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Climate change and reindeer herding – A bioeconomic model on the impact of climate change on harvesting profits for Saami reindeer herders in Norway and Sweden

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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 of pastures and growth of semi-domesticated reindeer, rising temperatures could also lead to increase the frequency of ice-locked pastures, which may negatively affect reindeer body mass, survival, and reproductive success. We create a stage-structured bioeconomic model of reindeer herding that incorporates such counteracting effects of climate change on the economics of reindeer herding in Norway and Sweden. The model is calibrated using historical data on reindeer numbers and slaughter weights, in combination with historical 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 possible future economic impacts of three climate change scenarios, under different assumptions about herders' information about future weather conditions. The negative impact of icing outweighs any positive impact of earlier spring for all scenarios, and the potential loss is greater the less information herders have about future weather conditions.

1. Introduction

Climate change is expected to lead to dramatic changes in living conditions in the Arctic. The main changes include general warming and more variation in temperatures 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 (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 herding communities in Norway and Sweden rely on natural pastures throughout the year and are directly exposed to the effects of climate change on plant productivity and accessibility. Reindeer follow a migratory pattern between winter and summer grazing areas in search for natural grazing grounds (e.g. Johannesen and Skonhoft, 2009 Pape and Löeffler, 2012), a traditional pattern that 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 a practice relying on motorized equipment, more use of supplementary feeding, and meat production for the market (Riseth, 2006 Åhman et al., 2022). Despite its modernization and market orientation, reindeer herding is still an important way of practicing and sustaining Saami culture (Bostedt, 2005 Johannesen and Skonhoft, 2009, 2011), and the central governments in Norway and Sweden have committed to sustain the Saami culture by signing the UN's International Covenant on Civil and Political rights, and emphasize the cultural value of reindeer herding in official statements and through different types of subsidies and compensation schemes (e.g., SMHI,

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2011; Meld. St.prp. Nr.322016–2017; Norwegian Reindeer Herding Administration (NRHA), 2022b).

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 reduce the energy intake and weight of reindeer (Helle and Kojoloa, 1994; Kitti, 2006; Kumpula, 2001). Furthermore, difficult winter conditions are found to increase reindeer mortality during the same winter and lower the number of calves born and surviving the following spring (Aanes et al., 2000; Bartsch et al., 2010; Gaillard et al., 2000; Hansen et al., 2011; Helle and Kojola, 2008; Kitti, 2006; Kumpula and Colpaert, 2003; Putkonen and Roe, 2003; