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Climate change and reindeer herding – a bioeconomic model on the economic implications for Saami reindeer herders in Sweden and Norway

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Abstract

The Arctic is warming three times faster than the global average. Rising temperatures could reduce the snow-covered season and increase plant productivity in the spring, fall and summer. While this may increase carrying capacity and growth of semi-domesticated reindeer, rising temperatures could also lead to an increase the frequency of ice-locked pastures, negatively affecting reindeer body mass, survival and reproductive success. We create a stage-structured bioeconomic model of reindeer herding that incorporates two counteracting effects of climate change on reindeer growth, reproduction, and survival. The model is calibrated using historical data on reindeer numbers and slaughter weights, in combination with weather data. We find that one more day with ice-locked pastures has a greater negative impact than the benefit of earlier spring. Then the model is used to simulate the economic impact of three climate change scenarios, and four areas in Norway and Sweden. All areas experience an improvement in herding profits in the Paris Agreement scenario. In the BAU scenario, the impact of climate change is negative for all areas. We also find that the potential loss in pasture related to certain emission mitigating policies may be more detrimental to reindeer husbandry than climate change itself.

Key words: reindeer husbandry, climate change, commons, livestock, food limitation

JEL codes: Q24, Q54

1. Introduction

Climate change is expected to lead to dramatic changes in living conditions in the Arctic. The main changes include rapidly shifting warm and cold periods during the winter coupled with a year-round increase in precipitation intensity, which are expected to result in increased frequency of wet weather, deep snow, and ice crust formation (Kelman and Næss, 2019). On the other hand, increased temperatures may also lead to earlier snow smelt and onset of spring, and improved plant productivity (ACIA 2005).

The impact of climate change is already evident in many natural resource dependent Arctic societies, and perhaps especially so for indigenous communities (Furberg et al. 2011). Saami reindeer herders in Norway and Sweden live close to nature and are directly exposed to the effects of climate change. Reindeer graze on natural pastures throughout the year following a migratory pattern between winter and summer grazing areas (e.g. Johannesen and Skonhoft 2009, Pape and Löffler 2012). Traditional reindeer herding following this seasonal pattern can be traced back to the 15th century when entire herds of wild reindeer were domesticated and parts of the Saami people became herding nomads (Bostedt 2005; Johansen and Karlsen 2005; Riseth 2006). Since then, reindeer herding has developed from a fully nomadic practice where all parts of the reindeer were utilized for subsistence to today's motorization of daily work and heavier focus on meat production to put to market (Riseth 2006). Despite this development, for many Saami communities, reindeer herding is an important way of practicing and sustaining Saami culture (Bostedt 2005; Johannesen and Skonhoft 2009, 2011), and the central governments in Norway and Sweden emphasize the cultural value of reindeer herding in both official statements and through different types of subsidies and compensation schemes (e.g., Riksdagens Revisorer, 1996; St.prp Nr.63 (2007-2008)).

Although the reindeer herders of today use modern equipment, the basic migration pattern, where reindeer are allowed to follow their yearly cycle and search for natural grazing grounds, has not changed, which means that climate change affects reindeer herding conditions both in the summer and winter grazing seasons. Winter grazing conditions are limiting factors for survival and productivity of reindeer (Tveraa et al. 2003). Snow depth, hardness of the snow and ice layers affect access to the vegetation below and hence the energy intake of reindeer (Kitti et al. 2006). Difficult winter conditions are found to lower animal weights, the number of calves born and surviving the following spring, and adult survival (Helle and Kojola 2008; Kitti et al. 2006; Kumpula and Colpaert 2003; Turunen et al. 2009; Tveraa et al. 2003). To some extent, reindeer can respond to such difficult winter conditions by digging through the snow to reach the plants below, move to areas where there is less snow, or change their diet to forage what remains exposed above the snow (Tyler 2010). However, as described by herders themselves, the ability to adapt to climate change is restricted by loss of pastures through various forms of land use change, such as forestry, settlement, and industrial development (see Fohringer, et al., 2021; Kitti et al. 2006; Linkowski, 2017; Stoessel et al. 2022; Turunen et al. 2009; Turunen et al. 2016; Tyler et al., 2021; Uboni et al. 2020).

The spring, summer and autumn grazing season is when reindeer gain weight. It is expected that climate change will cause snow to melt earlier in the spring and prolong the vegetation-growing season (Markkula et al. 2019) and in the autumn, the frost will be delayed, and soil frost and snow cover will appear later than before (Loe et al. 2021). Such changes have also been reported by reindeer herders themselves (Furberg et al. 2011). Earlier onset of spring is expected to provide additional forage and increase reindeer weights (Aikio and Kojala 2003; Albon et al. 2017; Bårdsen and Tveraa 2012; Pettorelli et al. 2005; Tveraa et al. 2013) and reproductive success (Aikio and Kojala 2003). On the other hand, delayed autumnal frost may cause waters to freeze later making migration to winter grazing areas more difficult (Furberg et al. 2011).

Climate change is just one of several external factors causing challenges and concern in Saami reindeer herding. Roughly 40% of the mainland in Norway and Sweden is designated reindeer pasture (Moen 2008; Tyler et al. 2007), see Figure 1. However, user rights to these areas are not exclusive to reindeer herders nor are the rights of reindeer herders protected from other land uses (Tyler et al. 2007). Over time, human activities and land use changes have caused a major decline in traditional reindeer grazing areas. In Norway, it is estimated that undisturbed pastures have decreased by 71 % during the twentieth century until present, whereas in Sweden the most productive areas are reduced by 70 % (Tyler, et al. 2021; Uboni et al. 2020). This loss is a result of a development over time where land has been converted to commercial forestry, roads and railroads, mining, tourism and private cabins, and industrial development piece by piece (Stoessel, et al. 2022; Tyler et al. 2021). Since the 1990s, there has been an increase in the number and size of wind farms motivated by governmental policies and subsidies to increase the production of renewable energy to meet national targets for reduced carbon emissions (Eftestøl et al. 2023). Wind farms are usually established in remote areas and increased future production may lead to further fragmentation and disturbances in reindeer grazing areas (Eftestøl et al. 2023). Thus, some national measures to reduce carbon emissions may reduce climate change but also further reduce reindeer grazing areas.

The contribution of this paper is twofold. First, we examine possible economic consequences of climate change for Saami reindeer herders in Norway and Sweden where the main contribution is to analyze the relative importance of future changes in winter and summer climate conditions. In doing so, we use a modified version of the simple age- and sex-structured reindeer herding bioeconomic model in Johannesen et al. (2019) and expand the model by including a climate-animal weight relationship. We estimate the climate-weight relationships using historical data on reindeer weights and various climate factors. We then insert the estimates into the bioeconomic model and apply the model to simulate possible future economic effects in reindeer herding using existing climate projections from the CMIP6 multi-model dataset (Eyring et al. 2016). When projecting the impact of future changes in the climate variables, we use the bioeconomic model to simulate the impact of three different climate change scenarios, i.e., an optimistic scenario corresponding to 1.5 °C in mean global temperature from the Paris agreement, an intermediate scenario corresponding to a 2.6 °C increase in mean global temperature, and a pessimistic scenario corresponding to a business as usual future with fossil fuel driven future development (Riahi et al. 2017). These will from now on be referred to as the Paris-scenario, the intermediate scenario, and the business-as-usual (BAU) scenario, respectively. To the best of our knowledge, no other studies using historical weather conditions and projected future climate variables exist for reindeer herding.

Related bioeconomic modelling contributions include Pekkarinen et al. (2022) who analyzed effects of changing winter climate conditions in reindeer herding in Finland. Their model is an extension of the extensive age-structured reindeer-vegetation model developed by Tahvonen et al. (2014) and Pekkarinen et al. (2015). Using knowledge from reindeer herders in Finland describing frequency, causes and consequences of difficult winter conditions, Pekkarinen et al. (2022) interpreted difficult winter conditions as deep and compact snow cover and extensive icing. They model difficult winter conditions as reducing the vegetation availability during winter but also as protecting winter pastures from grazing and thereby increase future vegetation biomass. The latter effect dampens the direct negative effect of a difficult winter, but they find that the net effect on net revenues is negative.

The theoretical model used in the present paper is simpler than Pekkarinen et al. (2022) in two ways: One, instead of modelling vegetation growth, we estimate the climate-weight relationships based on existing data and impose resulting estimates into the bioeconomic model, and, two, the number of age classes is limited to calves and adult animals according to the existing statistics on animal weights.

The second contribution of our paper is to add to ongoing discussions on pasture degradation due to conflicting land uses and their interaction with climate change (e.g. Bergius et al., 2020; Froese and Schilling 2019; Pape and Löffler 2012). We consider the case of establishing wind farms in reindeer herding areas to fulfill national goals on reduced CO2 emissions. This is a highly relevant and ongoing conflict in both Norway and Sweden, which is likely to increase in the future, as rural areas identified as advantageous for future wind power development in terms of wind conditions, overlaps with several reindeer herding areas (Knezevic et al. 2023, Szpak, 2019; Wretling et al., 2022). In this paper, we include a simulation where we allow for wind farms to reduce the carrying capacity of the pasture and then measure the tradeoff in the economics of reindeer herding between dampened climate change and reduced pasture area.

The rest of the paper is organized as follows. Section 2 gives a brief overview of Saami reindeer herding in Norway and Sweden. Because projected impacts of climate change differ across regions within countries and between the two countries, we analyze and compare economic effects across regions. Regions are defined in Section 2. Section 3 present a bioeconomic optimization model where the objective is to maximize net present profits in reindeer herding. That is, we ignore any cultural values or other non-marketed values inherent in reindeer herding (see, e.g., Bostedt (2005) and Johannesen and Skonhoft (2011)). Section 4 presents data on historical weather, climate projections, and reindeer weights, before estimating the climate-weight relationships. In Section 5, the estimates are inserted in the bioeconomic model together with existing climate projections to simulate possible future impact of climate change on profits in reindeer herding. This section also includes an analysis of the potential tradeoff involved in green energy production to reach national goals for carbon emissions. Finally, section 6 concludes the paper.

2. Saami reindeer herding in Norway and Sweden

Reindeer herding in Norway and Sweden is a traditional livelihood in several indigenous Saami communities. The reindeer are allowed, with some exceptions, to follow their yearly cycle in search for natural grazing areas, allowing grazing areas to replenish themselves as the reindeer move from winter grazing areas to summer grazing areas and back again. Therefore, reindeer herding requires large areas and in both Norway and Sweden, the Reindeer Husbandry Act gives Saami reindeer herding user rights to approximately 40 % of the land area (Tyler et al. 2021; Moen 2008).

2.1 Saami reindeer herding in Norway

In Norway, the Norwegian Reindeer Herding Act provides the Saami user rights to practice reindeer herding. Saami reindeer herding takes place in six administrative reindeer herding regions, from Trøndelag (consisting of South-Trøndelag and North-Trøndelag regions) in mid Norway to Finnmark (consisting of West-Finnmark and East-Finnmark regions) in far north. Finnmark is the main reindeer herding region, covering some 70% of the herding units and the reindeer population (NRHA 2022). Nationally, there are about 540 reindeer herding units and in total 3 300 people are involved in the industry (NRHA 2022). The total reindeer population counts some 220,000 animals (NRHA, 2022).

The migration pattern of reindeer varies across regions according to differences in climate, landscape and vegetation. Winter climate depends on elevation and distance to the coast, with wet and variable coastal winter climate being less favorable than a drier and stable winter climate in continental areas (Tveraa et al. 2007). In Finnmark, reindeer migrate across huge areas between summer and winter pastures (see Figure 1). Here, herds migrate from lush summer pastures close to the sea with mild climate and high precipitation to interior winter pastures in open mountainous areas where a dry, cold and stable climate and relatively shallow snow depth traditionally have provided good access to food (Tveraa et al. 2007; Weladji and Holand 2003). Reindeer herding in Trøndelag in mid Norway is more stationary with some populations having winter and summer pasture within the same geographical area, and some populations with shorter migration between inland winter and coastal summer pasture (Weladji and Holand 2003). In the remaining reindeer herding regions, Nordland and Troms, winter pastures are found in coastal areas where the climate is less favorable with mild temperatures and high precipitation (Risvoll Hovelsrud 2016; Tveraa et al. 2007; Weladji and Holand 2003).

Reindeer herding is a small economic activity relying mainly on meat production. The industry produces about 1700 tons of reindeer meat yearly, which amounts to 2 percent of the total production of red meat in Norway (NRHA 2022b, Statistics Norway 2015). Still, reindeer husbandry is of great importance to the Saami people, both culturally and economically (Johannesen and Skonhoft 2009) and nationwide for sustaining indigenous people's rights (Akhtar 2022). For many herders, cultural values are important when choosing to make a living through reindeer husbandry, and these values seem to be valued just as highly, and probably higher, than the income opportunities the industry provides (Johannesen and Skonhoft 2009).

