 4). A change from 29% males, as suggested by Skuncke (1969), to 9% males (the present average), and a concurrent increase in percentage of females from 39 to 67%, and reduction of calves from 32 to 24%, resulted in 6.1% lower energy requirement assuming the same total number of animals in the winter herd. We thus suggest that there is a probable effect of the change in herd structure, although it may compensate for only a minor part of the loss and degradation of previously good quality lichen pastures that reindeer husbandry has suffered since the 1950s.

Table 1 Average carcass weight (kg) of slaughtered reindeer recorded from the 1950s until 2015

Year	Females	Males	Calves	Notes
1950s	32 kg	25/47 kg	20 kg	Mountain reindeer Oct–Dec[‡]
1985	26/37 kg	29/39 kg	18 kg	Suggested as normal weights[§]
2005	32.2 kg	43.2 kg	21.2 kg	Whole reindeer husbandry area[†]
2015	33.7 kg	43.4 kg	21.1 kg	Whole reindeer husbandry area[†]

"Calves" are animals of both sexes under 1 year of age. "Females" and "Males" are animals older than 1 year. The category "Males" does not include castrates
[‡]Source: Kungliga utrikesdepartementet (1967), Chapter VII Table 6 (p. 279)
[§]Weights for 1985 are divided into young (1–2 years old) and older females and males, respectively. Source: Lantbruksstyrelsen/Rennäringsenheten (1985), Table 28 (p. 37)
[†]Original data from the Swedish Sami Parliament

Strategy 2—Supplementary feeding

Another response to loss of pasture and natural forage is to provide an alternative food resource, such as hay or factory-made reindeer feed. The use of supplementary feed increases the number of animals that can be kept within a given range (such as a herding district). Supplementary feeding with hay and grain has been practised within reindeer husbandry at least since the early 1970s (Persson and Nordkvist 1966; Helle and Saastamoinen 1980). Grain-based feed mixtures for reindeer were developed during the following decades (Jacobsen and Skjenneberg 1975), and factory-made feeds for reindeer were available on the market in the early 1980s (Additional file 3).

As an effect of the Chernobyl accident in 1986, reindeer were supplementary fed in many parts of Sweden in order to reduce the level of cesium in their meat (Åhman 1999). This became a start for a more intense use of supplementary feeding, and an increasing number of herders started to use factory-made reindeer feed also to overcome shortages of natural forage due to either adverse weather conditions or loss of natural winter pastures. The steady increase in the amount of reindeer feed sold since 1986 by the two main producers in Sweden (Fig. 4; linear regression model with square root transformation of the response variable: $\beta = 0.10$, SE = 0.02, p value = 0.0001) suggests that supplementary feeding has become increasingly important in reindeer husbandry, even though with large variations between years. However, it is important to note that using supplementary

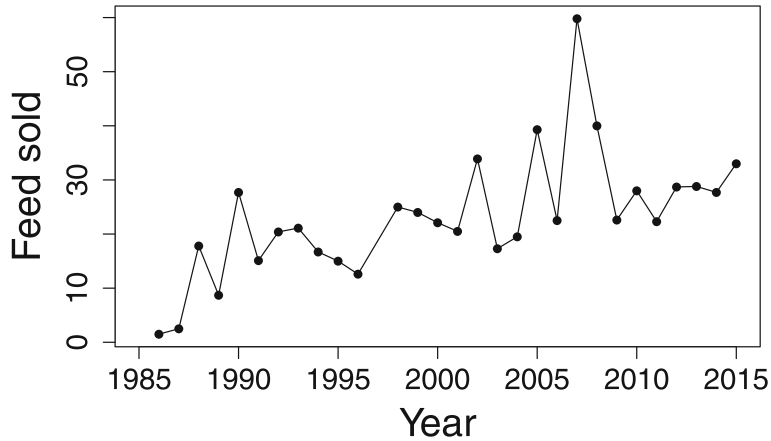

Fig. 4 Sale of factory-made reindeer feed in Sweden. Times series of the annual amount of factory-made reindeer feed (in kg per reindeer) sold by the two main producers in Sweden from 1986 to 2015

feeding one winter will give lichens a chance to grow and will thus save forage for coming winters.

To quantify to what extent the current practices of supplementary feeding in Sweden may have compensated for loss of pasture, we calculated the number of winter grazing days that can be replaced by the current use of supplementary feed in Sweden (for details, see Additional file 4). We used an average amount of 31 kg of factory-made feed per reindeer and year (from the years 2006–2015 in Fig. 4), assuming that reindeer were also offered some additional hay, grass silage, and lichens (25% of the total energy intake). The average annual amount of energy provided from this supplementary feeding was estimated to 387.5 MJ per reindeer and year. Assuming that the energy requirement of an "average reindeer" (based on the present herd structure in Sweden and energy requirements from White et al. 2014) is 22.4 MJ per day, this corresponds to 17.3 days of grazing and may compensate for about 10% of the energy needs during the period November–April. This alone, or combined with the change in herd structure described above, can thus counterbalance only part of the loss of natural winter forage.

