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Synergies and trade-offs between provisioning and climate-regulating ecosystem services in reindeer herding ecosystems

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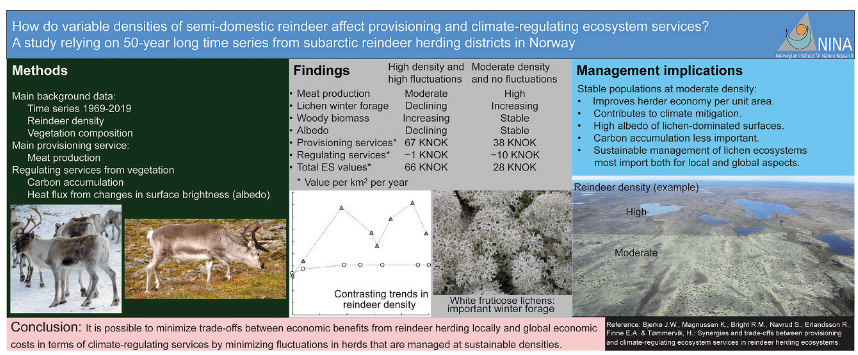
HIGHLIGHTS

- Boreo-arctic reindeer ecosystems are under threat from multiple pressures.
- Fluctuating herd density severely affects herder economy and grazing conditions.
- Declining lichen abundance leads to darker surfaces and increasing climate forcing.
- Stable sustainable herds preserve lichen forage resources and boost herder economy.
- Minimizing trade-offs between provisioning and regulating services is achievable.

GRAPHICAL ABSTRACT



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ABSTRACT

Reindeer (*Rangifer tarandus*) pastoralism utilizes vast boreo-arctic taiga and tundra as grazing land. Highly fluctuating population sizes pose major challenges to the economy and livelihood of indigenous herder communities. In this study we investigated the effect of population fluctuations on core provisioning and regulating ecosystem services in two Sámi reindeer herding districts with contrasting fluctuation trends. We compared 50-year long time series on herd size, meat production, forage productivity, carbon footprint, and CO_2-equivalence metrics for surface albedo change based on the radiative forcing concept. Our results show, for both districts, that the economic benefits from the provisioning services were higher than the costs from the regulating services. Still, there were major contrasts; the district with moderate and stable reindeer density gained nearly the double on provisioning services per unit area. The costs from increasing heat absorption due to reduction in surface albedo caused by replacement of high-reflective lichens with low-reflective woody plants, was 10.5 times higher per unit area in the district with large fluctuations. Overall, the net economic benefits per unit area were 237 % higher in the district with stable reindeer density. These results demonstrate that it is possible to minimize trade-

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offs between economic benefits from reindeer herding locally and global economic costs in terms of climate-regulating services by minimizing fluctuations in herds that are managed at sustainable densities.

1. Introduction

Reindeer (*Rangifer tarandus* L.) husbandry has developed over thousands of years from genuine hunting communities, via self-governed herding societies, to top-down governance of reindeer herding management and is quintessential for numerous arctic indigenous livelihoods (Riseth et al., 2016; Landauer et al., 2021). During this long period of managed reindeer pastoralism, the rangelands have converted into arctic agroecosystems by directed modification of vegetation structure for improved grazing conditions and by controlling predator density (Tveraa et al., 2007; Harris, 2012).

Reindeer manages to convert the otherwise low-degradable fungal polysaccharides into energy; hence, it is the only mammal that consumes lichens as a significant part of its diet (Hansen et al., 2018). Terricolous (ground-dwelling) lichens, and in some areas also arboreal lichens, are preferred forage during winter when the availability of digestible parts of vascular plants are limited. Additional adaptation towards a lichen-rich diet includes the ability to smell lichens through deep snow and dig through the snowpack to reach the lichens, and extension of its visual range into the ultraviolet for increased detectability of lichens in the landscape (Bergerud and Nolan, 1970; Riseth et al., 2011; Hogg et al., 2011).

Eurasian monitoring programs report that reindeer forage lichens are in decline (e.g., Joly et al., 2009; Tømmervik et al., 2012; Horstkotte and Moen, 2019; Erlandsson et al., 2022). In some areas, this decline was substantial already 140 years ago (Turi, 1910). The transition of reindeer herding from a non-monetary livelihood to a market economy led to increasing herds, which resulted in increased grazing pressure on lichen-dominated ecosystems and declining lichen abundance (Kumpula et al., 2019). Technical advancements – especially the introduction of snowmobiles – also made it possible to extend the winter grazing ranges and make use of previously little-grazed lichen tundra (Riseth et al., 2016). Non-herding factors such as air pollution, forestry, and other invasive land use practices have also contributed to the lichen decline (Korosuo et al., 2014; Akujärvi et al., 2014; Kumpula et al., 2014). Once the landscape-covering lichen mat becomes discontinuous, it leads to increased accessibility for seeds to the newly exposed soil; facilitating seedling emergence and plant establishment, thereby rapidly replacing lichens in areas where there previously was only a sporadic plant cover (Sedia and Ehrenfeld, 2003; Tømmervik et al., 2004). Declining lichen abundance has consequences for ecosystem functioning and herding practices. Reindeer's reduction in lichen intake must be compensated for by increased intake of vascular plants, and herders must often apply supplemental feeding with round bale silage or other harvested, reindeer fodder (pellets) and dried plant material as hay (Pekkarinen et al., 2015; Landauer et al., 2021).

Vegetation changes driven by reindeer grazing affect the regulating ecosystem services (ESs) of vegetation. While lichens accumulate relatively little carbon compared to plants with which they compete for space, intact reindeer lichen mats have a high albedo (Petzold and Rencz, 1975; Bernier et al., 2011). Surface albedo is the ratio of incoming solar radiation reflected at surface level which is an essential physical attribute of the climate system (Finne et al., 2023). Thus, it is increasingly understood that it is important and necessary to include albedo as a climate-regulating service in climate impact assessment studies, particularly at high latitudes (Euskirchen et al., 2013). For example, ocean ice reflects ca. 60 % of incoming solar radiation, thus the surface albedo feedback from declining sea ice is a primary driver of the Arctic amplification, as it allows more solar radiation to be absorbed by the darker surface of the ocean (Park et al., 2018; Dai, 2021). Likewise for the terrestrial biome, changes from high-reflective to low-reflective vegetation will reduce the albedo effect and contribute to climate forcing (Bonan, 2008; Lutz and Howarth, 2014). This is highly relevant for ES assessments of reindeer ecosystems, since the albedo of the various grazing habitats vary widely, with sustainably grazed lichen pastures having the highest albedos of all terrestrial non-cryospheric ecosystems in the world (Petzold and Rencz, 1975; Bernier et al., 2011; Finne et al., 2023).

In this study, we assessed the various categories of ESs that exist or are produced in two Norwegian Sámi reindeer ecosystems. ESs are generally divided into provisioning, regulating and cultural services, where food and timber are examples of provisioning services, climate mitigation and pollution control are examples of regulating services, while recreation and natural heritage are examples of cultural services (Millennium Ecosystem Assessment, 2005; Burkhard and Müller, 2008; TEEB, 2010). There may be significant trade-offs between ESs, particularly between regulating services that often act on a global scale and material contributions that often are most important for local users (Rodríguez et al., 2006; Dade et al., 2019; Malinauskaite et al., 2019).

Sámi reindeer herding systems have been widely studied from various socio-economic and ecological perspectives, including evaluation of ESs (e.g., Burkhard and Müller, 2008; Heikkinen et al., 2012). To our knowledge, however, the ES perspective and the pattern of synergies and trade-offs between provisioning and regulating services in reindeer ecosystems with diverging land use histories, applying time series covering several decades, have not been explored previously.

Here, we analyzed and compared 50-year long time series of the main ESs from two Norwegian reindeer herding areas with contrasting grazing and management history. The main objective was to identify potential synergies and trade-offs between the primary ESs over time – specifically between provisioning services from reindeer production and the regulating services of aboveground biomass in terms of carbon sequestration and the indirect carbon sink effect due to high surface albedo of lichen mats. We hypothesized that: (1) fluctuating reindeer densities have long-term impacts on the value of provisioning services, i.e., meat production and annual productivity of forage resources, (2) the value of climate-regulating ESs considered here (i.e., aboveground carbon accumulation and conversion of radiative forcings from albedo change into carbon dioxide equivalents) are associated with reindeer density, and (3) trade-offs between the regulating and provisioning services depend on rangeland management.

2. Material and methods

2.1. Study area

The reindeer herding ranges of Norway (Fig. 1) cover ca. 40 % of the country (Tømmervik and Riseth, 2011). Herding is organized in reindeer herding districts, which regulate the number of reindeer, areas for grazing, etc. Here, we study time series from two districts: Fæmund in Mid-Norway, and West Finnmark in northernmost Norway (Fig. 1). These two districts were selected because of the long and detailed time series of reindeer density and vegetation structure that are available. See Section 1 of online Supporting Information document for detailed information on geography, climate, landscape, and vegetation of the two herding districts.