Reindeer productivity measured by slaughter weights and income varies substantially across regions, with mid Norway (Trøndelag, dark green area in Figure 1) being among the best performing areas over time (NRHA 2022; Skonhoft et al. 2017). Even though the climate in both mid Norway and the northernmost Norway (Finnmark) is favorable for reindeer herding, productivity and the economy in reindeer herding differ substantially between the two areas. This is often explained by stronger internal cooperation between herders in mid Norway on the use of common pastures and on adjusting the size of the populations to the vegetation biomass (Skonhoft et al. 2017). In Section 6, to simplify the analysis of the future climate scenarios, we consider two stylized reindeer herding areas, denoted as mid Norway (Trøndelag, dark green area in Figure 1) and north Norway (Nordland, Troms and Finnmark, blue area in Figure 1).

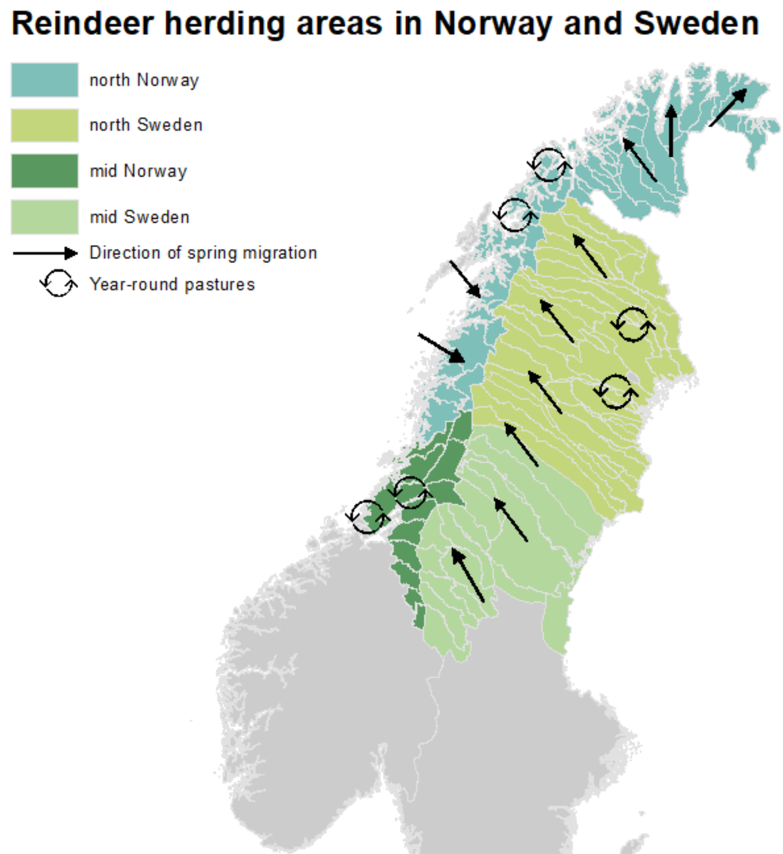

Figure 1 Reindeer herding regions and reindeer herding communities in Norway and Sweden, respectively. The colors indicate the four simulation areas. Arrows indicate spring migration and year-round pastures (Source: Pape and Löffler, 2012)

2.2 Saami reindeer herding in Sweden

The approximately 4700 individual Saami reindeer herders in Sweden are organized into 51 Saami villages, or reindeer-herding communities (RHCs), which are both geographical entities and economic organizations for reindeer herders. Each RHC have grazing rights in a specific area, and together all the 51 RHCs encompass virtually all the land in the two northernmost counties in Sweden, Norrbotten and Västerbotten, and large parts of Jämtland and Dalarna counties. The total reindeer populations counts about 250,000 to 300,000 animals (Sametinget, 2021).

Reindeer husbandry may be conducted all year round in the counties of Norrbotten and Västerbotten above the cultivation boundary[1] and above the Lapland boundary within the forest Saami villages, on the reindeer grazing mountains in Jämtland county and in specially leased areas in Jämtland and Dalarna counties (the light green areas in Figure 1). In winter (1 Oct - 30 April), reindeer husbandry may also be

[1] The cultivation boundary in Sweden is an administrative border that runs through Lapland from northeast to southwest below the mountain area. It was intended partly as a boundary for the spread of agriculture to the west, and partly to protect the interests of the reindeer herding industry. Today, the cultivation boundary is important for several provisions in the Reindeer Husbandry Act and for some laws that regulate hunting and fishing.

conducted in Norrbotten and Västerbotten in other areas above the Lapland border and otherwise as far east as it has been conducted by age . On the Norwegian side, reindeer herders from Sweden may, in accordance with Norwegian law, conduct reindeer husbandry in the summer in areas that are established in a convention between Sweden and Norway. In fact, north of Lake Torneträsk, the majority of the Saami villages' spring and summer grazing areas are on the Norwegian side of the border.

Of the 51 RHCs in Sweden, 33 are the mountain Saami communities (Sametinget, 2021). This is the type of Saami community that is most well-known and where the reindeer herds are migratory. Typically, the herds graze in pastures close to or in the mountain region during the summer and move to forests closer to the coast during the winter, where they mainly graze on lichens (*Cladina*, *Alectoria* and *Bruoria* spp.). Forest Saami RHCs is a type of Saami village that does not have grazing areas on the bare mountain. The members conduct forest reindeer husbandry in the forestland all year round. There are 10 forest Saami RHCs in Sweden. Finally, concession reindeer husbandry is a form of reindeer husbandry that is conducted in the easternmost part of the County of Norrbotten along the Torne and Kalix river valleys. In concession Saami RHCs the reindeer can be owned not only by Saami, but also by other locals. There are eight concession Saami RHCs, and they typically have small reindeer herds.

As in Norway reindeer herding is a small economic activity relying mainly on meat productions. The industry produces between 1200 to 2000 tons of reindeer meat yearly, which amounts to 0.8-1.3 percent of the total production of red meat in Sweden (Lannhard Öberg, 2022). Reindeer husbandry is of course of great importance to the Swedish Saami, both culturally and economically, but also to the Swedes in general. As demonstrated in Bostedt and Lundgren (2010) the cultural benefits of the Swedish reindeer industry are 2 to 4 times larger than the annual turnover of the reindeer herding industry. In Section 5, to simplify the analysis of the future climate scenarios, we consider two stylized reindeer herding areas in Sweden, denoted as mid Sweden (light green area in Figure 1) and north Sweden (lime colored area in Figure 1).

3. The bioeconomic model

3.1 Population model

The bioeconomic model utilized in this paper is a modified and extended version of Skonhoft et al. (2017 and Johannesen et al. (2019) where we ignore predation and expand the model by including a climate-animal weight relationship. The reindeer population at time (year) t is structured in three stage classes: calves $X_{c,t}(yr < 1)$, adult females $X_{f,t}$ $(yr \geq 1)$, and adult males $X_{m,t}$ $(yr \geq 1)$, and the fertility- and natural mortality rates are considered density dependent through animal weights. See also Bårdsen and Tveraa (2012) for the role of density dependence in reindeer herding.

The sequences over the year are illustrated in Figure 2. The reindeer population is measured in spring just before calving. The animals gain weight during spring, summer and early autumn, and the weight gain is affected by climate conditions in this period. For simplicity we neglect summer mortality but allow for weight gain during summer to affect natural mortality in the upcoming winter. Weights are registered in the autumn when slaughtering takes place (September-October). Then winter grazing conditions impact weights and natural mortality the following year. The latter is in line with previous ecological studies of reindeer herding in Norway (Tveraa et al. 2013, 2014) but differs from the model in Tahvonen et al. (2014) who use weight loss during winter as detrimental for natural mortality.

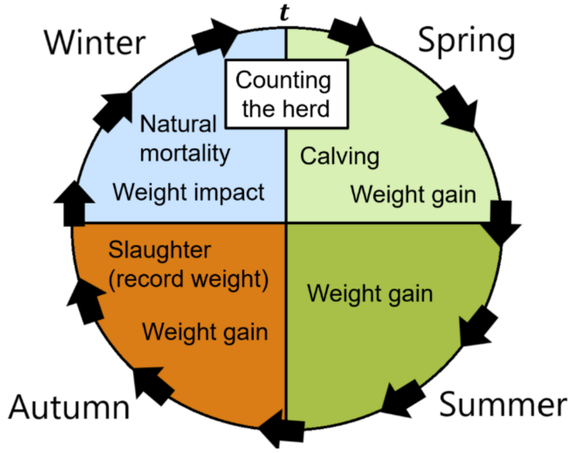

Figure 2 Events over the year cycle

The impact of climate conditions enters the model through its effect on slaughter weights. Thus, climate conditions only affect recruitment and natural mortality indirectly. This is a simplification, as extreme and difficult winters may increase mortality through winter starvation, even if weights in the autumn are high.

The number of calves (recruitment) in year *t* is governed by:

(1) $$X_{c,t} = f_t(w_{f,t-1})X_{f,t}$$

where $f_t > 0$ is the fertility rate (number of calves per female). Because calves are born in the spring, the fertility rate depends on female weight the previous year, $w_{f,t-1}$. Following Johannesen and Skonhoft (2019), the fertility function is specified as:

(2) $$f_t = \bar{f} \cdot (w_{f,t-1}/\bar{w}_f)^a,$$

where $\bar{f}$ is the maximum fertility rate when the adult female weight reaches its maximum value, $w_{f,t-1} = \bar{w}_f$, while the parameter $0 < a < 1$ indicates that fertility is a concave function of the weight.[2]

Also the natural survival rates $0 < s_{i,t} < 1$ depend on food conditions through the weights and are generally different for the different age classes. Following Johannesen and Skonhoft (2019), we specify the survival rate of category *i* as:

(3) $$s_{i,t} = \bar{s}_i \cdot (w_{i,t}/\bar{w}_i)^{b_i}; \; i = c, f, m,$$

[2] With the constraint that $f_t = 1$ if $w_{f,t-1} > \bar{w}_f$, which may be the case when climate impacts are included.

where $\bar{s}_i$ is the maximum survival rate for animal category i, and where the parameter $0 < b_i < 1$ generally differs among the animal categories. [3]

The weight of the animals in the autumn, just before slaughtering, depends on total grazing pressure through the spring, summer and fall, i.e., the total number of animals, and prevailing climate conditions. We define C_S and C_W as variables capturing summer and winter climate conditions, respectively. Because we measure the population size in spring and weight in the autumn, the weight of adult animals in year *t* ($w_{i,t}$) depend on summer climate conditions in year t ($C_{S,t}$) and winter climate conditions in year *t-1* ($C_{W,t-1}$). The autumn weight of calves born during spring in year *t* depends on summer climate conditions in year *t* and the weight of the adult females raising calves (Tveraa et al. 2003). We then have:

(4) $$w_{i,t} = w_i(X_{c,t} + X_{f,t} + X_{m,t}, C_{S,t}, C_{W,t-1}) = w_i(X_t, C_{S,t}, C_{W,t-1}); \; i = f, m,$$

and

(5) $$w_{c,t} = w_i\left(X_{c,t} + X_{f,t} + X_{m,t}, C_{S,t}, \; w_{f,t-1}\right) = w_i\left(X_t, C_{S,t}, w_{f,t-1}\right);$$

with $w_{iX_t}{}' \leq 0$. The weight-density relationships are specified as sigmoidal functions, see Figure 3 (Mysterud et al. 2001, Nielsen et al. 2005, and Skonhoft et al. 2017). The parameter $K > 0$ is the stock size for which the density-dependent weight effect is equal to density-independent weight effect. This parameter scales the population sizes, and its value is contingent upon factors like the size and productivity of the pasture. The parameter $\beta > 0$ indicates to what extent density-independent factors compensate for changes in the stock size. Following Johannesen et al. (2013), the relationship between autumn body weight and the climate variables are specified as linear. Therefore:

(4') $$w_{i,t} = \frac{\bar{w}_i}{1+(X_t/K)^{\beta}} + \alpha_{1,i} C_{S,t} + \alpha_{2,i} C_{W,t} \; ; \; i = f, m.$$

and

(5') $$w_{c,t} = \frac{\bar{w}_c}{1+(X_t/K)^{\beta}} \left(\frac{w_{f,t-1}}{\overline{w_f}}\right) + \alpha_{1,c} C_{S,t} \; .$$

The parameters $\alpha_{1,\mathrm{i}}$ and $\alpha_{2,\mathrm{i}}$ are estimated in Section 4 using historical data on animal and weather factors in Norway and Sweden. Previous studies suggest that more favourable summer climate conditions have a positive impact on weights whereas less favourable winter conditions have a negative impact (Aikio and Kojala 2003; Albon et al., 2017; Bårdsen and Tveraa 2012; Furberg et al. 2011; Pettorelli et al. 2005; Tveraa et al., 2013).