However, as suggested for example by Helle and Kojola (2006) and Pekkarinen et al. (2015), supplementary feeding makes reindeer husbandry less density dependent. The large variation between years in the amount of reindeer feed sold (Fig. 4) indicates that feeding is not a recurrent part of reindeer management for most herders in Sweden. It confirms that feeding is rather used to overcome occasional periods with poor grazing conditions due to excessive snow cover or thick ice layers preventing access to natural forage, when alternative pastures are no longer available. The increased use of supplementary feeding may thus have aided recovery from low reindeer numbers in the early 1970s in Sweden (Fig. 2), similar to large regions of Finland and Norway (Helle and Kojola 2006; Uboni et al. 2016). Low reindeer numbers lasting for several years may also give lichens a chance to recover, resulting in improved winter forage resources and enabling later herd growth.

Strategy 3—Mechanization and changes in land use

Loss of land and decreasing quality of pastures may also have been compensated for by better utilizing the remaining land through the introduction of modern equipment. Snowmobiles, all-terrain vehicles, helicopters, trucks, GPS collars, and fences have all been increasingly used in reindeer husbandry, starting in the 1960s (Pelto 1973; Jernsletten and Klokov 2002; Riseth et al. 2016, see also Additional file 3). Snowmobiles and all-terrain vehicles make movements easier, helicopters are at times used to herd the animals, trucks can be used to transport reindeer between summer and winter pastures or among fragmented seasonal pastures, and fences are used to steer the animals or to keep them in preferable areas. Today, many herding districts use GPS and Geographic Information System (GIS) technology to keep track of their animals and map key pasture areas and migration routes within their district (Sandström 2015).

Mechanization is an expensive process (e.g. Pelto 1973; Nordin 2007), which in Sweden has been partially supported by the government through a subsidy programme which started in 1973 (SOU 1983). Herders could apply for funds to develop their business or to finance e.g. investments in machinery and infrastructure. From 1977 until 1993, the support for rationalization and equipment was 0.5–3.3 million Swedish crowns (SEK), equivalent to 0.06-0.37 million USD, per year (adjusted to CLI 2015, Additional file 2, Table A2.3). From 1994, this kind of support was not specified separately, but was included in the more general governmental funding for "promotion of reindeer husbandry". This included "project support", with an average annual sum at 6.4 million SEK (0.72 million USD) from 1997 to 2014 (adjusted to CLI 2015). We do not know, however, to what extent this support was used for further technical development.

Irrespectively of governmental support, the use of modern machinery has a substantial effect on the economy. Although the meat prices paid to herders by the slaughter companies (Additional file 2, Fig. A2.3) are increasing and presently about 50% higher than prices paid to producers of lamb or beef (official statistics from the Swedish Board of Agriculture), indicating a good market for reindeer meat, the income is low and rather unpredictable because of large variations in annual harvest. The average annual income from slaughter during the last two decades (adjusted to CPI 2015) has been 363 SEK per live reindeer in the winter herd. For an average reindeer herding enterprise with 250 reindeer, this corresponds to a revenue of 91,000 SEK (equivalent to about 9000 euros), which should cover running costs as well as provide salary for the herder.

Strategy 4—Changes in grazing intensity

Lastly, loss of land may be compensated for by returning more often to the same pastures and increasing the grazing pressure on the remaining land. This has been shown to be the case in Finland (several national reports reviewed by Helle and Kojola 2006), and according to interviews with herders, this also seems to apply to herding districts in Sweden (Horstkotte et al. 2014; Axelsson Linkowski 2017). Since lichens have slow growth rates (Skuncke 1969), hard grazing that does not allow regrowth of the lost biomass before the next grazing event will eventually lead to a long-term deterioration of the pastures (i.e. decrease in the lichen-mat thickness).