2.2. Reindeer data

Time series on reindeer population (number of reindeer) and meat production were extracted from publicly available reports and statistics provided by the bailiffs in West Finnmark and Fæmund for the period

1968–1979 (Anonymous, 1969–1979) and from the Directorate for Agriculture, Department of Reindeer Husbandry, for the period after 1979 (Ims and Kosmo, 2001; Norwegian Agriculture Agency, 2021a).

The economic key numbers of reindeer herding in the siidas (i.e., Sámi reindeer herding communities) in Norway have been reported since the 1960s, rendering accurate reindeer densities, reported meat production and economic outcomes in Norwegian kroner, NOK (Norwegian Agriculture Agency, 2021a, 2021b). We report these numbers for selected years, corresponding to the years from which we have detailed vegetation biomass and albedo data; see Section 2.3.

The primary annual productivity measures applied are the production of live adult females (average meat in kg per female) and the percentage of slaughtered females. Specifically, we analyzed time series of meat production per km^2 of the winter range and of reindeer density, i.e., the number of overwintering individuals per km^2. The available data series on meat production are given as a function of the number of live females (reindeer cows). The official statistics on live females and the total number of overwintering reindeer reflect the situation in the

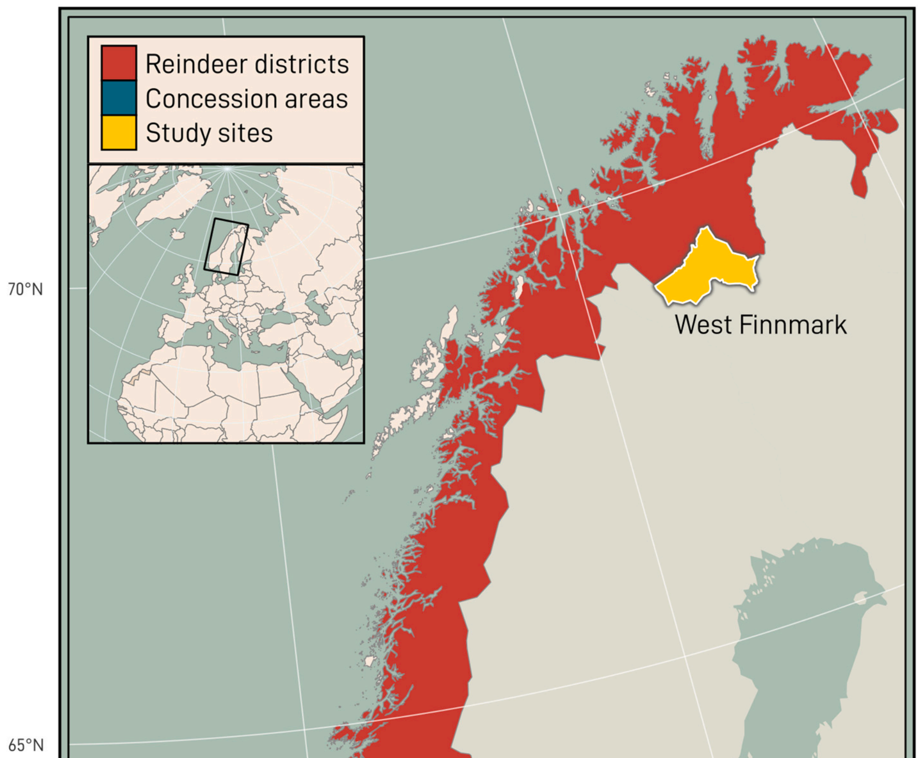

Fig. 1. Reindeer herding areas in Norway, with the two study areas, the winter grazing areas Fæmund and West Finnmark, marked in yellow. Red and yellow areas are Sámi reindeer districts and teal blue areas are concession areas allocated to both Sámi and non-Sámi reindeer herding, following the Norwegian Reindeer Herding Act. Map data were retrieved from the geoportal *Kilden* (Norwegian Institute of Bioeconomy Research, 2022).

winter-spring herds before calving, i.e. by 31 March each year, and these data are adjusted for change in total reindeer population size within each district. Thus, slaughter data provide the fraction (%) of slaughtered females from the total herd size before spring calving (Norwegian Agriculture Agency, 2021a).

Provisioning ESs include material benefits. The main market product from reindeer grazing is meat, while fur, handicraft and other by-products constitute a minor proportion as compared to the market income from meat (Labba and Riseth, 2007; Larsen et al., 2019). The provisioning ESs was accounted for in kg meat and valued at market price of reindeer meat. Slaughter weight and meat production are density-dependent, i.e., high density leads to high grazing pressure and reduced slaughter weight. We applied the average price in 2020 (excluding VAT) for reindeer meat in Norway, viz. about 80 NOK kg^{-1} (Norwegian Agriculture Agency, 2023), as a fixed price allows for comparison between years. We applied 6 NOK per forage unit (FU) as the fixed price for forage production over time from biomass growth, as this has been the average price in recent years (Tømmervik et al., 2022). We assume that these market prices, which include government subsidies, reflects both the marginal costs of production and the Norwegian households' willingness-to pay (WTP) to preserve the cultural heritage aspects and other external benefits attached to reindeer herding. Consequently, these market prices are also the correct prices to use in cost-benefit analyses (CBAs) of affected ecosystem services.

2.3. Vegetation data

Vegetation trends in the two study areas were assembled from published sources (Lyftingsmo, 1965, 1974; Tømmervik et al., 2009, 2021; Johansen et al., 2019). The vegetation trends described in these reports rely on field data collected from 1961 to 2019 combined with remote sensing analyses of Landsat and Sentinel-2 imagery from 1973 to 2020.

Table 1
Vegetation types identified within the two study areas and their corresponding albedo characteristics. Classification of vegetation types follow the system developed by Fremstad (1997) for Norway. Albedo (α) information was extracted from Sentinel 2-imagery as described in Supporting Information, and from published field measurements. See Table S2 for corresponding biomass data. Treeless non-wetland vegetation is called "heath" below the treeline and "tundra" above the treeline.

Vegetation type	α Fæmunden	α West Finnmark
Ridge with short evergreens and lichen tundra[1,a]	0.225	0.225
Ridge with ericoid shrubs and lichen tundra[2,a]	0.225	0.225
Bilberry (*Vaccinium myrtillus*) heath and tundra[b]	0.163	0.163
Alpine *Calluna*-lichen tundra[b]	0.136	0.136
Graminoid-dominated tundra and heath[b]	0.159	0.159
Strongly grazing-modified dwarf shrub and lichen tundra[b]	0.163	0.163
Lichen-dwarf shrub heath[a]	0.212	0.212
Birch forest with lichen carpets[b]	0.165	0.147
Scots pine forest with lichen heath[b]	0.158	0.131
Dense coniferous forests[c]	0.107	0.127
Mixed forest with *Vaccinium* and/or *Empetrum*[a,d]	0.140	0.140
Mesic, deciduous woodland[b,d]	0.128	0.128
Relatively dry shrub bog[b]	0.182	0.145
Moist dwarf shrub (*Salix-Betula nana*) bog[b]	0.139	0.139
Poor and intermediate fen[a]	0.167	0.167
Alpine snowbed vegetation and boulder fields[b]	0.119	0.139
Other alpine nearly vegetation-free areas (barrens)[b,c]	0.119	0.119
Lakes[b]	0.050	0.050

[a–d]Data sources: a = Finne et al., 2023; b = Sentinel 2; c = Bright and Alstrup, 2019, d = Petzold and Rencz, 1975.

[1] Very wind-exposed, limited snow protection; with creeping or cushion-forming evergreens.

[2] Wind-exposed, but with some snow protection; with slightly erect evergreen shrubs.

Analyses rely on biomass trends from 17 different terrestrial vegetation types; see type names in Table 1.

The bottom vegetation layer consists primarily of bryophytes, the lichen layer consists of light-coloured fruticose lichens readily consumed by reindeer (*Cladonia stellaris*, *C. mitis*, *C. rangiferina*, *C. stygia* plus a large number of associated species in lower abundance), the field layer consists of forbs and graminoids (hereafter, termed "forbs-graminoids"), the shrub layer is composed of dwarf birch (*Betula nana*), ericoid shrubs (*Calluna*, *Empetrum*, *Vaccinium*) and willow shrubs (*Salix phylicifolia*, *S. glauca* and associated species), while the tree layer is characterized by downy birch (*Betula pubescens*) with scattered occurrences of Scots pine (*Pinus sylvestris*) and aspen (*Populus tremula*) stands.