Figure 3 illustrates the weight-density relationship where negative density effect is weak, or negligible, for low densities, but stronger as the density increases before it diminishes for high densities. The shift from the solid line to the dashed line illustrates a possible climate shift causing worse grazing conditions

[3] Similarly, $s_{i,t} = 1$ if $w_{i,t} > \bar{w}_i$.

(i.e. where $\alpha_{1,i}C_{S,t} + \alpha_{2,i}C_{W,t} < 0$) and shifts the entire weight-density relationship down. Hence, if the animal density is constant, weight will reduce accordingly. On the other hand, herders may reduce their herd size and, hence, limit the weight reduction by a movement upwards the new weight-density curve.

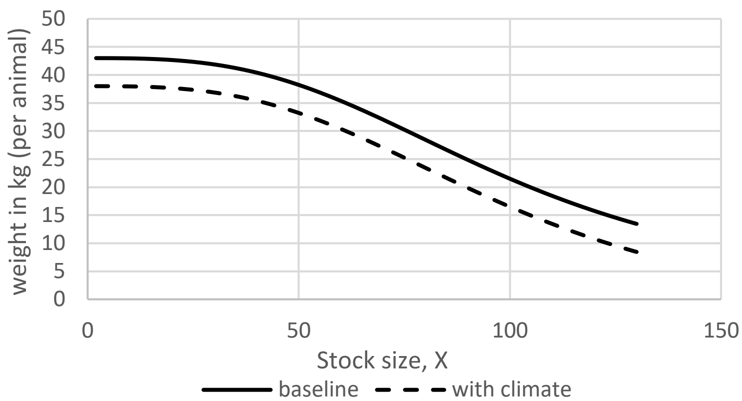

Figure 3 Climate and slaughter weight - density relationship, baseline parameter values (see Table 5) and net negative climate effect

Finally, with ψ as the fraction of female calves (usually about 0.5) and $0 \leq h_{i,t} \leq 1$ as the harvest (slaughter) rates $i = f, m, c$, the change in the size of the female and male population over time is written as:

(6) $$X_{f,t+1} = \psi(1 - h_{c,t})X_{c,t}s_{c,t} + (1 - h_{f,t})X_{f,t}s_{f,t}$$

and

(7) $$X_{m,t+1} = (1 - \psi)(1 - h_{c,t})X_{c,t}s_{c,t} + (1 - h_{m,t})X_{m,t}s_{m,t},$$

3.2 Economic model

The economic effects of climate change are studied under the assumption of economic optimizing reindeer herding management, as in Johannesen et al. (2019) and Tahvonen et al. (2014). That is, we consider the objective of maximizing net present value of revenue from slaughtering. This differs from Johannesen and Skonhoft (2011) and Bostedt (2005) who also include non-market values of reindeer in the objective function, and is clearly a simplification due to cultural values inherent in Saami reindeer herding. Still, this simplification enables us to highlight the impact of climate change on productivity and, hence, economic return in Saami reindeer herding.

We consider a stylized reindeer herding area where the number of animals slaughtered in year *t* is given by $H_t = h_t X_t$, $i = f, m, c$. Thus, the current net income from slaughtering may be written as

(8) $$I_t = p(w_{c,t}h_{c,t}X_{c,t} + w_{f,t}h_{f,t}X_{f,t} + w_{m,t}h_{m,t}X_{m,t}),$$

where p is the net meat price (EUR/kg), i.e., the unit harvest value adjusted for the cost of slaughtering. The assumption of a fixed unit price follows from Johannesen et al. (2019) and is based on the notion that the volume of meat produced in reindeer herding is only 1-2 percent of the domestic production of red meat, see Section 2. A fixed unit price is also assumed by Pekkarinen et al (2015), Pekkarinen et al. (2017), and Tahvonen et al. (2014).

We ignore any seasonal differences in operating costs and simply assume that costs are related to the total stock size as:

(9) $$C_t = C\left(X_{c,t} + X_{f,t} + X_{m,t}\right) = C(X_t),$$

where $C' > 0, C'' \geq 0$. It is evident that climate factors may affect herding costs, e.g., difficult winter conditions require supplementary feeding, while delayed onset of winter may interrupt the migration route (Furberg et al. 2011). However, ignoring any (direct) impact on costs, enables a strict focus on how relative changes in winter and summer climate affect animal weights and thereby the economic return in reindeer herding.

The optimization problem is then to $\max_{h_c, h_f, h_m} \sum_0^\infty \left(p\left(w_{c,t}h_{c,t}X_{c,t} + w_{f,t}h_{f,t}X_{f,t} + w_{m,t}h_{m,t}X_{m,t}\right) - C(X_t)\right)$ subject to eqs. (1), (6), and (7), and $h_{m,t} \leq \bar{h}_m$, an upper constraint on the harvest of adult males.

4. Data and estimation

The climate-weight relationships are now estimated using historical data on herd sizes and slaughter weights (NRHA 2022) and weather data from the CMIP6 multi-model ensemble of historical climate projections (Copernicus Climate Change Service, Climate Data Store 2021). This section also presents the future climate projections used in the numerical illustration of the model in Section 5.

4.1 Reindeer data

We use Norwegian reindeer herding district level data on slaughter weights from 1996 to 2020 for adult females and males, and from 1984 to 2020 for calves, and where the reindeer herding districts is a sub-administrative unit of a reindeer herding region. The data also include information on the total number of reindeer in each district. The data set covers 67 of the 71 reindeer herding districts in Norway. For Sweden, we have country level average slaughter weights for the time period 1997 to 2020, and average number of reindeer per reindeer herding community (RHC).[4] Thus, the empirical estimations in section 4.3 are based on 68 cross-sectional units, which mainly reflect the Norwegian setting. That said, the average slaughter weights from Sweden correspond well to the mean slaughter weights observed in

[4] Calculated as total number of reindeer divided by 51 RHCs.

Norway. Table 1 reports descriptive statistics for the autumn slaughter weights of adult females, males, and calves, as well as the number of reindeer per district. The maximum observed weight for calves is 35.3 kg, though this is considered an outlier as the second highest observed weight is at 28 kg. There are great differences in the number of reindeer per district, and the distribution is skewed to the left with a herd size of 1710 as the median, and 3998 as the third quartile.

Table 1. Descriptive Statistics of Reindeer data

Variables	Mean	Std.dev	Min	Max
Slaughter weight female (kg)	31.1	4.1	21.8	43.5
Slaughter weight male (kg)	29.6	5.6	18.4	55.05
Slaughter weight calves (kg)	19.6	2.9	11.4	35.3
Reindeer per district	3000	3998	23	34639

4.2 Weather data

The weather variables of focus in this paper include the onset of spring, snow depth, and weather conditions predicting icing. The paper utilises weather data for two purposes: in Section 4.3 historical weather data is used to estimate the climate-weight relationship, and in Section 5 data on future climate projections is used in the numerical simulation of the model. For both purposes we use multi-model ensemble data from the sixth phase of the Coupled Model Intercomparison Project (CMIP6).[5]

The dataset includes daily ensemble means of temperature and total precipitation, and monthly ensemble means of snow depth. In addition, we construct variables for the onset of spring and the number of days that meet the conditions for ice-locked pastures (rain-on-snow events, and thaw-freeze cycles).[6] The data are aggregated to reindeer herding regions in Norway and to the similar aggregation level of counties in Sweden.[7] Although more detailed datasets, such as the ERA5 reanalysis data, allows for a finer granularity of the weather data, we have chosen reindeer grazing regions as the level of aggregation (instead of districts or reindeer herding communities) to take into account that reindeer often migrate across huge areas and are exposed to weather conditions outside their reindeer herding districts.

Panel A in Table 2 presents descriptive statistics on the historical weather data, the data covers the entire study area for the time period 1984 to 2014. In the dataset, the average onset of meteorological spring was May 10th, though it has been observed as early as April 10th and as late as July 25th. Figure 4 indicates that there is a slight trend towards earlier onset of spring in the historical data. When it comes to the number of days with conditions for icing, the mean number of days is 4.7, with some regions experiencing

[5] An overview of the models used is found in the supplementary material. For the historical data we also considered weather station data, but the coverage available for Finnmark was unsatisfactory. ERA5 reanalysis data has been used for robustness.

[6] The meteorological definition of spring is when the daily mean temperature is between 0°C and 10°C, and increasing. Following SMHI (2011), the meteorological onset of spring is calculated as the first day in a series of at least seven consecutive days with temperatures between 0 and 10.

[7] For the empirical analysis in section 6 the weather data for Sweden (spesifically Norrbotten, Västerbotten and Jämtland) was further aggregated to the country level to match the observational unit for slaughter data.

extreme years with up to 24 days with icing conditions. Spatially disaggregated descriptive statistics can be seen in Appendix A.1.

Panel B to D in Table 2 presents descriptive statistics for the three future climate projections; the Paris scenario which corresponds to the 1.5 °C target from the Paris agreement (socially shared pathway (SSP) 1-1.9), the intermediate scenario with an approximate increase in global mean temperature of 2.6 °C (SSP 2-4.5), and finally the fossil fuel driven business-as-usual scenario (BAU) (SSP 5-8.5) (CMIP6, 2022).From Figure 4 it appears that the Paris scenario may be considered a continuation of the historical dataset, as there is a continued trend in earlier spring, and no specific trend in the occurrence of icing. For the Intermediate scenario, there is a much stronger future trend of earlier spring, as well as a linearly increasing trend in the number of days with icing. In the BAU scenario, the changes in both variables are quite extreme, with trends that might be considered exponential. Descriptive statistics disaggregated by the four simulation areas can be seen in Appendix A.1.[8] In general, the southern areas will experience earlier onset of spring and more icing events than the northern areas, furthermore in the BAU scenario Norrbotten is the only area that is expected to experience onset of spring after May. [9]

Table 2. Descriptive statistics of historical weather data (1984-2014) and climate projections (2023-2100) for Norway and Sweden.

	Variables	Mean	Std.dev	Min	Max
A. Historical data	Start of spring (#days since 1.Jan.)	130.1	8.5	100	205
	Start of spring month	4.9	0.34	4	7
	Dummy for spring earlier than May	0.11	0.32	0	1
	Dummy for spring later than May	0.01	0.09	0	1
	#days with icing Nov-Mar	4.7	5.8	0	24
	Mean snow depth Dec-Jan (cm)	43.86	6.98	20.44	88.71
	Mean snow depth Feb-Mar (cm)	75.5	9.5	50.97	1267.8
B. Paris scenario (SSP 1-1.9)	Start of spring (#days since 1.Jan.)	111.78	14.2	67	156
	#days with icing Nov-Mar	2.53	3.69	0	26
	Mean snow depth Dec-Jan (cm)	46.39	16.44	15.50	107.84
	Mean snow depth Feb-Mar (cm)	61.56	23.54	18.92	146.18
C. Intermediate scenario (SSP 2-4.5)	Start of spring (#days since 1.Jan.)	89.55	21.85	1	154
	#days with icing Nov-Mar	18.32	16.77	0	90
	Mean snow depth Dec-Jan (cm)	34.69	13.58	6.67	82.48
	Mean snow depth Feb-Mar (cm)	32.17	16.43	8.01	108.47

[9] Weather is also differentiated with regards to altitude, but we are unable to account for this with the current dataset.