Kumpula et al. (1997) determined that lichen mats should be at least 3 cm thick to provide sufficient nutritional support to reindeer in winter. According to Skuncke (1958), a lichen mat with an average thickness of 5–6 cm gives an annual lichen production that is double compared to a lichen mat with an average thickness of 4–5 cm. On the other hand, according to Sveinbjörnsson (1987), the productivity of a lichen mat (species *Cladonia rangiferina*) with a thickness between 6 and 8 cm is about twice as high as in thicker mats (namely 9, 12, and 15 cm thick). Skuncke (1969) stated that an "overgrazed" lichen mat (presumably 0–2 cm thick) may take some 15–45 years to reach an average thickness of 6 cm. Based on those studies, we hypothesize that the most suitable and productive winter reindeer pastures should have a lichen-mat thickness ranging between 3 and 8 cm. According to our own measurements, the thickness of lichen mats in lichen-abundant boreal forests of northern Sweden is on average 3.95 cm (± SD = 1.45 cm). Nearly 27% of the investigated forests had lichen mats with a thickness < 3 cm (Fig. 5). These figures suggest that the current grazing pressure on lichen ranges may not be optimal and that the loss of lichen pastures due to competing land use (primarily forestry) has forced the herders to use the remaining pastures more intensively or frequently. This is also evident in the herder interviews on rotational grazing reported in Axelsson Linkowski (2017).

Discussion

Reindeer herders in Sweden have responded to the long-term loss of land and negative trends in pasture quality with a suite of parallel strategies that interact in securing reindeer herd productivity on the remaining pastures. Changes in land use were partly enabled by mechanization (Riseth and Vatn 2009) and could thus be a response to forage losses and pasture fragmentation, even though many other factors were certainly also involved (e.g. Riseth et al. 2016). Supplementary feeding has been a way to provide reindeer enough nutrients during periods with poor grazing conditions (Pekkarinen et al. 2015; Riseth et al. 2016; Turunen et al. 2016) and is increasingly important when lichen resources are declining and alternative pastures are not available (Helle and Kojola 2006). A change in herd structure has reduced the individual forage needs and thus enabled large herd sizes. However, the change in herd structure

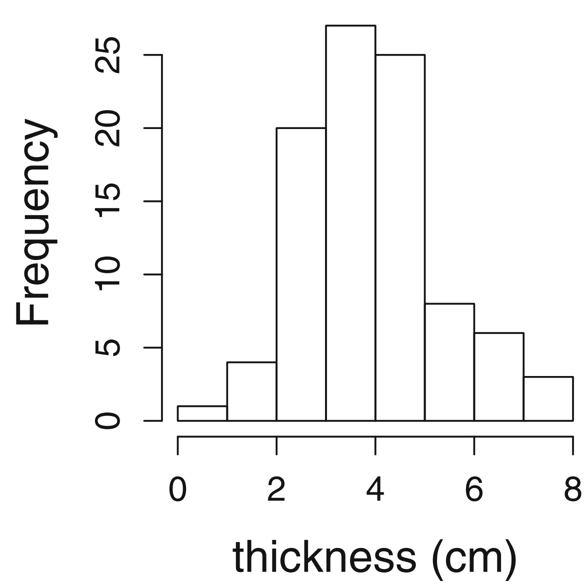

Fig. 5 Distribution of lichen-mat thickness in northern Sweden. Histogram of lichen-mat thickness in the boreal forests of northern Sweden. Data were collected in 2015 and 2016 in 94 forest stands located in the Swedish northern-most counties. See the section "Data on lichen conditions" for more details

together with the introduction of calf slaughter has occurred as an effect of a gradual transition to a market economy and increased demand of income from harvest (to cover increasing costs; see e.g. Kitti et al. 2006; Holand 2007; Karlsson 2015), rather than as a response to loss of land and forage. Moreover, following the rapid development of technical equipment and herding techniques that has characterized livelihoods since the 1960s (Pelto 1973; Jernsletten and Klokov 2002; Riseth et al. 2016), strong adult reindeer males were no longer needed for transportation and were replaced by snowmobiles, motorcycles, and all-terrain vehicles. A focus on a herd structure composed predominantly of females, combined with calf slaughter, may have increased meat production (and thus income) per area up to 50% compared to traditional herd structures (Holand 2007). From 1993 and onwards, calf harvest was encouraged by the Swedish authorities by giving a higher subsidy for calf meat than for adult reindeer meat (Statistics Sweden 1999).