Biomass of the various vegetation layers (Tables S1, S2) was estimated as tons km^{-2} and converted to FUs following the methods and data in Labrecque et al. (2006), Tømmervik et al. (2009), and Eid et al. (2016). Average lichen volumes for the different vegetation types were obtained from the field surveys and converted to biomass (Table S3). The design and methods of the different surveys undertaken during the study period differ slightly from each other, but data are comparable over time (Tømmervik et al., 2009). Prior to use, the quality of previously collected data was assessed (i.e., methodology applied, reliability of species identifications, etc.). 1 kg of dry matter of feed is estimated to be 0.6–0.7 FUs (The Norwegian-Swedish Reindeer Pasture Convention, 1967). We applied the median (0.65) of this interval for conversion from biomass (kg) to FUs.

2.4. Regulating ecosystem services

Regulating ESs are benefits obtained from the regulation of ecosystem processes. For this approach, we analyzed two components: (1) the net change in aboveground biomass (i.e., carbon sequestration), and (2) CO_2 equivalents (eq.) from altered surface albedo due to vegetation change. Changes in methane emissions from reindeer's rumen microbial fermentation and vegetation alteration were not accounted for as these are complex relationships (Hartley et al., 2012; Hansen et al., 2018; Treat et al., 2018), for which we lack necessary data.

Changes in kg CO_2-eq. from surface albedo changes were estimated based on the recent review and recommendation of CO_2-eq. metrics (Bright and Lund, 2021), as detailed below. The economic value of net changes in tonnes CO_2-eq. would ideally be based on the global damage costs caused by 1 ton of CO_2 emission, which is termed the Social Cost of Carbon (SCC) (Pearce, 2003). SCC is estimated from Integrated Assessment models (IAMs) and vary widely due to different assumptions about the social discount rate, accounting for uncertainty and coverage of various factors, for example environmental impacts and extreme weather events from climate change (Wang et al., 2019). We applied an alternative approach, assessing the marginal abatement costs for mitigation of greenhouse gases for Norway, which is the approach recommended for cost-benefit analyses of public projects (Norwegian Ministry of Finance, 2021), and which tends to be higher than the SCC estimates. Thus, in order not to underestimate the value of this ES, we applied Norwegian carbon prices to value net changes in CO_2-eq. from changes in albedo within the study areas.

The climate-regulating value of biomass changes within the study areas were calculated from the general rule for relationship between carbon stored in the biomass and CO_2 absorbed from the atmosphere. For each unit of carbon storage, 3.67 units of CO_2 is absorbed (Khodakarami et al., 2022).

In addition, there are cultural ESs associated with reindeer herding and their ecosystems. Cultural ESs include the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences (Millennium Ecosystem Assessment, 2005; Fish et al., 2016). In our case, the cultural ESs include preservation of cultural tradition of reindeer herding as an important part of the Sámi culture, which incorporates cultural heritage and attached non-use values, the increased recreational and aesthetics value of an area with reindeer herding, and cultural tourism based on reindeer herding (Larsen et al., 2019). These cultural ESs are vital to the Sámi reindeer herding communities. While we qualitatively discuss these ESs, they are not accounted for in monetary terms, as we lack data both on their cultural and economic value as well as how these ESs are dependent on the number of reindeer and the economic outcome.

Changes in accumulated CO_2-eq. over time from vegetation-induced albedo differences (Table 1) in the two reindeer herding areas were calculated from the biomass changes of the various vegetation types, applying CO_2-equivalence metrics for surface albedo change based on the radiative forcing concept (Bright et al., 2015, 2016; Bright and Lund, 2021); see Sections 2 and 3 in Supporting Information for further information on albedo assumptions and calculation of local annual radiative forcing (RF).

Specifically, the metric called "time-dependent emissions equivalence", or *TDEE*, was applied (Bright and Lund, 2021). The *TDEE* metric (Bright et al., 2016) is analogous to the CO_2-forcing-equivalent emissions metric (CO_2-fe) of Jenkins et al. (2018) giving a time-dependent series of CO_2 fluxes (emissions or removals) that yields a time-dependent radiative forcing profile (in our case from the surface albedo change). Summing over the time series of CO_2-eq. fluxes rendered an accumulated measure (i.e., a CO_2-eq. stock) that is directly comparable with the CO_2 stock in biomass.

The Norwegian Ministry of Finance (2021) recommends the application of CO_2 prices for improved resource exploitation and fulfilment of national climate targets. The most relevant prices for our calculations are prices for non-quota sector and emissions/sequestration in forest and agriculture. Since we do not have any prognosis or scenarios for how the albedo effect and greenhouse gas equivalents will develop in the coming years, we applied the same approximation as for prices on reindeer meat and forage, i.e., the current price per ton CO_2 in sectors outside the quota system following the Ministry of Finance (2021). In 2022 (the first year with "carbon prices") the prices were 766 and 614 NOK per ton CO_2-eq. for the non-quota sector and for the forest and agricultural sector, respectively. For this study, we applied the lowest price (i.e., 6,142,020-NOK per ton CO_2-eq.). $\sum TDEE$ were converted to monetary units for the near-identical study periods (West Finnmark: 1969–2018, Fæmund: 1973–2020) suitable for between-district comparisons.

2.5. Statistical analyses

Significance (p) of trends over time were tested by simple linear regression. Trends were considered significant when $p < 0.05$. Multiple linear regression analyses were undertaken to further explore trends in key parameters. Akaike Information Criterion values were used to rank candidate models (Burnham and Anderson, 2002). Confidence level for models was set to 95 %. Models were evaluated on their accuracy (0–100 %), and predictors included in the models were evaluated on their relative importance (0–100 %); the sum of all predictors in a model is 100. Tests were run with SPSS Statistics 27 (IBM Corporation, Armonk, NY, USA). Statistics of all presented linear trends are summarized in Table 2. Value changes of the assessed provisioning and regulating ecosystem services were summed and analyzed in a cost-benefit test.

3. Results

3.1. Temporal changes in reindeer density and meat production

At the start of the study period, in the late 1960s, Fæmund and West Finnmark had near-identical reindeer densities at 6.8 and 6.5 individuals per km^2, respectively (Fig. 2a). However, from the late 1960s to 2019, the two study areas experienced highly contrasting reindeer density trends; while the reindeer density from 1968/69 to 1987/88 increased by 14 % in Fæmund, it increased by 170 % in West Finnmark.

Table 2
Statistics of linear regressions, given as $y = ax + b$, where y is the response variable, a is the coefficient, x is the predictor, and b is the constant. Regression coefficients (r) and significance values (p) are also provided in the statistics columns. Regressions are trends over time unless otherwise specified (1969 = time 0 in regressions). FNS = figure not shown.