D. BAU scenario (SSP 5-8.5)	Start of spring (#days since 1.Jan.)	63.41	42.92	1	250
	#days with icing Nov-Mar	51.7	43.53	0	151
	Mean snow depth Dec-Jan (cm)	30.1	14.68	1.57	83.59
	Mean snow depth Feb-Mar (cm)	27.77	16.29	3.85	98.68

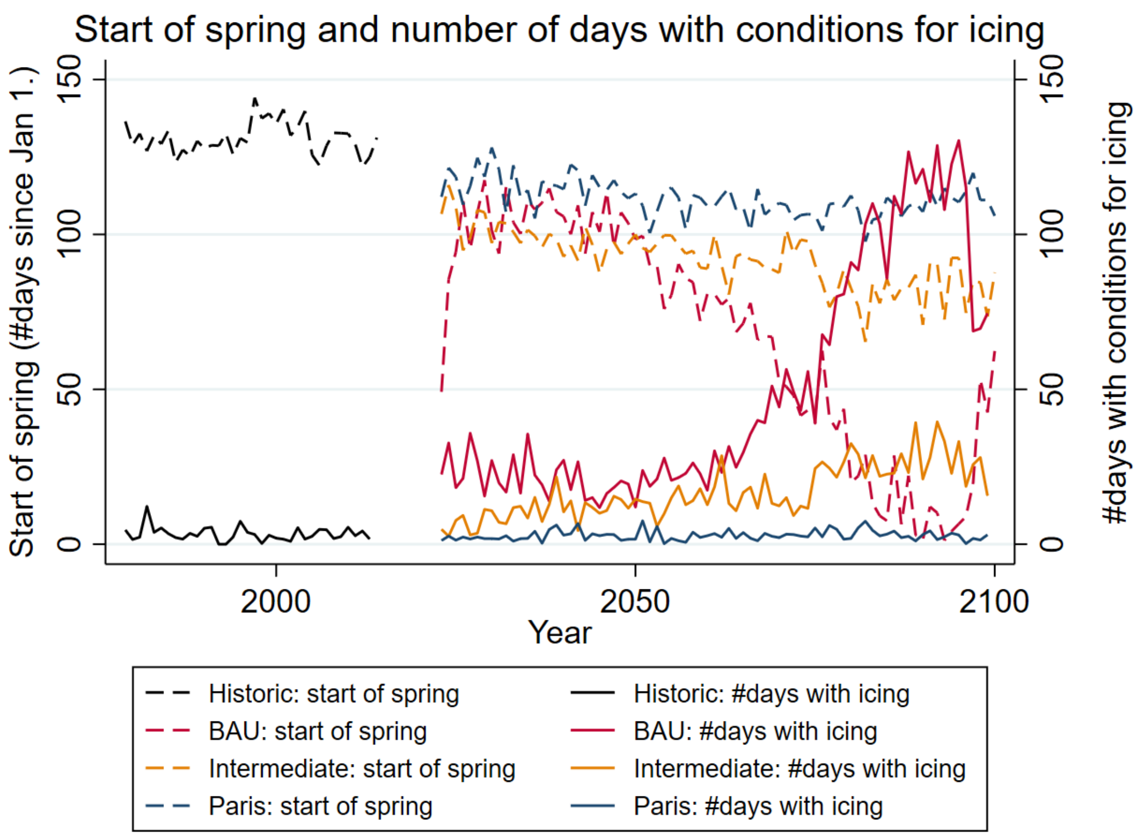

Figure 4 Past and projected start of spring and number of day with conditions for icing

4.3 Empirical analysis

Using historical data described above we now estimate the climate-weight relationships. Because the CMIP6 historical climate projections are only available until 2014, the estimations are based on 19 years for adult males and females and 31 years for calves.

Table 3 reports different linear specifications of the relationship between weight and the climate variables. The first column reports the results from a regular OLS, while the second column also include reindeer herding district (I.e., lower-level reindeer herding administrative units) fixed effects. District fixed effects are included to control for any district specific effects that may affect weight, such as management responses to weather conditions or differences in landscape and vegetation. Column three follows the standard procedure in weather econometrics literature, with the inclusion of year fixed effects, where the weather variables can be interpreted as shocks and the identifying variation will be each district's variation in weather conditions over time (Dell et al. 2014). However, the inclusion of year fixed effects will also remove some of the extreme years we are interested in.

As expected, an increase in the total number of reindeer sharing the same pasture has a negative impact on slaughter weights, thus confirming the density dependence of slaughter weights. However, the effect size is relatively small, and an increase in district level herd size by 10 animals is related to a decrease in the slaughter weight of adult females by 2-4 grams, depending on the specification. Based on the coefficients in column two, spring starting one day earlier than average is associated with slaughter weights that are 28.7 grams higher than average. This is a 0.09 percent increase in the average slaughter weight of adult females. One more day with icing, compared to the average amount of icing days, is related to a decrease in slaughter weights of 67 grams. This is a reduction of 0.22 percent compared to the average. During harsh winters, herders may compensate for pasture shortages by using supplementary feeding (e.g., Pekkarinen et al. 2015). As we are unable to control for supplementary feeding, the impact of icing may be underestimated and the potential weight loss of icing alone may be even greater. The impact of mean snow depth is more ambiguous, as increasing snow depth in February and March is related to decreasing slaughter weights while snow depth in December and January is related to increasing weights. The latter is in line with ongoing research in other fields that indicate possible positive effects of snow depth as it protects the underlying pasture (Pekkarinen et al. 2022; Tveraa 2022).

Table 3. Different specifications of the relationship between weather conditions and the slaughter weight of adult females.

VARIABLES	(1) slaughter weight females	(2) slaughter weight females	(3) slaughter weight females	(4) slaughter weight females	(5) slaughter weight females
Total herd in district	-0.000396***	-0.000246***	-0.000210**	-0.000221***	-0.000192**
	(2.90e-05)	(7.72e-05)	(8.13e-05)	(7.11e-05)	(7.78e-05)
Start of spring	-0.0652***	-0.0287***	-0.0160		
	(0.0155)	(0.00757)	(0.0120)		
Start of spring before May				0.616***	0.381
				(0.209)	(0.235)
Start of spring after May				-0.809***	-1.085***
				(0.191)	(0.251)
#days with icing	-0.109***	-0.0673***	-0.0555**	-0.0602***	-0.0513**
Nov-Mar = L	(0.0278)	(0.0223)	(0.0254)	(0.0216)	(0.0252)
Mean snow depth	-0.0364	0.155***	0.112**	0.142***	0.105**
Dec-Jan = L	(0.0471)	(0.0358)	(0.0428)	(0.0333)	(0.0427)
Mean snow depth	0.0448	-0.0811***	-0.0476*	-0.0744***	-0.0439
Feb-Mar = L	(0.0313)	(0.0212)	(0.0261)	(0.0203)	(0.0266)
Constant	39.77***	35.28***	33.52***	31.42***	31.33***
	(1.928)	(1.176)	(1.866)	(0.721)	(0.808)
Mean slaughter weight	31.1 kg	31.1 kg	31.1 kg	31.1 kg	31.1 kg
Observations	925	925	925	925	925

R-squared	0.243	0.069	0.148	0.070	0.153
Number of districts		68	68	68	68
District fixed effects		X	X	X	X
Year fixed effects			X		X

Standard errors in parentheses:
**** p<0.01, ** p<0.05, * p<0.1*

While the continuous specification of start of spring allows for convenient comparison of our two main climate effects, that is, one day earlier spring versus one additional day with icing conditions, there is reason to believe that the true relationship between slaughter weights and start of spring is non-linear. Firstly, the relationship between onset of spring and slaughter weights is a simplification, which excludes the grazing pasture and the availability of food. For a grazing pasture of fixed size, it is not given that the availability of food is linearly increasing in the start of spring. It may be more realistic to assume that there is a limit to how much food one pasture area can supply, and when the limit is reached further change in the onset of spring will not influence the availability of food. Furthermore, the relationship may even change as even earlier spring may be related to earlier summers, and drought degrading the pasture too early.

Secondly, even with endless availability of food there is a limit to how much the reindeer can consume and increase its weight. These uncertainties related to the relationship between onset of spring and slaughter weights may become particularly problematic when projecting future slaughter weights for levels of the weather variables that have not yet been observed. To account for this, column four considers a dummy specification for the onset of spring. With onset of spring during May as the baseline, "start of spring before May" is a dummy indicating the impact of spring earlier than average, whereas "start of spring after May" is a dummy indicating the impact of spring later than average.[10] An onset of spring earlier than average is related to slaughter weights that are 0.6 kg higher than the mean, whereas a late onset of spring is related to a decrease in slaughter weights by 0.8 kg. This asymmetry in effects is a further indication that the linearly increasing relationship between onset of spring and slaughter weights is an imperfect specification. Finally, column five again incorporates year fixed effects. Alternative specifications using temperature and precipitation have also been considered, and while temperatures could capture some of the additional stressors of a warmer climate, such as insect harassment, it is not the main consideration of our paper.

Table 4 continues with the specification from column four in Table 3, and displays results for adult females, adult males, and calves. Columns one and two are the specifications for the slaughter weight of adult females and males, respectively. Column three is the specification for calves, albeit it deviates from the theoretical expression presented in eq.(5') by the linear inclusion of $w_{f,t-1}$. This is mainly to confirm our hypothesis of a positive relationship between the slaughter weight of calves and the weight of females during gestation.

Table 4. Estimated coefficients: impact of weather variables on slaughter weight

	(1)	(2)	(3)

[10] We also considered specifications with second order polynomials, but these were not found to be significant.

VARIABLES	slaughter weight female	slaughter weight male	slaughter weight calves
Total herd in district	-0.000221***	-0.000123**	-2.25e-05
	(7.11e-05)	(5.13e-05)	(4.53e-05)
Start of spring before May	0.616***	0.838**	-0.160
	(0.209)	(0.361)	(0.148)
Start of spring after May	-0.809***	-1.276**	-0.00935
	(0.191)	(0.566)	(0.186)
#days with icing Nov-Mar = L	-0.0602***	-0.0581***	
	(0.0216)	(0.0215)	
Mean snow depth Dec-Jan = L	0.142***	0.276***	
	(0.0333)	(0.0476)	
Mean snow depth Feb-Mar = L	-0.0744***	-0.173***	
	(0.0203)	(0.0312)	
slaughter weight female = L,			0.205***
			(0.0402)
Constant	31.42***	30.92***	13.09***
	(0.721)	(1.080)	(1.255)
Mean slaughter weight	31.1 kg	29.6 kg	19.6 kg
Observations	925	865	817
R-squared	0.055	0.076	0.061
Number of districts	68	67	65
District fixed effects	X	X	X

Robust standard errors in parentheses :
**** p<0.01, ** p<0.05, * p<0.1*

5. Numerical analysis

This section presents the numerical analysis of possible economic effects of projected future climate changes by implementing the estimated coefficients of the weight-climate relationships and the climate projections from CMIP6 into the bioeconomic model. Section 5.1 presents the parameter values used in the bioeconomic model, while Section 5.2 presents numerical results. Then Section 5.3 considers the case of establishing wind farms in reindeer herding areas to fulfill national goals on reduced CO2 emissions to shed light on the tradeoff in the economics of reindeer herding between dampened climate change and pasture degradation.

5.1 Parameter values

Table 5 presents the baseline parameter values. Most of the parameters are based on Johannesen et al. (2019) but have been further calibrated to the current model. Maximum slaughter weights as reported in the baseline parameter values are based on maximum observed weight in the dataset. Baseline carrying capacity is based on district (Norway) and reindeer herding communities (RHC) (Sweden), state regulated upper limits on reindeer numbers and net pasture area.[11] On average, the upper limit is 5.4 animals/km^2 in Swedish RHC and 4.8 animals/km^2 in Norwegian reindeer herding districts. Assuming that the maximum reindeer numbers are set at a lower point than the pastures' true carrying capacity, the carrying capacity is set to 100 animals per 10 km^2. Initial number of reindeer are set to 15 of each category, this amount to a total of 45 animals per 10 km^2, which is just below the average upper limit in the RHCs in Sweden and reindeer herding districts in Norway. As such, the results can be considered as district or RHC level results. Simulations a run over 70 years where the last 10 years are excluded from the figures below to mimic the steady state solution of an infinite time horizon. We assume equal price for calf and adult meat, and a fixed per animal maintenance cost.

The summer/spring and winter weather coefficients are the coefficients for "Start of spring before May", "Start of spring after May" and "#days with icing Nov-Mar = L" which was estimated in section 4.3 and reported in Table 4. All simulation results reported in the paper include the effect of both variables. Table A2 in Appendix illustrates the impact on net present value when the variables are considered separately. For comparison, table A2 also includes simulation results when applying the continuous variable specification of onset of spring.

Yearly projected data on the onset of spring and number of days with icing conditions are constructed from the CMIP6 multi-model ensemble. To account for the spatial heterogeneity in climate within and across countries, the yearly weather variables are aggregated into four different simulation areas; northern Norway (Nordland, and Finnmark and Troms), mid Norway (Trøndelag), northern Sweden (Norrbotten and Västerbotten), and mid Sweden (Jämtland).[12]

[11] Total gross area available for reindeer herding in Norway is about 140 000 km^2, while net area is about 90 000 km^2. As a simplifying assumption this proportion is assumed to be the same for all Norwegian districts in the calculation of net pasture area (Ministry of Local Government and Districts 2009)

[12] The climate will also vary with altitude and the proximity to the ocean, however these are differences we are unable to account for in this paper.