Overall, the strategies used are often, if not always, connected to increased costs, either as pure financial costs or as indirect costs, such as increased workload or stress, although mechanization also facilitates much of the work connected to herding. The financial costs include, for instance, costs for supplementary feed, transport of reindeer, and buying, maintaining, and running a fleet of vehicles (Karlsson 2015; Sámediggi/The Sámi Parliment in Sweden in press n.d.). The increased use of technologies, such as GPS and GIS, in reindeer husbandry has further required a larger monetary input into the herding enterprises. On top of this, transaction costs, i.e. costs associated with defining, establishing, and maintaining rights, have increased strongly as consultation processes with other land users, such as forest, mining, and wind power companies, increase (Bostedt et al. 2015). The increase in costs has consequences for the sustainability of reindeer husbandry and for reindeer herders. For instance, some older reindeer herders find it difficult to motivate young people to take up reindeer herding because it is so difficult to meet the costs (Folke Fjällström, *pers. comm.*). According to a recent questionnaire survey made by the Sami Parliament in Sweden (Sámediggi/The Sámi Parliment in Sweden in press n.d.), many herders are reluctant to recommend reindeer herding as a livelihood to younger Sami, and poor economic returns is raised as a main reason. Reindeer herders also show significantly higher levels of anxiety and depression compared to both urban and other rural people (Kaiser et al. 2010). The strongest factors related to emotional disorders are work-related, caused for example by large losses due to predators, extreme weather conditions, financial pressure, and conflict with competing land users. This is well described by a young reindeer herder: "[Income] is everything in reindeer herding. There are so many things that depend on money to make it possible to subsist on reindeer herding. It's so easy to be knocked over by a bad year of calving, or high pressure from predators or poor grazing conditions, and it can run up to hundreds of thousands of crowns … that can beat anyone down … you have to think so long-term and you know so very little about what's going to happen" (quote from Kaiser et al. 2013).

Low income and high costs may be a reason for an observed change in the number of reindeer enterprises with different herd sizes. Both large (more than 500 reindeer) and small (less than 100 reindeer) enterprises have increased since at least the mid-1990s, while medium-sized enterprises have decreased (Additional file 2, Table A2.4). This might indicate that enterprises need to have more reindeer to be economically sustainable than in the past. However, the right to own and herd reindeer, which is an important aspect of the Sami culture, is connected to a membership in a herding district and the ownership of an earmark. Therefore, in order not to lose this right and to give the younger generation a chance to establish as reindeer herders in the future, some enterprises still maintain a small reindeer herd, often in their children's name (Nordin 2007; Karlsson 2015).

Overall, the apparent paradox of loss of land and forage not resulting in reductions in animal numbers can be resolved by looking at both management actions and ecological factors. Increased supplementary feeding, changes in herd structure, more efficient ("modern") herding practices, and more intense use of the remaining pastures have managed to compensate so far. However, all of these strategies seem to result either in an increased pressure from an economic perspective or in a higher grazing pressure on the remaining pastures, which causes a reduction in their productivity. This, together with increasing encroachment on pastures from other forms of land use, has led several authors to discuss the long-term sustainability and resilience of reindeer husbandry in Sweden in its current form (Danell 2005; Moen et al. 2010).

Unlike Bårdsen et al. (2017), we do not presume that a crisis in reindeer husbandry should necessarily be reflected in declining animal numbers, but rather in fewer herders being able to make a living of this activity. Indeed, middle-sized reindeer herding enterprises have gradually been replaced by both large and very small enterprises. Moreover, in a recent questionnaire survey to Swedish reindeer herders (Sámediggi/The Sámi Parliment in Sweden in press n.d.), 66% of the respondents answered that income from other sources is as important, or even more important, than income from reindeer slaughter. We suggest that the increased economical and psychosocial costs incurred by loss of productive reindeer pastures may challenge the long-term sustainability of reindeer husbandry in its current form in Sweden. Should this happen, reindeer husbandry in Sweden would likely shift to a system based on supplementary winter feeding, rather than natural pastures (i.e. farming, see also Helle and Jaakkola 2008; Turunen and Vuojala-Magga 2014 for the situation in Finland). However, there are also strong counteracting forces to maintain the current form of extensive grazing on natural pastures, such as the importance of reindeer for the Sami culture and society (e.g. Riseth 2006; Nordin-Jonsson 2011) and the connection between reindeer husbandry and land rights in the current Swedish legislation (Brännlund and Axelsson 2011; Sarkki et al. 2016; Brännström 2017).

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s13570-020-00177-y.

Additional file 1. Swedish National Forest Inventory classification, reindeer numbers, and lichen condition sampling.

Additional file 2. Reindeer husbandry.

Additional file 3. Rationalization of reindeer husbandry.

Additional file 4. Impact of changes in herd structure and supplementary feeding.

Abbreviations

NFI: Swedish National Forest Inventory; CLI: Cost-of-Living Index; ACF: Autocorrelation function; AIC: Akaike information criterion; GLS: Generalized least squares models; GIS: Geographic Information System; SEK: Swedish crowns; TEK: Traditional Ecological Knowledge

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Authors' contributions

AU collected the data, did the statistical analyses, and co-wrote the paper. BÅ collected and compiled reindeer husbandry data and co-wrote the paper. JM designed the study, structured the paper, and co-wrote it. The authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated and analysed during the current study can be provided by the authors on reasonable request. Previously unpublished data on reindeer numbers and slaughter are available from the Sami Parliament in Sweden, but restrictions apply to the availability of these data, which were used under license for the current study and are not publicly available. Data are however available from the authors upon reasonable request and with permission of the Sami Parliament.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

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