Panel (s)	Dataset	Fæmund (F)	West Finnmark (WF)
2c	Slaughter fraction	$y = 0.259x - 461.6$; $r = 0.769$; $p = 0.043$	$r = 0.351$; $p = 0.394$
2a–2c	Slaughter fraction vs. density	$y = 11.348x + 33.776$; $r = 0.927$; $p = 0.003$	$r = 0.085$; $p = 0.238$
2a–2b	Density vs. meat production	$r = -0.249$; $p = 0.591$	$y = 27{,}164x + 148{,}485$; $r = 0.738$; $p = 0.037$
2b–2d	Live female productivity vs. meat production per km^2	$y = 0.1413x - 1.737$; $r = 0.956$; $p \leq 0.001$	$r = 0.096$; $p = 0.820$
3a–3b	Tree biomass	$r = -0.571$; $p = 0.180$	$y = 37{,}379x + 1{,}604{,}499$; $r = 0.810$; $p = 0.015$
3a–3b	Shrub biomass	$r = -0.423$; $p = 0.345$	$y = -1520x + 1{,}731{,}723$; $r = -0.787$; $p = 0.021$
3a–3b	Forb-graminoid biomass	$r = -0.590$; $p = 0.163$	$r = 0.620$; $p = 0.101$
3a–3b	Moss biomass	$r = 0.280$; $p = 0.543$	$r = -0.352$; $p = 0.393$
3c	Total plant biomass	$r = -0.567$; $p = 0.184$	$y = 6.404x + 935.3$; $r = 0.801$; $p = 0.017$
3a–3c	Total vegetation biomass (plants + lichens)	$r = -0.359$; $p = 0.429$	$y = 31{,}191x + 5{,}864{,}806$; $r = 0.701$; $p = 0.053$
3d	Tundra lichen biomass – whole period	$y = 4.278x + 216.88$; $r = 0.926$; $p = 0.003$	$r = -0.658$; $p = 0.076$
3d	Tundra lichen biomass 1969 to 2000 (WF) or 2002 (F)	$r = 0.812$; $p = 0.095$	$y = -4.009x + 186.55$; $r = -0.997$; $p < 0.001$
3a	Tree biomass (% of total biomass)	$y = -0.001 + 0.665$; $r = -0.848$; $p = 0.016$	$y = 0.0038x + 0.279$; $r = 0.891$; $p = 0.005$
3a	Shrub biomass (% of total biomass)	$r = -0.351$; $p = 0.441$	$y = -0.0014x + 0.293$; $r = -0.790$; $p = 0.020$
3a	Forb-graminoid biomass (% of total biomass)	$r = -0.203$; $p = 0.663$	$y = -0.0013x + 0.3546$; $r = -0.744$; $p = 0.034$
3a	Lichen biomass (% of total biomass)	$y = 0.001x + 0.034$; $r = 0.930$; $p = 0.002$	$y = -0.0012x + 0.0732$; $r = -0.761$; $p = 0.028$
4a	Albedo	$r = 0.134$; $p = 0.800$	$y = -0.0005x + 0.1792$; $r = -0.892$; $p = 0.003$
4b	Albedo vs. lichen biomass	$r = 0.561$; $p = 0.247$	$y = (4.87 \times 10^{-h})x + 0.153$; $r = 0.810$; $p = 0.015$
4b	Albedo vs. tree biomass	$r = 0.503$; $p = 0.309$	$y = (-9.33 \times 10^{-i})x + 0.190$; $r = -0.785$; $p = 0.021$
4b	Albedo vs. shrub biomass	$r = 0.553$; $p = 0.255$	$y = (-2.08 \times 10^{-g})x + 0.185$; $r = -0.732$; $p = 0.039$
FNS	Albedo vs. forb-graminoid biomass	$r = 0.770$; $p = 0.073$	$r = -0.483$; $p = 0.225$
4b	Albedo vs. total plant biomass	$r = 0.618$; $p = 0.191$	$y = (-5.28 \times 10^{-e})x + 0.225$; $r = -0.770$; $p = 0.025$
4b	Albedo vs. total vegetation biomass	$r = 0.755$; $p = 0.083$	$r = -0.638$; $p = 0.089$
4b	Albedo vs. reindeer density	$r = -0.533$; $p = 0.276$	$r = -0.610$; $p = 0.108$
4,5	Albedo vs. ΣTDEE	$y = -387x + 6518.9$; $r = -0.954$; $p = 0.003$	$y = -45{,}807x + 8249$; $r = -0.980$; $p < 0.001$

(*continued on next page*)

Table 2 (*continued*)

Panel (s)	Dataset	Fæmund (F)	West Finnmark (WF)
6c	ΣTDEE vs. lichen biomass	$r = -0.321$; $p = 0.535$	$y = -0.0017x + 1140$; $r = -0.728$; $p = 0.040$
6b	ΣTDEE vs. tree biomass	$r = -0.434$; $p = 0.390$	$y = 0.0005x + 569.6$; $r = 0.833$; $p = 0.010$
FNS	ΣTDEE vs. shrub biomass	$r = -0.317$; $p = 0.541$	$y = -0.010x + 17{,}523$; $r = -0.756$; $p = 0.030$
FNS	ΣTDEE vs. forb-graminoid biomass	$y = -0.006x + 27{,}172$; $r = -0.842$, $p = 0.036$	$r = 0.587$; $p = 0.126$
6a	ΣTDEE vs. total plant biomass	$r = -0.605$; $p = 0.203$	$y = 2.635x - 2279$; $r = 0.820$; $p = 0.012$
FNS	ΣTDEE vs. yearly lichen production	$r = -0.319$; $p = 0.537$	$y = -4.258x + 1201$; $r = -0.728$; $p = 0.041$

From 1987/88 to 2019/20, density remained stable at 8.2 reindeer per km^2 in Fæmund, while it fluctuated substantially in West Finnmark; first it declined by 36 % from 1987/88 to 1999/2000. Thereafter, until 2013/14, it again increased, this time by 62 % (=4.8 % per year), reaching a new record-high density of 18.3 reindeer per km^2. This was a 220 % higher density than at the same time in Fæmund. During the last five years of the study period, density once again declined in West Finnmark, this time with 27 % (=−5.4 % per year) to a final density of 13.3 reindeer per km^2, which was 63 % higher than the final density in Fæmund (Fig. 2a).

The density fluctuations led to contrasting trends in meat production (Fig. 2b). While meat production in Fæmund peaked at 185 kg km^{-2} in the early 1970s and later stabilized around 120 kg km^{-2}, production in West Finnmark was generally much lower and fluctuating substantially. Production in West Finnmark nearly doubled at two occasions, first from 1973 to 1987 (83 %), then from 2000 to 2005 (94 %). The reductions in production were also strong (1987–2000: −42 %; 2000–2018: −44 %). In the last year of the period with data, the production was 54 % higher in Fæmund than in West Finnmark.

As the value of meat is kept constant during the study period, income at district level is identical to the trends in meat production (Fig. 2b). Thus, the average income over the entire study period is 10,327 NOK y^{-1} km^{-2} in Fæmund and 6211 NOK y^{-1} km^{-2} in West Finnmark, i.e., a 39.9 % higher income per km^2 in Fæmund.

The fraction of slaughtered individuals was completely different between the two districts. In West Finnmark, the highest fraction slaughtered was 37.6 %, while it was never lower than 42.1 % in Fæmund (Fig. 2c). Slaughter fraction increased with time in Fæmund, but not in West Finnmark (Table 2). Slaughter fraction was strongly correlated to density in Fæmund but not in West Finnmark (Table 2). This resulted in a strong positive relationship between reindeer density and meat production in West Finnmark but not in Fæmund (Table 2); compare trends of panels *a* and *b*. However, it is important to note that, in West Finnmark during the post-2000 population increase, meat production started to decline before peak density was reached, leading to a 36 % decline in meat per live female from 2005 to 2013 (Fig. 2d). The significant relationship between reindeer density and meat production is thus caused by pre-2000 trends.

Meat production per live adult overwintering female differed considerably between the two districts (Fig. 2d). The average productivity per live female over the entire study period was 16.5 kg in Fæmund and 6.9 kg in West Finnmark (average of all years with data). While Fæmund over time shows a strong correlation between individual live female productivity and meat production per km^2, there is no such correlation in West Finnmark (Table 2); compare trends of panels *b* and *d*.

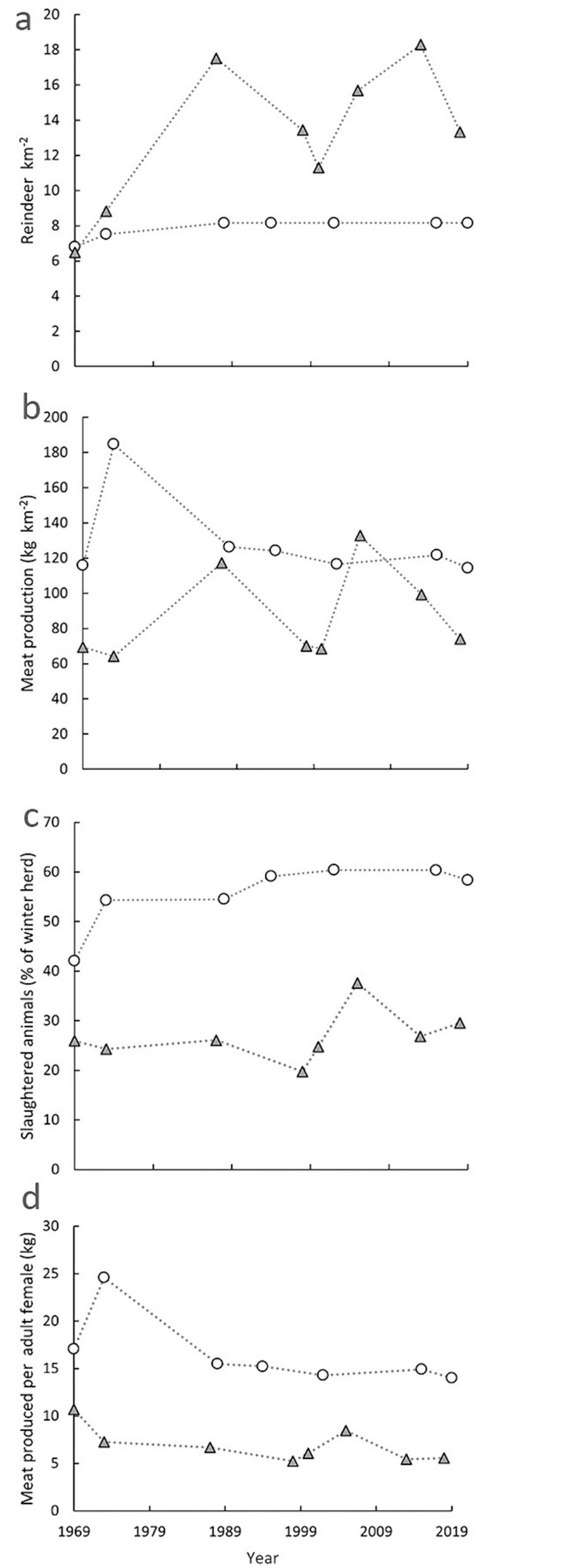

Fig. 2. Essential reindeer herding statistics from 1969 to 2019 from Fæmund (open circles) and West Finnmark (filled triangles). (a) Reindeer density (overwintering individuals per km^2 based on official statistics from 31 March each year), (b) total meat production, (c) fraction of slaughtered individuals as a function of total winter herd size (per 31 March), and (d) meat production (kg) per live adult female in the winter herd.