Table 5. Baseline Parameter Values

Description	Parameter	Value	Unit	Reference
Sex ratio	φ	0.5		Assumed
Maximum fertility rate	$\bar{f}$	0.95	Calves/female	NRHA (2014)
Parameter fertility rate	a	0.4		Johannesen et al. (2019).
Maximum weights[13]	$\overline{w}_c, \overline{w}_f, \overline{w}_m$	28, 44, 55	Kg/animal	Department of Agriculture (2022) and Sametinget (2022)
Weight parameter	β	3		Johannesen et al. (2019).
Maximum survival rates	$\bar{s}_c, \bar{s}_f, \bar{s}_m$	1,1,1		Assumed
Parameter survival rate	b_c, b_f, b_m	0.85,0.4,0.4		Johannesen et al. (2019).
Carrying capacity	K	100	Animals/10 km^2	NRHA (2021) and Sametinget (2022)
Meat price	p	7	EUR/kg	NRHA (2020b)
Maintenance cost	c	10.5	EUR/animal	Johannesen et al. (2019).
Discount rate	δ	0.03		Assumed
Male harvest constraint	$\bar{h}_m$	0.7		Skonhoft et al. (2013)
Initial herd size	$X_{f,0}, X_{m,0}, X_{c,0}$	15,15,15		Assumed
Summer/spring weather coefficient	$\alpha_{1,f}, \alpha_{1,m}$	[0.616, -0.809], [0.838, -1.276]		Estimated
Winter weather coefficient	$\alpha_{2,f}, \alpha_{2,m}$	-0.0602, -0.0581		Estimated
Yearly projected onset of spring (dummies for early/late spring)	$C_{S,t}$			Projected data (Copernicus Climate Change Service, Climate Data Store 2021)
Yearly projected number of days with icing conditions	$C_{W,t-1}$		Number of days per year	Projected data (Copernicus Climate Change Service, Climate Data Store 2021)

5.2 Results

The bioeconomic model is solved for three future climate scenarios, the Paris, Intermediate, and BAU-scenarios, and for four simulation areas, mid and northern Norway and Sweden. We also consider both a linear and a convex specification of the herding cost function, as the differences between them are

[13] Maximum observed slaughter weight for calves is 35 kg, but this appears to be an outlier with the next observation at 28 kg.

negligible we only continue with the linear specification.[14] For the sake of readability, Figure 5 reports 5-year moving average optimal paths for slaughter weights, herd size, total animals slaughtered and current value profits (with total NPV in the legend) for the intermediate scenario only. The Paris and BAU scenarios are included in appendix A3. For comparison, Figure 5 also includes a benchmark scenario without any climate effect ($C_{S,t} = C_{W,t-1} = 0$), which is the point of departure for all areas and is used to compare the impact of future climate changes with a present average situation. That is, any future differences between the four geographical areas are due to differences in climate projections. The initial herd size is close to the optimal herd size without climate effects, and thus it only takes a few years for the benchmark scenario to reach its steady state. When including future climate changes according to the Intermediate scenario, the yearly weather variables act as unpredictable shocks to the slaughter weights, preventing the system from reaching a steady state. Instead, all variables will fluctuate around some steady state, with a slight trend as determined by future changes in the climate. This is more pronounced in Figure 6, which presents the yearly current profits underlying the 5-year moving averages seen in Figure 5. Figure 6 also highlights the increased instability that follows from the instability in future climate conditions.

Figure 5 indicates some interesting distributional effects of future climate changes. Mid Norway seems to be worse off in terms of current profits, both relative to the remaining geographical areas and compared to the benchmark scenario. The latter shows that the impact of more difficult winter conditions dominate the impact of an earlier onset of spring in mid Norway. This result is mainly driven by the difference in number of days with conditions for icing between the areas, where mid Norway will experience a steady and significant increase in the conditions for icing in the intermediate scenario which by far exceeds what is expected for the other areas. In fact, the average number of days with conditions for icing is projected to 32.7 in mid Norway whereas the same number for northern Norway, mid Sweden and northern Sweden is 17.15, 4.10, 13.34, respectively (see Table A1). Figure 5 shows that mid Norway will experience lower slaughter weights, lower herd sizes and lower slaughter numbers compared to the benchmark scenario and the other geographical areas.

The results for the Intermediate scenario further suggest that favorable spring conditions dominate the adverse effects of more difficult winter conditions in northern Norway, mid Sweden and northern Sweden. Figure 5 suggests that mid Sweden will experience fluctuations above the benchmark scenario the with higher slaughter weights and profits compared to the other areas. In terms of profits, the projections for the northern areas seem to deviate less from the benchmark scenario.

The optimal harvest rate of adult males is fluctuating extremely close to the limit 0.7. For adult females, the optimal harvest rate is around 35 percent, but this is the harvest rate that fluctuates the most and generates most of the variation in yearly total harvest rate. This may be seen in Table 6, which reports average harvest rates, stock sizes, weights and profits over the entire simulation period, and all areas. With baseline maximum weights no calves should be harvested as they are worth more (in terms of a larger slaughter weight) when they are adults. However, if the maximum weight of calves is increased to 37 kg it is optimal to harvest calves and leave the adult females. Thus, if consumers preferences for calves generate a higher price for calf meat, this could also change the harvest rates.

[14] In the model with convex herding costs ($C_2 = c_2 X_t^2$) c_2 is calibrated to 0.21 such that total herding cost for the benchmark steady state herd size is approximately equal with the linear and convex cost function. The results are very similar to the model with a linear cost function.

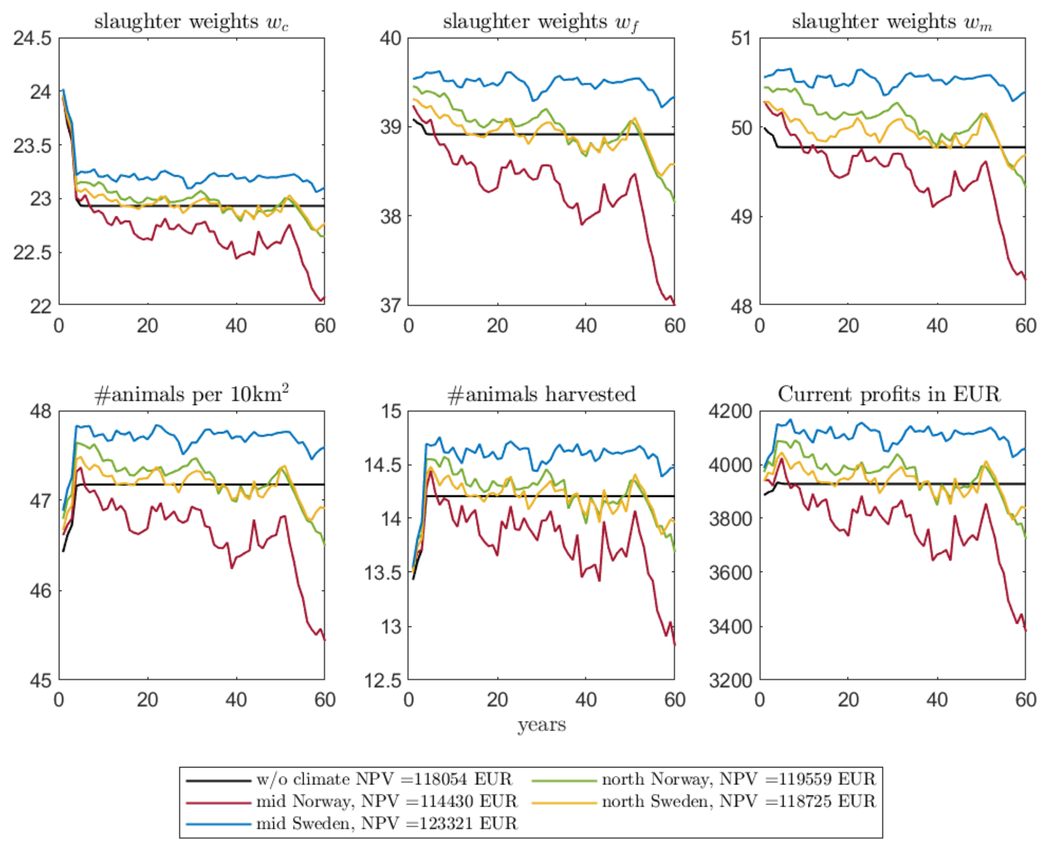

Figure 5 5-year moving average optimal paths for the intermediate scenario with icing and onset of spring, all areas

Table 7, first column (baseline carrying capacity), reports the percentage change in net present value profits compared to baseline for all climate scenarios and for each geographical area. The model projects

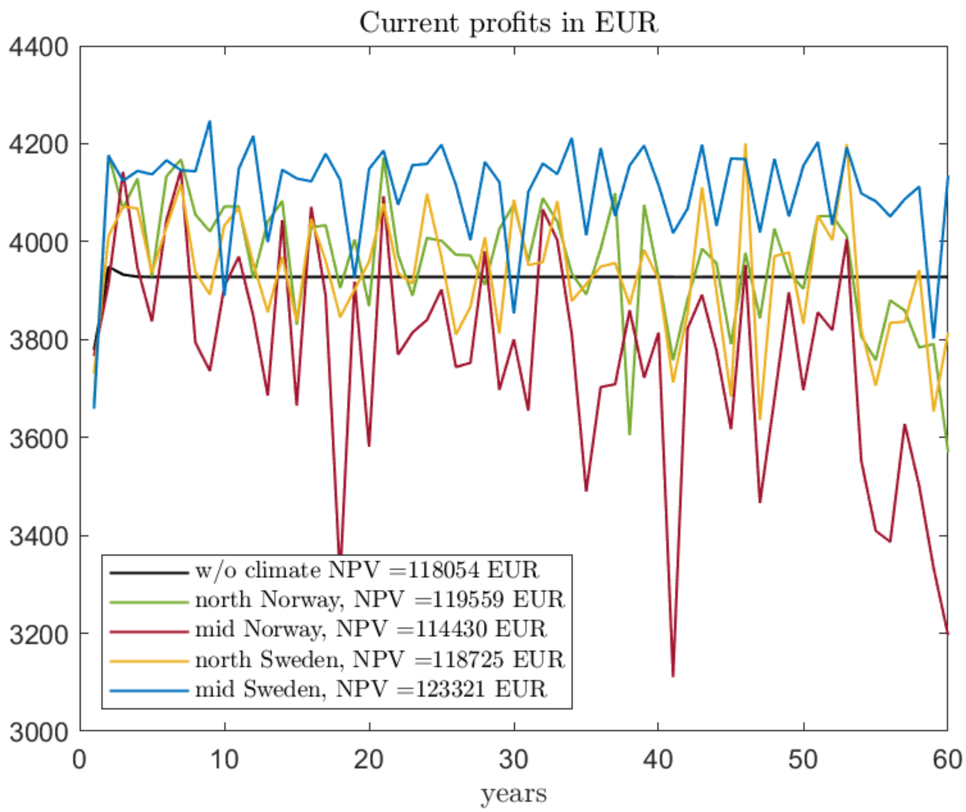

Figure 6 Optimal yearly current value profits for the intermediate scenario with icing and onset of spring, all areas

that all reindeer herding areas will be better off under the Paris scenario, whereas alle areas are worse off in the BAU scenario. BAU scenario predicts a strong increase in the number of days with icing conditions in the winter in all areas, but also a considerable earlier onset of spring (see Table A1). The total effect on slaughter weights and net present value profits is negative for all areas, and mid Norway and northern Sweden will experience the largest reduction with a 10% and 6% drop, respectively. On the other hand, all areas except mid Norway will experience more favorable climate conditions in both summer and winter, and hence increased profits. Mid Norway will have a slightly lower increase in present value profits as the more unfavorable winter conditions be offset by the advantages of an earlier onset of spring. It is difficult to identify any adjustment in harvesting strategy. Yearly current value profits are strongly correlated with the weather shocks through its impact on slaughter weights, and it is not evident whether it is optimal to offset this by increasing the number of animals slaughtered. Table 6 considers the average harvest rates, stock sizes, weights and profits over the simulation period, and all areas. The harvest rate for adult females' declines as we move through the climate scenarios. The number of animals in all stage classes also decrease as we shift from one scenario to the next. Thus, from one scenario to the next, lower profits are a result of decreases in all components, i.e. w_i, h_i, X_i *(i =c,f,m)*. Furthermore, the increase in standard deviations when moving from the Paris scenario to the BAU scenario again illustrates how weather conditions may become more unpredictable and that reindeer herders will face greater uncertainty in the BAU scenario compared to the intermediate scenario.