3.2. Changes in vascular plant, moss, lichen, and total vegetation biomass

Both study areas experienced significant biomass changes during the near 50-y study period. Total plant biomass (i.e., sum of trees, shrubs, forbs-graminoids, and moss, but excluding lichens) in the two study areas showed contrasting trends (Fig. 3a–c). In Fæmund, total plant biomass declined by 17 % from 1969 to 1988, and thereafter showed a modest, increasing trend (Fig. 3c). For the whole period, there was no change in total plant biomass (Table 2). In West Finnmark, total vascular plant biomass peaked in 2005, and showed an overall increase of 20 % for the entire study period (Fig. 3c, Table 2).

In Fæmund, none of the separate plant types changed over the entire study period ($R^2 < 0.35, p > 0.16$) (Fig. 3a). In West Finnmark, however, tree biomass increased by 67 % and shrub biomass was reduced by 4 %, while there was no change in biomass of forbs-graminoids and moss (Fig. 3b, Table 2).

Lichen biomass of the tundra areas showed contrasting trends between the two study areas. In Fæmund, it increased by 152 % from the first to the last year (Fig. 3d, Table 2), corresponding to an increase of 1.66 metric tonnes per km^2 per year. For the whole period, lichen biomass of the lichen tundra area in West Finnmark decreased near-significantly (Fig. 3e, Table 2). Lichen biomass reached a minimum in 2000. From 1969 to 2000, 85 % of the lichen biomass was lost (Fig. 3e, Table 2). From 2000 to 2005, lichen biomass increased by 470 %, until it once again declined. At the end of the study period, lichen biomass was 48 % of the biomass at the start of the study period, but still 3.2 times higher than the minimal level reached in 2000.

The relative contribution from the various vegetation layers to the total biomass showed some significant trends over time. In Fæmund, the contribution from trees to the total biomass declined from 67.6 % in 1969 to 63.0 % in 2020 (Table 2), the contribution from lichens increased from 2.7 % to 7.5 % (Table 2), whereas the relative contributions from shrubs and forbs-graminoids were constant over time (Table 2; relative contributions not shown, but interpretable from Fig. 3a).

In West Finnmark, the contribution from trees to the total biomass increased from 28 % to 48 % during the study period (Table 2). From 2005 to 2018, this contribution declined by 27 %. This decline from 2005 to 2018 may be partly related to increasing outbreaks of geometrid moths that feed on birch leaves (Table S3). The contributions from all other vegetation types to the total biomass declined over time in West Finnmark (Table 2; interpretable from Fig. 3b).

In Fæmund, total vegetation biomass (i.e., the sum of plants and lichens) was 9.7 % lower at the end than at the start of the study period, but there was no trend over time (Table 2). In West Finnmark, total vegetation biomass show a clear tendency to an increase over the study period, albeit with p-level of 0.053, i.e. slightly above the threshold at 0.05 (Table 2).

3.3. Changes in albedo and CO_2-equivalent emissions, $\sum TDEE$

Maximum albedo for both districts was recorded in the first year with albedo data, i.e., 1969 in West Finnmark and 1973 in Fæmund (Fig. 4a). In 1973, albedo at district level was 6.9 % higher in West Finnmark than in Fæmund. Albedo in West Finnmark was nearly stable from 1969 to 1980 (0.16 % decline; with an 0.13 % increase from 1972 to 1980), while Fæmund experienced a 1.40 % decline from 1973 to 1980. Albedo in Fæmund reached a minimum level in 1988 being 3.0 % lower than in 1973. In West Finnmark, albedo declined gradually from 1980, reaching a minimum level in 2000, and this coincided with the year with the lowest lichen biomass (Fig. 3c). Albedo declined by 12.3 % from 1980 to 2000. After the minima, albedo gradually increased in both districts until the end of the study period. From 2000 to 2018, it increased by 3.0 % in West Finnmark, but was still 9.9 % lower than in 1969. Albedo in Fæmund in 2020 was 0.5 % lower than in 1973 (Fig. 4a). In 2018 (the last year with data from both districts), the albedo was 2.3 % higher in Fæmund than in West Finnmark. For the whole study period, there was no linear trend in albedo in Fæmund, while there was a clear decline in West Finnmark; see grey trendline in Fig. 4a and statistics in Table 2.

The temporal variation in albedo in Fæmund was near-significantly correlated with biomass of forbs-graminoids and with total vegetation biomass, while correlations with biomass of lichens, shrubs, trees, total

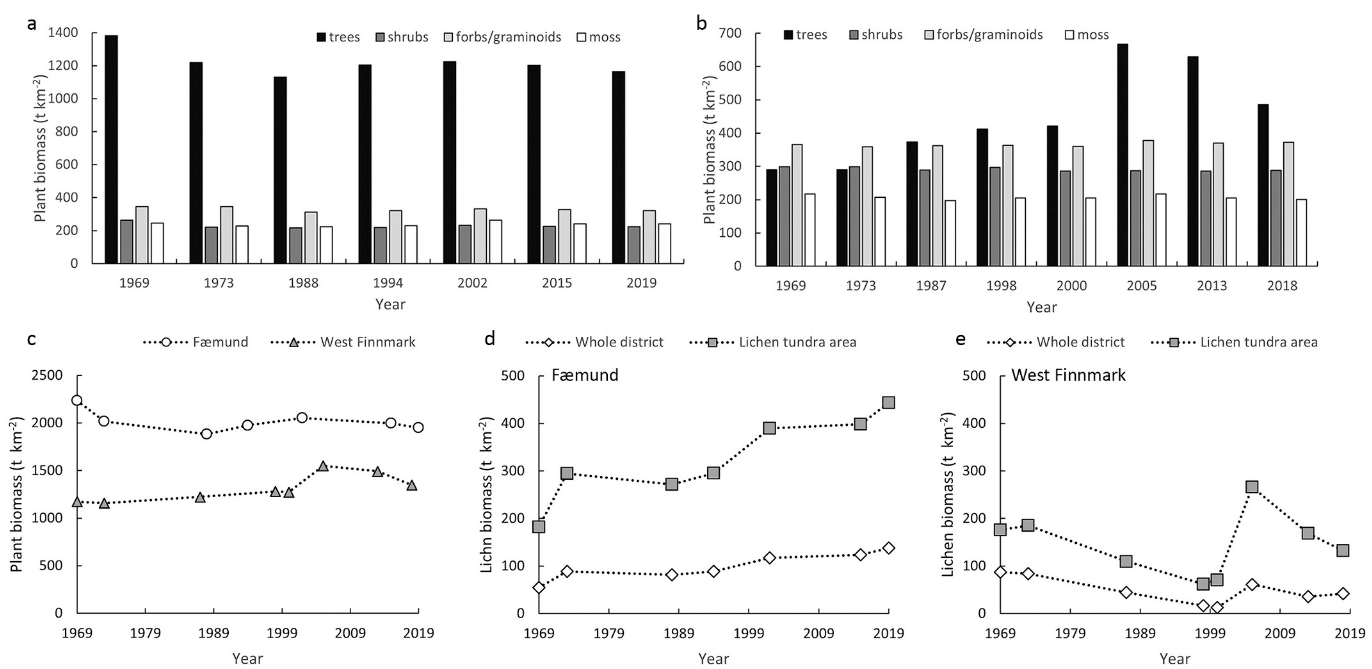

Fig. 3. Plant and lichen biomass in Fæmund and West Finnmark. (a–b) Trends in four plant cover types: trees, shrubs, forbs-graminoids and moss in Fæmund (a) and West Finnmark (b). (c) Trends in total plant biomass, i.e., sum of trees, shrubs, forbs-graminoids and moss, in Fæmund (open circles) and West Finnmark (filled triangles). (d–e) Trends in biomass of ground lichens foraged by reindeer in Fæmund (d) and West Finnmark (e) as functions of total district area (open circles) and district's lichen tundra area (filled triangles), i.e., area with >25 % lichen cover in first year of study.

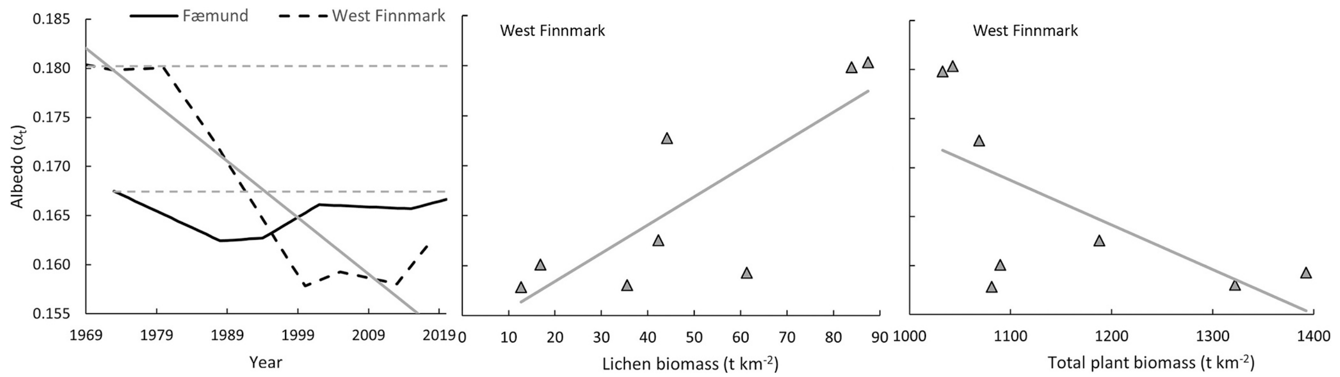

Fig. 4. Yearly surface albedo. (a) Trends in in Fæmund (solid line) and West Finnmark (stippled line). Reference (initial) values are shown as horizontal, grey stippled lines. Significant trendline for West Finnmark shown as grey, solid line (no significant trend for Fæmund). (b–c) Correlation between albedo and lichen biomass (b) and total plant biomass (c) in West Finnmark. Significant correlations with tree and shrub biomass not shown. For Fæmund, there were no significant correlations with plant cover types; see text for further information.

plant biomass, and reindeer density were far from being significant (Table 2). The best linear model for albedo had an accuracy of 96.9 % and includes two parameters, viz. biomass of forbs-graminoids and ratio of tree biomass explaining 63 and 37 %, respectively, of the model.

Albedo in West Finnmark was positively correlated with lichen biomass (Fig. 4b, Table 2) and negatively correlated with tree biomass, shrub biomass, and total plant biomass (Fig. 4c, Table 2). Reindeer density was not correlated with albedo (Table 2). The best linear model for albedo had an accuracy of 99.4 % and included three parameters, which were lichen biomass, total plant biomass and reindeer density, explaining 61, 34 and 4 %, respectively, of the model.

Given that CO_2-equivalent emission ($\sum TDEE$) is a function of albedo, it was as expected that these two parameters show nearly perfect inverse linear relationships (Table 2). $\sum TDEE$ increased at an average yearly rate of 14.35 t CO_2e km^{-2} y^{-1} in Fæmund from 1973 to 1988 (Fig. 5a). The increase continued to 1994, but at a much lower rate of 2.89 t CO_2e km^{-2} y^{-1}; i.e., an average annual increase of 1.3 %. Thereafter, it declined at an average rate of 6.1 % y^{-1} until 2002, viz. an average annual change of −14.08 t CO_2e km^{-2} y^{-1}. From 2002, $\sum TDEE$ increased very modestly until 2015 (0.14 % y^{-1}; corresponding to 0.17 t CO_2e km^{-2} y^{-1}) until another decline by 5.4 % y^{-1} (=−14.08 t CO_2e km^{-2} y^{-1}) took place from 2015 to 2020. Thus, $\sum TDEE_{1973–2020}$ for Fæmund was 89.04 t km^{-2}, viz. an average of 1.86 t CO_2e km^{-2} y^{-1}.

In West Finnmark, $\sum TDEE$ increased marginally from 1969 to 1980 with an average annual rate of 1.22 t CO_2e km^{-2} y^{-1} (Fig. 5b). From 1980 to 2000, it increased rapidly and near-linearly from 13.4 t km^{-2} to 921.7 t km^{-2} (note data points also in 1987 and 1998), which means an average yearly increase of 134 % (=45.41 t CO_2e km^{-2} y^{-1}). From 2000 to 2013, $\sum TDEE$ increased by 13 % (=12.18 t CO_2e km^{-2} y^{-1}) and was followed by a decline of 10 % from 2013 to 2018 (=−21.02 t CO_2e km^{-2} y^{-1}). Overall, $\sum TDEE_{1969–2018}$ for West Finnmark was 974.93 t km^{-2}, equivalent to 19.90 t CO_2e km^{-2} y^{-1}.

Considering the various vegetation components, trends in $\sum TDEE$ were significantly correlated with changes in biomass of forbs-graminoids in Fæmund, but not to biomass changes in any of the other vegetation components (Table 2). Trends in $\sum TDEE$ in West Finnmark were most closely correlated with changes in tree biomass (Fig. 6b, Table 2). The relationships with lichen biomass (Fig. 6c) and yearly lichen production were also significant (Table 2). The declining $\sum TDEE$ trend from 2013 to 2018 is associated with a 17 % increase in lichen biomass and a 23 % reduction in tree biomass.

The best linear models for trends in $\sum TDEE$ have high accuracy in both districts. For Fæmund, the model accuracy is 99.7 % and consists of two parameters, viz. albedo and forbs-graminoids explaining 90 and 10 %, respectively. The best model for West Finnmark is explained by albedo alone and has an accuracy of 95.3 %. Excluding albedo from the modelling reduces the accuracy of the best model to 63.6 % in Fæmund, with forbs-graminoid biomass as the only predictor, and to 89.9 % in West Finnmark, which includes the ratio of lichen biomass, and forb-graminoid biomass, explaining 71 and 29 % respectively of the model.

3.4. Economics of the carbon dioxide equivalent

The 11-fold difference in $\sum TDEE$ per km^2 between the two study areas result in similarly large differences in the accumulated social costs of CO_2-eq. The mean annual costs of CO_2-eq. are 12,216 NOK km^{-2} y^{-1} in West Finnmark and 1163 NOK km^{-2} y^{-1} in Fæmund (Table 3). The aggregated economic costs for each of the two districts are strongly

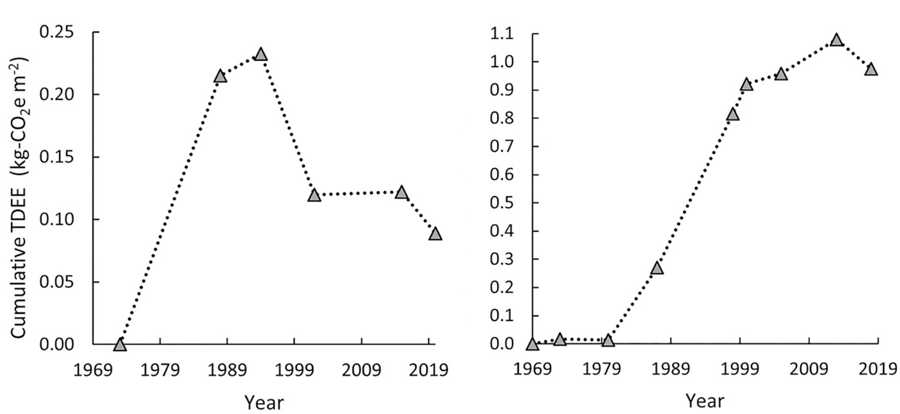

Fig. 5. Accumulated CO_2-equivalent budget ($\Sigma TDEE$) over time in Fæmund (a) and West Finnmark (b), where increasing trends are equivalent to CO_2 emissions and declining trends are equivalent to CO_2 removals. Note different scales in *a* and *b*.

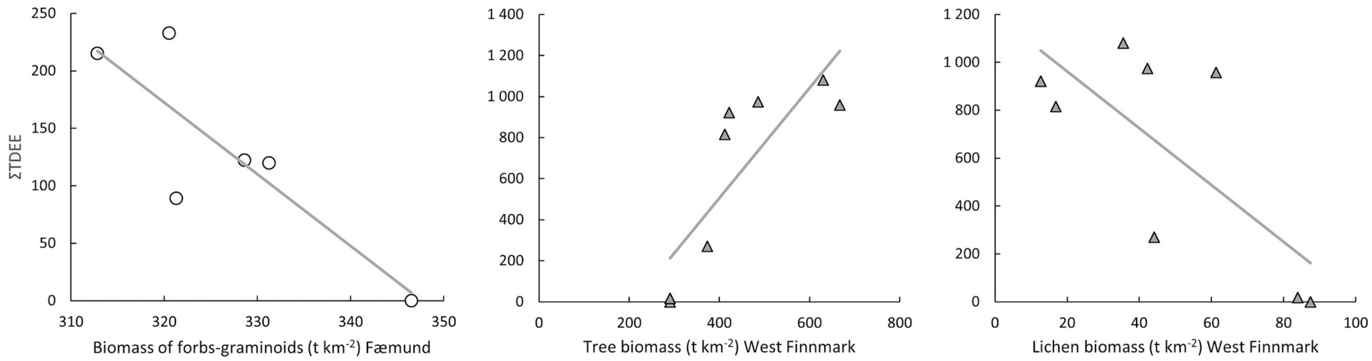

Fig. 6. Relationships between cumulative CO_2-equivalent emissions ($\sum TDEE$) and biomass of vegetation layers. Only significant linear correlations are shown. (a) Biomass of forbs-graminoids in Fæmund, (b) tree biomass in West Finnmark, (c) lichen biomass in West Finnmark.