Table 6. Average simulation results of harvest rates, stock size, weights and profits over the simulation period and all areas (standard deviation in parenthesis)

	h_c	X_c	w_c	h_f	X_f	w_f	h_m	X_m	w_m	Yearly Current Value Profits in Euros
w/o climate	0.00	17.50	22.98	0.356	19.15	38.92	0.70	10.49	49.78	3,925.59
	(0.00)	(0.33)	(0.36)	(0.030)	(0.55)	(0.06)	(0.00)	(0.60)	(0.08)	(19.77)
Paris scenario	0.00	17.67	23.20	0.364	19.24	39.41	0.70	10.69	50.41	4,079.43
	(0.00)	(0.36)	(0.34)	(0.035)	(0.57)	(0.17)	(0.00)	(0.57)	(0.20)	(92.29)
Intermediate scenario	0.00	17.51	23.00	0.356	19.15	38.95	0.70	10.51	50.02	3,949.89
	(0.00)	(0.40)	(0.44)	(0.037)	(0.59)	(0.54)	(0.00)	(0.63)	(0.49)	(183.45)
BAU scenario	0.00	17.22	22.63	0.342	18.99	38.10	0.70	10.20	49.23	3715.37
	(0.00)	(0.50)	(0.63)	(0.042)	(0.64)	(1.02)	(0.00)	(0.74)	(0.92)	(313.81)

Implications of policies to mitigate climate change

The bioeconomic model predicts that all reindeer herding areas will be better off in terms of increased slaughter profits in the Paris scenario and three of the four areas will be better off in the intermediate scenario. Limiting climate change according to the Paris scenario, or even the intermediate scenario , will however, require national policies and regulations to mitigate CO2 emissions. One strand of emission reduction policies emphasizes the need to shift from fossil energy towards renewable energy sources, such as wind turbines. The development of wind power plants is increasing and represents an expanding pressure on land use with their associated infrastructure, road networks, and fragmented landscapes. Wind turbines located in areas of reindeer pastures may impact the reindeer negatively, both directly and indirectly. Direct effects are related to pastures being transferred to roads and infrastructure, while indirect effects are related to disturbances and stress as reindeer may avoid pastures close to wind turbines and reduce use of exploited areas (Vistnes and Nellemann 2008, Skarin and Åhman 2014, Skarin et al. 2018). Existing studies show limited to strong negative effects on reindeer behavior and pasture selection depending on geographical and seasonal differences across studies (see Skarin et al. 2018 and references therein).

Some studies have estimated the amount of reindeer pastures lost to wind turbines. Stoessel et al. (2022) find that 3 % of the pasture in Fennoscandia is covered by wind turbines; this estimate excludes potential buffer zones, or zones of avoidance, with indirect effects. When including buffer zones, Lundmark (2022) find that up to 12 % of all available high-quality reindeer pastures in Sweden are within wind turbine areas. Tømmervik et al. (2022) estimate the pasture loss related to windfarms in mid Norway (Trøndelag) and that the direct loss amounts to 5 % and up to 25 % when including related infrastructure and a 3 km buffer zone.

In this section we assume that establishment of windfarms reduces the carrying capacity of reindeer pastures, that is, it is assumed to have a direct negative effect on the size of reindeer pasture. Furthermore, we assume that wind power reduces the use of fossil energy in the society, which may affect the realized future climate scenario. With this simplified exercise we attempt to illustrate the tradeoff between pasture loss and limited climate change in the economy of reindeer herding.

Figure 7 illustrates a case where we assume that the intermediate scenario is reached at a cost of a 5 % reduction in carrying capacity per 10 km^2 to establishment of wind turbines. The benchmark scenario is defined as above, without climate effects and no change in carrying capacity. When comparing with Figure 5 we see that loss of pasture leads to reduced herd sizes in all areas, while slaughter weights are maintained. Still, profits are reduced due to reduced harvest.

Table 7 reports the percentage change in NPV profits with a 5 % loss, and a 25 % loss in carrying capacity for all climate scenarios and all areas. For comparison, the table also includes the percentage change in NPV profits for the baseline carrying capacity. For all cases, the percentage change in NPV profits is relative to the benchmark scenario without climate change, and baseline carrying capacity. As such, the table presents different trade-offs inherent in regulating CO2 emissions by establishing wind farms in reindeer herding areas. For instance, all areas are better off in the intermediate scenario with a 5 % reduction in

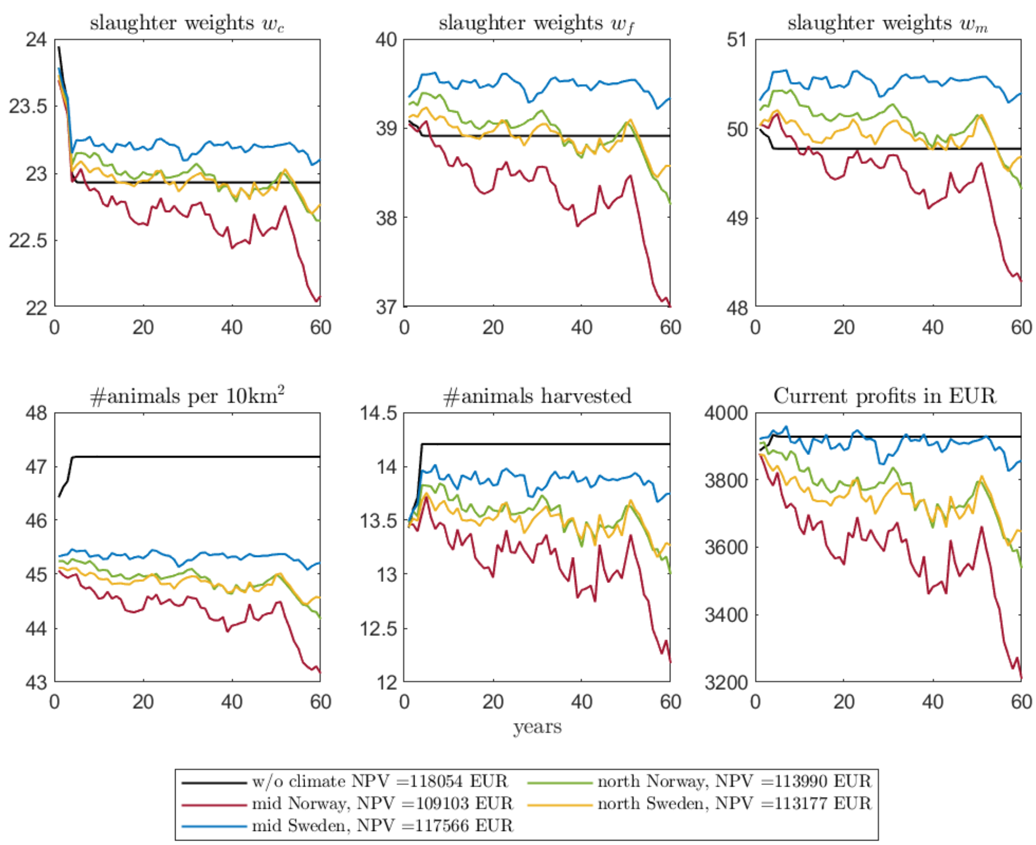

Figure 7 5-year moving average optimal paths for the intermediate scenario with icing and onset of spring, all areas, and a 5 % reduction in carrying capacity (K), all areas.

carrying capacity, than in the BAU scenario with baseline carrying capacity. That is, profits are higher if giving up 5 % of the pastures implies avoiding the BAU scenario. If the slaughter profit is the only value attaced to reindeer herding, then wind farm development of this size may be reasonable. In contrast, if we also account for loss of pastures due to infrastructure and buffer zones (i.e., 25% reduction in carrying capacity), all areas are better off in the BAU scenario with no establishment of wind turbins. In this case, the potential benefit from reaching a lower global mean temperature cannot offset the cost of direct and indirect loss of pastures.

The results indicate the minimum amount of compensation reindeer herders would require to give up some of their pasture for wind turbines. In the Paris scenario, a reindeer-herding district in mid Norway will earn a NPV of 122,287 Euros over the next 70 years. If that district had to give up 5 % of its pasture, the NPV would be 116,555 Euros. In order to compensate for the loss in carrying capacity, the district would require a total sum of 5,732 Euros, or 82 Euros per year. If the wind turbines led to a loss of 25 % carrying capacity, the compensation required would be 28,973 Euros, or 414 Euros per year. That said, these are at best minimum estimates as the values only consider slaughter profits. The value of cultural loss would be much greater, especially if the cultural value is attached to the size of the herd, but also due to the cultural and historical values attached to the specific pasture area that is lost. In any case, from table 7 it is evident that the economic loss of pasture is much greater than the economic loss due to climate change.

Table 7 Percentage change in NPV profits with a loss in carrying capacity, all areas and all scenarios.

	Scenario	Baseline carrying capacity	5 % reduction in carrying capacity	25 % reduction in carrying capacity
north Norway	Paris	4.04	-0.82	-20.61
	Intermediate	1.27	-3.44	-22.71
	BAU	-3.77	-8.25	-26.49
mid Norway	Paris	3.59	-1.27	-20.96
	Intermediate	-3.07	-7.58	-25.96
	BAU	-10.27	-14.41	-31.37
north Sweden	Paris	3.31	-1.52	-21.18
	Intermediate	0.57	-4.13	-23.23
	BAU	-6.35	-10.65	-28.41
mid Sweden	Paris	4.09	-0.75	-20.59
	Intermediate	4.46	-0.41	-20.29
	BAU	-2.81	-7.32	-25.78

6. Concluding remarks

In this paper, we presented a simple stage-structured model, which incorporates the impact of two counteracting climate effects on the economics of Saami reindeer herding in Norway and Sweden; the onset of spring and the frequency of ice-locked pastures. Climate change and yearly weather conditions affect the model through its impact on slaughter weights. We have used historical data to estimate the empirical effect of onset of spring and icing on slaughter weights and used these estimates to parameterize the bioeconomic model. The model has then been simulated for three projected climate scenarios.

We find that one more day with ice-locked pastures has a greater negative impact on slaughter weights than the benefit of spring arriving one day earlier. However, our results are limited by the fact that we cannot control for any supplementary feeding that may have occurred during extreme years, thus the estimated effect of icing may be considered a lower-bound estimate. Furthermore, there are also a number of potential climate change effects that have been excluded from the analysis presented here. For instance, there has been some concern that earlier onset of spring could generate phenological mismatches (Post and Forchhammer, 2008). In addition, the review paper by Mallory and Boyce (2018) mention parasites, insect harassment and wildfires as additional stressors that increase with a warmer climate. In Norway, Hagemoen and Reimers (2002) observed reindeer running from insect harassment all day long, seeking relief on windy hilltops, snowy patches, and other unproductive areas (Mallory and Boyce, 2018). Such behavioural responses can have negative implications for summer reindeer body mass growth but has not been included in the model.

Climate change will have spatially heterogeneous effects. To account for this, we have simulated the model for four different areas. While the results are relatively similar for northern Sweden and northern Norway, mid Norway will experience the greatest loss in NPV in the BAU scenario, while mid Sweden is the least affected area. This is mainly due to a difference in the number of days with icing. In general, as we move towards a higher global mean temperature the economic profits in reindeer herding decrease as a result of both lower slaughter weights, smaller herd sizes and decreaseing harvesting rates. A limitation of the study is that we do not allow herding costs to change with the climate change scenarios. For instance, more frequent icing may increase the need for supplementary feeding, while warmer autumns could make the herd more dispersed, thus making it more time consuming to gather the herd. If the lakes no longer freeze over, herders may have to travel longer distances, and earlier snowmelt could change the method of transportation for herders (Furberg et al., 2011). Including such costs would strengthen the negative economic effect of climate change. Policies required to mitigate climate change may encroach on the reindeer's grazing pasture. Uboni et al. (2020) find that reindeer herders have been able to adapt to previous pasture loss by changing herd structure, management and use of the pastures. In Sweden herders have adjusted the herd by reducing the number of large male reindeers in favor of smaller but a larger number of female reindeer, which can increase the total number of animals above what a given pasture can support (Uboni et al. 2020). A herd with a greater number of females relative to males is in line with what we find in our optimization as well. However, we also find that any potential loss in carrying capacity related to pasture loss appears to be more detrimental to the economics of reindeer husbandry than climate change itself. This supports the idea that reindeer herders are better equipped to adapt to climate change when they have access to larger and unfragmented pasture areas (Tyler et al. 2021, Uboni et al. 2020).

Finally, it is worth noting that this paper only considers economic profits from reindeer herding. There are great cultural values attached to traditional reindeer herding. With a changing climate, herders may have to change the reindeer herding practices, for instance by increasing the use of supplementary feeding and restricting traditional the nomadic practice. Such changes may further affect the total economic value related to reindeer herding, both due to a direct increase in herding costs, but it may also affect the cultural values of reindeer husbandry. In future work we aim to extend upon the current model by incorporating cultural values and policies such as supplementary feeding.

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Appendix

A.1 Summary statistics by area

Table A.1 *Descriptive statistics of historical weather data (1979-2014) and weather data projections (2023-2100) for North and South Norway and Sweden. Standard deviation in parenthesis.*

		Norway		Sweden[15]	
	Variables	north	mid	north	mid
A. Historical	Start of spring (#days since 1.Jan.)	131.90	123.81	144.16	144.16
		(4.88)	(7.68)	(8.17)	(8.17)
	#days with icing Nov-Mar	5.18	1.23	3.28	3.28
		(3.67)	(2.81)	(3.03)	(3.03)
	Mean snow depth Dec-Jan (cm)	44.42	38.74	64.05	64.05
		(5.19)	(5.70)	(10.82)	(10.82)
	Mean snow depth Feb-Mar (cm)	76.05	70.44	98.20	98.20
		(6.10)	(6.56)	(11.30)	(11.30)
B. Paris scenario (SSP 1-1.9)	Start of spring (#days since 1.Jan.)	113.12	98.29	121.87	113.23
		(7.63)	(10.16)	(6.68)	(6.80)
	#days with icing Nov-Mar	1.46	5.73	1.36	2.68
		(1.43)	(3.98)	(1.28)	(2.75)
	Mean snow depth Dec-Jan (cm)	39.90	51.64	61.59	31.42
		(5.85)	(8.11)	(7.02)	(5.72)
	Mean snow depth Feb-Mar (cm)	51.54	64.92	82.58	52.87
		(5.17)	(7.52)	(6.42)	(7.60)
C. Intermediate scenario (SSP 2-4.5)	Start of spring (#days since 1.Jan.)	88.36	74.87	97.93	106.87
		(12.44)	(13.76)	(11.65)	(7.49)
	#days with icing Nov-Mar	17.15	32.73	13.34	4.10
		(9.73)	(15.87)	(6.65)	(4.53)
	Mean snow depth Dec-Jan (cm)	36.19	29.91	41.51	24.64
		(9.18)	(7.25)	(6.79)	(8.46)
	Mean snow depth Feb-Mar (cm)	28.31	25.40	45.18	35.16
		(6.22)	(6.44)	(8.89)	(10.64)
D. BAU scenario (SSP 5-8.5)	Start of spring (#days since 1.Jan.)	59.77	50.65	73.40	83.51
		(36.11)	(32.69)	(43.18)	(40.96)
	#days with icing Nov-Mar	52.01	66.57	45.38	33.35
		(44.17)	(38.27)	(35.43)	(35.20)
	Mean snow depth Dec-Jan (cm)	30.67	25.83	38.22	19.61
		(11.79)	(8.70)	(8.08)	(7.66)
	Mean snow depth Feb-Mar (cm)	24.37	21.32	40.16	29.43
		(7.89)	(7.90)	(9.77)	(13.21)

[15] Because we only have country level data on slaughter weights for Sweden, the historical weather data has been aggregated to one combined area (north and south).

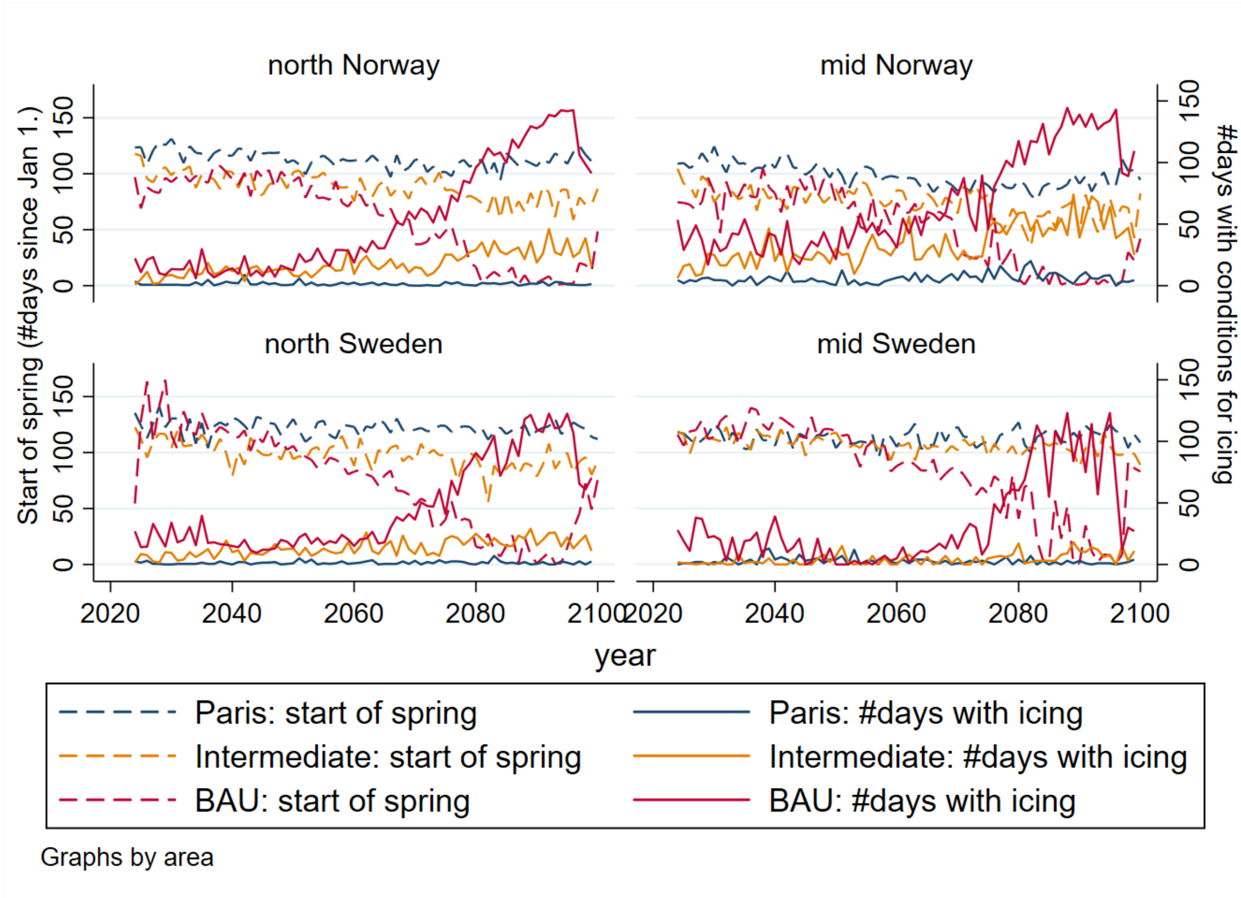


Figure A 1 Future projections of onset of spring and #days with conditions for icing for all three scenarios and all areas.

A.2. Simulation results for separate variables

Table A.2 Percentage change in NPV for different inclusions of climate variables.

	Norway						Sweden					
	north			mid			north			mid		
Model /scenario	Paris	Inter-mediate	BAU	Paris	Inter-mediate	BAU	Paris	Inter-mediate	BAU	Paris	Inter-mediate	BAU
Icing	1.12	-2.52	-7.55	-0.08	-6.89	-13.98	1.19	-1.91	-7.79	0.61	0.74	-5.41
Onset of spring dummy	2.93	3.84	3.87	3.68	3.93	3.93	2.13	2.46	1.54	3.47	3.75	2.68
Continous onset of spring	2.35	5.63	7.81	4.25	7.81	9.65	1.22	4.32	4.94	2.73	3.25	3.78
Standard (icing and spring dummy)	4.04	1.27	-3.77	3.59	-3.07	-10.27	3.31	0.57	-6.35	4.09	4.46	-2.81

A.3. Simulation results for all areas

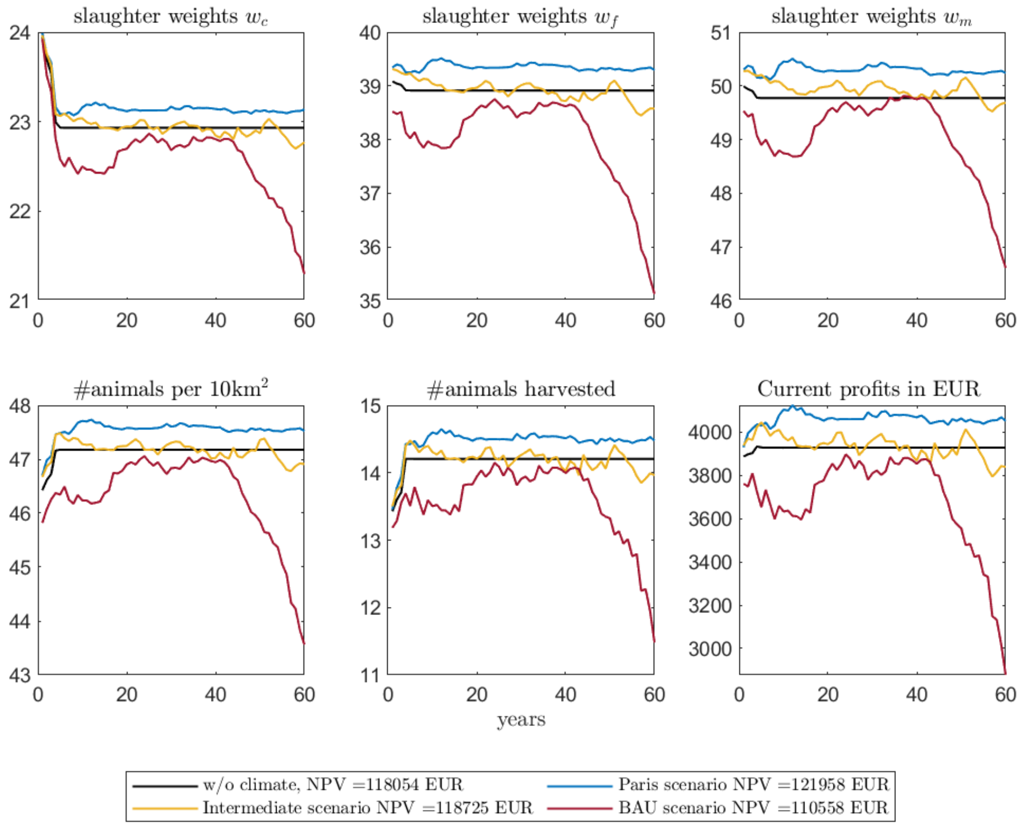


Figure A 2 5-year moving average optimal paths for north Sweden, all scenarios with icing and onset of spring

Figure A 3 5-year moving average optimal paths for mid Sweden, all scenarios with icing and onset of spring