Table 3
Social costs of CO2-eq. in Fæmund and West Finnmark in NOK and its equivalence to meat production. See Fig. 2 for average meat production per slaughter animal.

Unit	Fæmund	West Finnmark
Time (y)	47	49
$\sum TDEE$ (t km^{-2})	89.04	974.93
CO_2-eq. (t km^{-2} y^{-1})	1.89	19.90
CO_2-eq. cost (NOK)	614	614
CO_2-eq. cost (NOK km^{-2} y^{-1})	1163	12,216
CO_2-eq. cost (NOK district^{-1} y^{-1})	1,283,016	70,904,165
Meat value (NOK kg^{-1})	80	80
Meat per slaughter animal (kg)	14.8	6.2
CO_2-eq. cost (kg meat km^{-2} y^{-1})	14.5	152.7
CO_2-eq. cost (t meat district^{-1} y^{-1})	16.0	886.3
CO_2-eq. cost (slaughter animals km^{-2} y^{-1})	0.98	24.63
CO_2-eq. cost (slaughter animals district^{-1} y^{-1})	1084	142,952

influenced by the 5.3 times larger size of West Finnmark; and the annual costs are 70.90 MNOK for West Finnmark and 1.28 MNOK for Fæmund.

The annual global damage costs of CO_2-eq. correspond to the value of 152.7 kg of reindeer meat per km^2 in West Finnmark and 14.5 kg per km^2 in Fæmund (Table 3). Given the average meat produced per live female during this period, the annual costs of CO_2-eq. correspond to the loss of 24.6 live females per km^2 in West Finnmark, and 1.0 live females per km^2 in Fæmund (Table 3). At district level, these values correspond to an average annual loss of 142,952 live females in West Finnmark and 1084 live females in Fæmund.

3.5. *Economics of biomass change and productivity*

By applying the general 3.67:1 relationship between CO_2 absorption and carbon storage in the biomass, the variation over time in total aboveground biomass is expressed in CO_2-eq.: the 13.9 % biomass accumulation in West Finnmark from 1969 to 2018, corresponding to 842,093 t, has a district-level CO_2-eq. value of 517.0 MNOK, which equals 1818 NOK per km^2 per year (Table 4). The 9.7 % difference in total biomass from the first to the last year in the time series from Fæmund was far from significant; see above, and there is therefore no costs or gains.

Biomass productivity from both lichen and green vegetation, expressed in FUs, show that there was an 81.5 % higher productivity per km^2 in Fæmund than in West Finnmark ("Forage productivity" in Table 4).

3.6. *Economics of all valued ecosystem services*

The monetary values from changes in the four assessed ESs are summarized in Table 4. There were clear gains from two provisioning services in both districts, but the gain per km^2 was 75.5 % higher in Fæmund (Table 4; row a). Forage productivity was 4.9 (West Finnmark) and 5.5 (Fæmund) times more valuable than meat production per unit area. There were costs associated with the regulating services in both districts (Table 4; row b), and these costs were 8.9 times larger in West Finnmark per unit area.

Table 4
Economic value per km^2 and for each district of the provisioning (a), regulating (b) and for both (c) ecosystem services in Fæmund and West Finnmark districts. Positive signs are gains and negative signs are costs[a]. Units are in NOK y^{-1}.

Ecosystem service value (in NOK y^{-1})	Fæmund		West Finnmark	
	Km^2	District	Km^2	District
a) Provisioning ESs				
Meat production	10,327	11,390,681	6953	40,356,063
Forage productivity	56,619	62,450,804	31,188	181,014,328
Total value provisioning ESs	66,946	73,841,485	38,141	221,370,391
b) Regulating ESs				
Social costs of CO_2-eq. from $\Sigma TDEE$	−1163	−1,283,016	−12,216	−70,904,165
Aboveground carbon accumulation[b]	0	0	1818	10,551,672
Total value regulating ESs	−1163	−1,283,016	−10,398	−60,352,493
c) Total value both ES types	65,783	72,558,738	27,743	161,017,898

[a] Note change of sign direction from Table 1 where positive values were costs.
[b] Trend in West Finnmark (p = 0.053) is here considered significant.

As the economic benefits of the provisioning ESs were larger than the costs of the regulating ESs, the current reindeer management passed the benefit-cost test. There was a net economic benefit in both districts, which was 237 % larger per km^2 in Fæmund than in West Finnmark, i.e., nearly 66 KNOK per km^2 per year in Fæmund vs. nearly 28 KNOK in West Finnmark (Table 4; row c).

3.7. *Identification of external drivers of fluctuations in reindeer populations and forage resources*

For the study period, in total 13 natural and man-made events with potential impacts on reindeer herding practices and reindeer density were identified (Table S3). For example, the snowmobile revolution starting in 1965 facilitated extended herding range, and hence increased availability to forage resources that previously were too remote. This can be linked to the increasing population sizes in both district from the late 1960s to the late 1980s (see Fig. 2a). The two periods of declining population trends in West Finnmark (1988–2000 and 2013–2018) were largely a consequence of increased winter mortality from severe winter conditions and of government-induced stock reduction programmes. These connections between herding situation and events are treated further in the Discussion.

4. Discussion

This assessment of diverging trends in density of herded reindeer populations has shown major impacts on the rangeland's core ecosystem services. While one generally could expect trade-offs between provisioning and regulating services from northern lands (see Introduction), our analysis of time series covering five decennia identifies previously unknown relationships between provisioning and regulating services.

4.1. Relationship between reindeer meat production and state of vegetation

The moderate and stable reindeer density in Fæmund resulted in much higher income from provisioning services than in West Finnmark, where reindeer density fluctuated much during the study period – thus, confirming our first hypothesis. The 149 % higher meat production per unit area in Fæmund than in West Finnmark is largely explained by the stable and more predictable forage resources in Fæmund (Johansen et al., 2019; Tømmervik et al., 2009, 2021) with their cascading effects on calf birth rates and individual body weights (Tyler, 2010; Tveraa et al., 2022).

While meat production for own use and for sale is the essential final product from reindeer herding, the vegetation's ability to regrow and produce new forage for reindeer is in both districts the most valuable of the two provisioning ESs. Without this extensive regrowth, the fundament for sustainable, ecological reindeer herding (i.e., no supplementary feeding with pellets, hay, or silage) would dwindle. In other words, the forage productivity is the reindeer herders' main assets for future investments. The 6 NOK price per FU applied here was based on official statistics (Tømmervik et al., 2022), and it is likely that the price will increase in line with the general price increase of animal fodder and steadily increasing need for supplementary feeding in European reindeer herding (Åhman et al., 2022). Overall, the 178 % higher forage productivity per unit area in Fæmund is a clear indication that moderate and stable reindeer density contributes to long-term sustainability.

As winter is the most critical season for survival of reindeer (Tyler, 2010; Turunen and Vuojala-Magga, 2014), lichen tundra is the most valuable vegetation type for reindeer herding. Therefore, it would be reasonable to apply a higher price per FU of lichens than per FU of green plants. With such price differentiation, there would be even larger district-level contrasts in gains from vegetation productivity, since lichen biomass increased in Fæmund but declined in West Finnmark over the study period. However, reliable economic valuation of lichen FUs is challenging and would require a separate study.

4.2. Valuation of climate-regulating ecosystem services from vegetation change in reindeer grazing lands

The two climate-regulating ESs valued here are linked to vegetation properties. Carbon stored in aboveground biomass changed little (West Finnmark) or was constant (Fæmund) over the study period, hence contributing only modestly or nothing to the change in economic value of the ESs. However, the time-dependent emissions equivalent from change in albedo ($\Sigma TDEE$) contributed considerably to the overall value of the assessed ESs. Reduction in albedo led to negative $\Sigma TDEE$ (= costs) in both districts, but 10.5 times higher costs per unit area in West Finnmark than in Fæmund. In fact, the costs of changes in $\Sigma TDEE$ in West Finnmark were 176 % higher than the gains from meat production. While the potential climate-regulating importance of the high albedo from light-coloured ground lichens has been emphasized previously (e.g., Bernier et al., 2011), to our knowledge, this is the first time $\Sigma TDEE$ is measured from lichen-rich ecosystems and converted into monetary terms. This pricing system has primarily been assessed in relation to forest management (Bright et al., 2016, 2020), while CO_2-equivalency metrics form an integral part of emission reporting and climate agreements; see summary in Bright and Lund (2021).