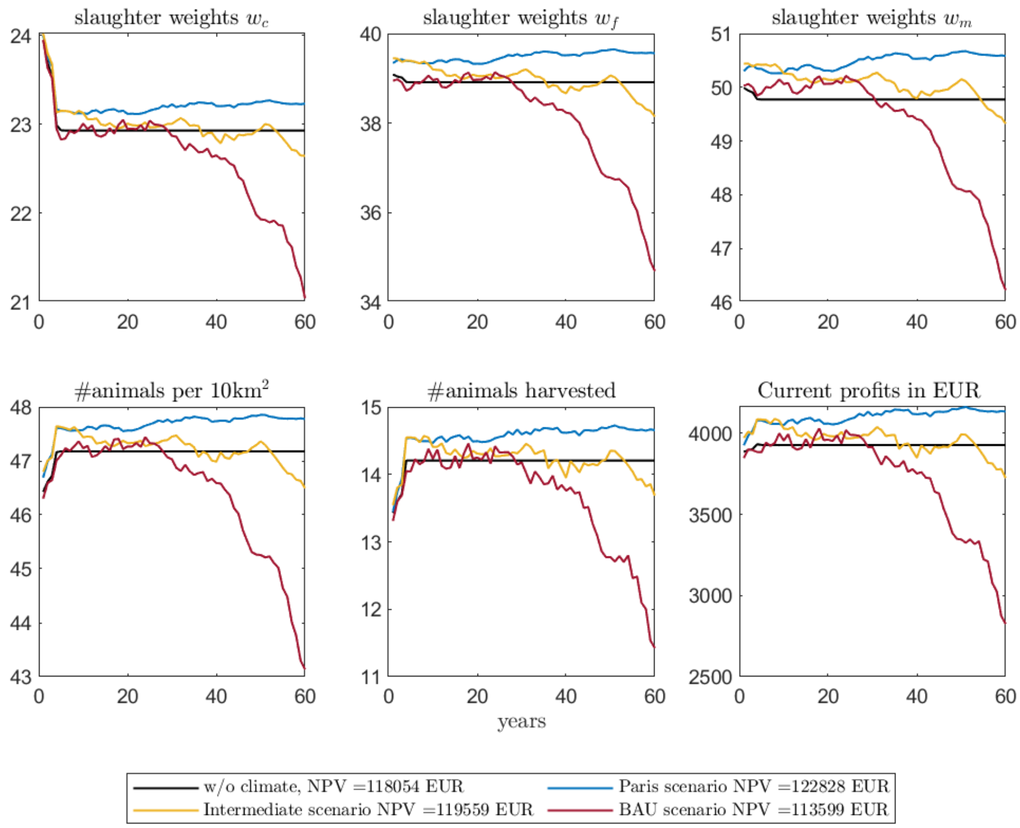
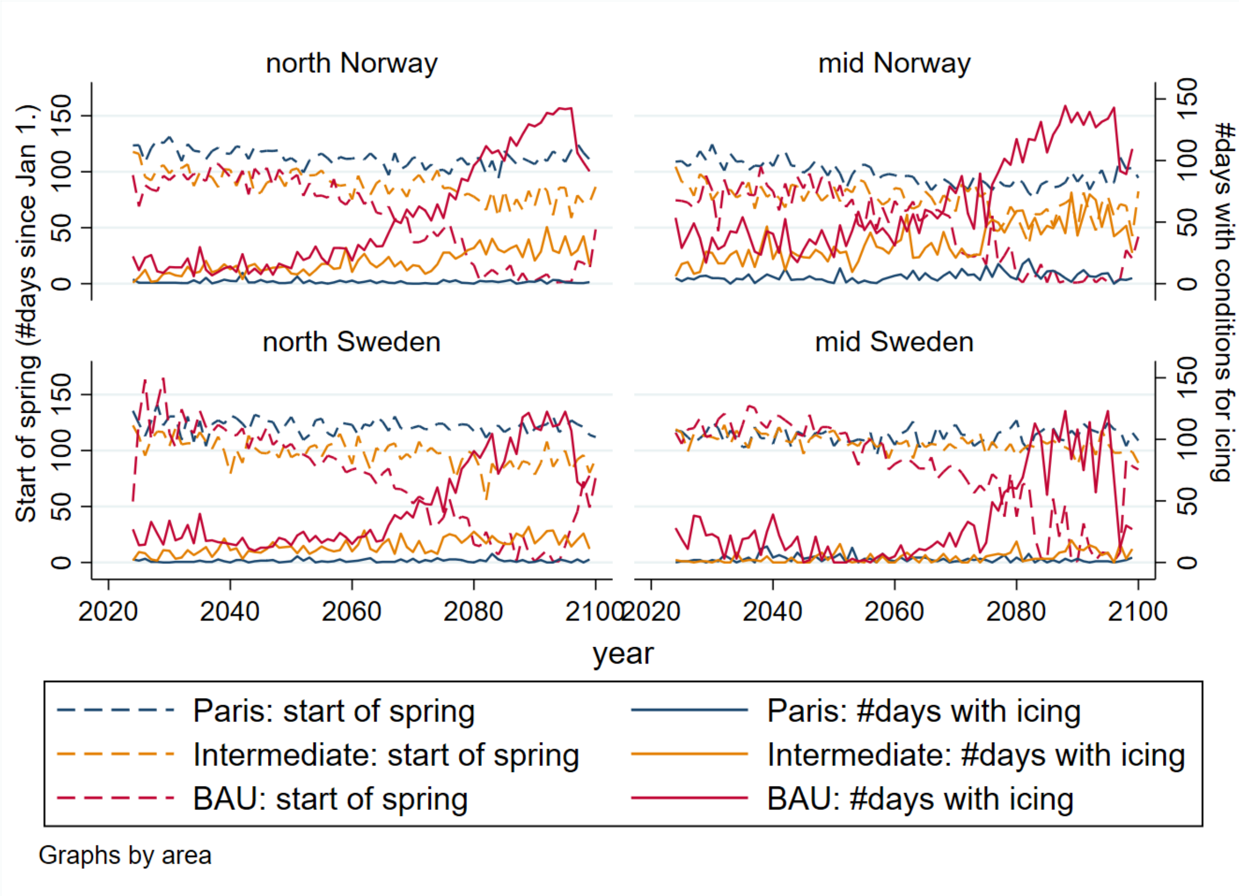


Figure A 4 5-year moving average optimal paths for north Norway, all scenarios with icing and onset of spring

Figure A 5 5-year moving average optimal paths for mid Norway, all scenarios with icing and onset of spring


north Norway
mid Norway
north Sweden
mid Sweden
Start of spring (#days since Jan 1.)
#days with conditions for icing
0
50
100
150
2020
2040
2060
2080
2100
year
Paris: start of spring
Intermediate: start of spring
BAU: start of spring
Paris: #days with icing
Intermediate: #days with icing
BAU: #days with icing
Graphs by area

Supplementary Material (available online)

List of general circulation models (gcms) from the CMIP6 multi-model ensemble used in this study. All variables have been accessed using the Copernicus Climate Change Service, Climate Data Store.

Table S 1. Overview of general circulation models from the CMIP6 multi-model ensemble used in this study

Model (gcm)	experiment	variables	Institution id	Institution
ACCESS-CM2	ssp245, ssp585, historical	Precipitation, near surface air temperature	CSIRO-ARCCSS	Commonwealth Scientific and Industrial Research Organisation (CSIRO)Australian Research Council Centre of Excellence for Climate System Science (ARCCSS)
ACCESS-ESM1-5	historical	Precipitation, near surface air temperature	CSIRO	Commonwealth Scientific and Industrial Research Organisation
AWI-CM-1-1-MR	ssp245, ssp585, historical	Precipitation, near surface air temperature	AWI	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research
AWI-ESM-1-1-LR	Historical	Precipitation, near surface air temperature		
BCC-CSM2-MR	ssp245, ssp585, historical	Precipitation, near surface air temperature, snow depth	BCC	Beijing Climate Center
BCC-ESM1	Historical	Precipitation, near surface air temperature, snow depth		
CAMS-CSM1-0	ssp119, ssp245, ssp585	Precipitation, near surface air temperature	CAMS	Chinese Academy of Meteorological Sciences
CESM2	ssp245, ssp585, historical	Precipitation, near surface air temperature, snow depth	NCAR	National Center for Atmospheric Research, Climate and Global Dynamics Laboratory
CESM2-FV2	Historical	Precipitation, near surface air temperature, snow depth		
CESM2-WACCM	ssp585, historical	Precipitation, near surface air temperature, snow depth		

CIESM	ssp245, ssp585, historical	snow depth	THU	Department of Earth System Science
CMCC-CM2-HR4	Historical	Precipitation, near surface air temperature	CMCC	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici
CMCC-CM2-SR5	ssp245, ssp585, historical	Precipitation, near surface air temperature, snow depth		
CMCC-ESM2	ssp245, ssp585, historical	Precipitation, near surface air temperature, snow depth		
CNRM-CM6-1	ssp245, ssp585, historical	Precipitation, near surface air temperature	CNRM-CERFACS	Centre National de Recherches Meteorologiques (CNRM) and Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique (CERFACS)
CNRM-CM6-1-HR	ssp245, ssp585, historical	Precipitation, near surface air temperature		
CNRM-ESM2-1	ssp119, ssp245, ssp585, historical	Precipitation, near surface air temperature		
CanESM5	ssp119, ssp245, ssp585, historical	Precipitation, near surface air temperature, snow depth	CCCma	Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada
CanESM5-CanOE	ssp245, ssp585, historical	snow depth		
EC-Earth3	ssp119	Precipitation, near surface air temperature, snow depth	EC-Earth-Consortium	"AEMET, Spain; BSC, Spain; CNR-ISAC, Italy; DMI, Denmark; ENEA, Italy; FMI, Finland; Geomar, Germany; ICHEC, Ireland; ICTP, Italy; IDL, Portugal; IMAU, The Netherlands; IPMA, Portugal; KIT, Karlsruhe, Germany; KNMI, The Netherlands; Lund University, Sweden; Met Eireann, Ireland; NLeSC, The Netherlands; NTNU, Norway; Oxford University, UK; surfSARA, The Netherlands; SMHI, Sweden; Stockholm University, Sweden; Unite ASTR, Belgium; University College Dublin, Ireland; University of Bergen, Norway;
EC-Earth3-AerChem	historical	Precipitation, near surface air temperature, snow depth		
EC-Earth3-Veg	ssp119	snow depth		

				University of Copenhagen, Denmark; University of Helsinki, Finland; University of Santiago de Compostela, Spain; Uppsala University, Sweden; Utrecht University, The Netherlands; Vrije Universiteit Amsterdam, the Netherlands; Wageningen University, The Netherlands.
FGOALS-f3-L	historical	Precipitation, near surface air temperature	CAS	Chinese Academy of Sciences,
FGOALS-g3	ssp119, ssp245, ssp585, historical	Precipitation, near surface air temperature, snow depth		
GFDL-ESM4	ssp119, ssp245, ssp585, historical	Precipitation, near surface air temperature, snow depth	NOAA-GFDL	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory,
GISS-E2-1-G	ssp119, historical	near surface air temperature, snow depth	NASA-GISS	Goddard Institute for Space Studies,
GISS-E2-1-H	historical	snow depth		
HadGEM3-GC31-LL	ssp245, ssp585, historical	Precipitation, near surface air temperature	MOHC	Met Office Hadley Centre
HadGEM3-GC31-MM	ssp585, historical	Precipitation, near surface air temperature		
UKESM1-0-LL	ssp119, ssp245, ssp585, historical	Precipitation, near surface air temperature		
IITM-ESM	ssp245, ssp585, historical	Precipitation, near surface air temperature	CCCR-IITM	Centre for Climate Change Research, Indian Institute of Tropical Meteorology Pune,
INM-CM4-8	ssp245, ssp585, historical	Precipitation, near surface air temperature	INM	Institute for Numerical Mathematics, Russian Academy of Science
INM-CM5-0	ssp245, ssp585, historical	Precipitation, near surface air temperature		
IPSL-CM5A2-INCA	Historical	Precipitation, near surface air temperature	IPSL	Institut Pierre Simon Laplace
IPSL-CM6A-LR	ssp119, ssp245,	precipitation		

	ssp585, historical	near surface air temperature snow depth		
KACE-1-0-G	ssp245, ssp585, historical	Precipitation, near surface air temperature	NIMS-KMA	National Institute of Meteorological Sciences/Korea Meteorological Administration, Climate Research Division
KIOST-ESM	ssp245, ssp585, historical	precipitation near surface air temperature snow depth	KIOST	Korea Institute of Ocean Science and Technology
MIROC-ES2L	ssp119, ssp245, ssp585, historical	precipitation near surface air temperature snow depth	MIROC	Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Atmosphere and Ocean Research Institute (AORI),
MIROC6	ssp119, ssp245, ssp585, historical	precipitation near surface air temperature snow depth		National Institute for Environmental Studies (NIES), and RIKEN Center for Computational Science (R-CCS)
MPI-ESM1-2-HR	Historical	Precipitation, near surface air temperature	MPI-M	Max Planck Institute for Meteorology, Hamburg 20146, Germany
MPI-ESM1-2-LR	ssp245, ssp585, historical	Precipitation, near surface air temperature		
MRI-ESM2-0	ssp119, ssp245, ssp585, historical	Precipitation, near surface air temperature, snow depth	MRI	Meteorological Research Institute (MRI)
NESM3	ssp245, ssp585, historical	Precipitation, near surface air temperature	NUIST	Nanjing University of Information Science and Technology
NorESM2-LM	ssp245, ssp585	Precipitation, near surface air temperature, snow depth	NCC	NorESM Climate modeling Consortium consisting of CICERO (Center for International Climate and Environmental Research)
NorESM2-MM	ssp245, ssp585, historical	Precipitation, near surface air temperature, snow depth		MET-Norway (Norwegian Meteorological Institute), NERSC (Nansen Environmental and Remote Sensing Center), NILU (Norwegian Institute for Air Research), UiB (University of Bergen), UiO (University of Oslo) and UNI (Uni Research), Norway.
SAM0-UNICON	historical	Precipitation, snow depth	SNU	Seoul National University

TaiESM1	ssp245, ssp585, historical	Precipitation, near surface air temperature, snow depth	AS-RCEC	Research Center for Environmental Changes, Academia Sinicas

Copernicus Climate Change Service, Climate Data Store, (2021): CMIP6 climate projections. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.c866074c (Accessed on 24.02.2022)

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