In West Finnmark, $\Sigma TDEE$ was best explained by a combination of increase in tree biomass and declines in lichen biomass, which were inter-connected. The increase in woody biomass is largely an effect of declining lichen biomass because lichen removal increases the success rate for windborne birch seeds to reach to open soil where they can germinate (Sedia and Ehrenfeld, 2003; Tømmervik et al., 2009). In an intact lichen-dominated ecosystem, seeds land on top of the lichen mat and will rarely reach to the soil layer. Increased precipitation may be a secondary factor for increasing tree biomass (Tømmervik et al., 2019). Overall, the rapidly declining lichen biomass is the primary factor for the very high CO_2-equivalent costs from albedo change reported here for West Finnmark. The budget for the two climate-regulating service shows an overall cost in both districts, but with 8.9 times higher costs per unit area in West Finnmark, confirming our second hypothesis.

4.3. Joint valuation of provisioning and regulating ecosystem services

For the provisioning and regulating ESs assessed together, Fæmund experienced a 137 % higher income per unit area than West Finnmark. As the social (economic) benefits of the provisioning services were higher than the social costs of the regulating services, the net social benefits for both districts were positive, and they passed the benefit-cost test. However, the district with near-stable reindeer densities had much higher income from provisioning services and much lower costs from regulating services per unit area than the district with highly fluctuating reindeer densities, confirming our third hypothesis. This reveals that, by facilitating stable, moderate reindeer densities, it is possible to minimize the trade-offs between local economic optimalisation of income from reindeer herding and global interests in terms of climate-regulating services. Such management schemes, which can be maintained through reducing populations densities and/or increasing internal rotation of winter pastures, have been argued for previously, but then primarily from the perspective of stable, sustainable animal populations (Andrejev, 1977; Mysterud, 2006; Stark et al., 2023). We here see that such management has wider-ranging impacts by also contributing to slowing down climate change. It possibly also leads to increasing value of cultural ESs.

4.4. Potential effect on cultural and other non-valued ecosystem services

This study focussed on the primary provisioning and regulating ecosystem services from reindeer rangelands, while ESs not accounted for here include additional products from reindeer other than meat, i.e., clothes and handicraft made from fur, blood as an additional food ingredient, and antlers which are sold intact or modified and used in handicraft and art (Blicharska et al., 2017; Sara et al., 2022). The income from these additional materials were not possible to quantify. However, it is likely that the income from such products is minor compared to the value of meat. Still, these materials have been invaluable for the Sámi reindeer herding communities since all winter garments traditionally were made from fur. Thus, their traditional livelihood would not have been possible without the fur, and the clothing is hence an important part of their cultural identity (Svensson, 1992).

For other ESs, there could be synergies with the ESs valuated here. For example, increased ecotourism and net income to tour operators, recreational use of herding areas, and sale of handicraft are activities that render income to reindeer herding families (Viken and Müller, 2006; Olsen, 2015). On the other hand, tourists and recreationists can have negative effects on provisioning and regulating services through disturbance to both reindeer and vegetation (Olsen, 2015). Further, the cultural ES value of Sámi culture could also be negatively affected by increasing intervention from tourists and recreationists (Müller and Huuva, 2009). Overall, it is likely that the values from handicraft, arts, tourism, and cultural identity are closely correlated with meat income. After all, in periods with starving reindeer and/or high mortality, it is not only meat production that is affected – the quality and quantity of side products such as fur, blood and antlers would also be reduced, and this again would potentially affect both tourism and cultural identity negatively. Thus, if the economic value of these services could have been estimated, the difference in ES values between the two study areas would have increased even further.

We studied the CO_2-equivalence from changes in summer albedo. Extending the albedo studies to include the winter season would probably have further increased the contrasts between the two districts for this ES, because low-stature lichen-dominated heath and tundra facilitate the build-up of a landscape-wide uninterrupted snow layer with high reflectance, while forests and shrubland are full of dark spots also in winter and spring from all the woody vegetation that only occasionally are draped in snow (Cohen et al., 2013). These dark trunks of trees and shrubs also contribute to earlier landscape-wide snowmelt in spring, since trunks that protrude through the snowpack and are warmed up by the sun and radiate heat to the adjacent snowpack, and from these melting points near trunks, the melt process extends to the snowpack further away from trunks (Vikhamar and Solberg, 2002).

Concerning methane emissions from reindeer digestion, it is favourable to balance the use of lichen pastures such that the intake of lichen is lower than the lichen recovery rates, thus minimizing the need for supplementary feeding with pellets and hay (Stark et al., 2023). Such sustainable use of lichen mats will reduce methane emissions from reindeer herding (Hansen et al., 2018) and reduce costs for supplementary feeding. During the winter 2019–2020, supplementary and extraordinary feeding in West Finnmark was accounted to ca. 10 MNOK in state subsidies alone (Norwegian Agriculture Agency, 2021b).

4.5. Climatic events and governmental actions affecting herd densities

The trends in reindeer densities presented here are a result of multiple factors, where management is only one factor (Riseth et al., 2016; Skonhoft et al., 2017). In Table S3, we summarized key climatic events and governmental management regulations. This summary shows that West Finnmark has been exposed to several winters with challenging grazing conditions, i.e., either very deep snow or rain falling on snow resulting in ground-ice, or a combination of these two types of events leading to a thick snowpack with ice layers. When such events occur in periods with above-average reindeer densities, high mortality is the unavoidable result. To our knowledge, Fæmund has not been exposed to such numbers of challenging winter conditions as West Finnmark during the study period. This may partly explain why it has been possible to maintain such a stable density level over this long period. That said, the snowpack was hard during the winter 2019–20 in Fæmund, but meat production was only modestly affected, since the reindeer was in good condition due to moderate density (Norwegian Agriculture Agency, 2021a, 2021b).

4.6. Implications for management

Climate change will make herding even more challenging in the future (Stark et al., 2023). Under such scenarios, avoiding large population fluctuations will be a prerequisite to maintain viable reindeer populations and stable meat production. This study shows that it is indeed possible to boost both provisioning and regulating services from reindeer herding rangelands through systematic directed management, as the reindeer density regulation in Fæmund, or as a sustainable winter grazing rotation regime (i.e., annual shifts of winter grazing areas in 3-year cycles) to maintain an optimal abundance of lichen cover, as proposed in Stark et al. (2023). Managing for achieving population stability at moderate, sustainable density will further result in predictable forage resources, which will improve the herders' adaptability to periods of harsh winter conditions, with positive ripple effects on private finances and well-being, and it will increase the value of indigenous cultural ecosystem services. In an era when climate-regulating services from rangelands are becoming increasingly important, the results from this case study are potentially highly valuable for the management of reindeer herding and wild reindeer populations elsewhere, for example in the neighbouring countries (Sweden, Finland and Russia) and domestic reindeer and wild reindeer/caribou in North America, and may also be useful for management of other types of rangelands for wild and domesticized herbivores.

5. Conclusion

This study aimed at assessing the relative importance of provisioning versus regulating ecosystem services from indigenous Sámi reindeer herding communities. To that end, 50-year long time series of food production and vegetation state were applied, comparing a rangeland with large fluctuations in herd density with a rangeland with moderate and stable density. Values of both provisioning and climate-regulating ecosystem services were remarkably higher in the rangeland with stable density, and the economy of this rangeland was also shown to be much less susceptible to the adverse effects of harsh weather events. Agreeing on a given density for a rangeland and being able to follow up that agreement, or a sustainable winter range rotation regime, over a 50-year period is only possible with mutual understanding of its importance and with good communication between herders. *Trust* is a key for such long-lasting mutual work towards a common goal, and public administration at various levels is a central actor in the building and maintaining of trust. While local administration may be mostly concerned with sustainable delivery of locally produced provisioning services, national authorities concerned with international climate policy will potentially find the high delivery of climate-regulating services as valuable. Thus, extensive collaboration between national and local administrations are vital for continued delivery of both provisioning and regulating services.

CRediT authorship contribution statement

Jarle W. Bjerke: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kristin Magnussen:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ryan M. Bright:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis. **Ståle Navrud:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Rasmus Erlandsson:** Writing – review & editing, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Eirik A. Finne:** Writing – review & editing, Methodology, Data curation. **Hans Tømmervik:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data applied in this study are publicly available, and all sources are properly cited in this submission.

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Appendix A. Supplementary data

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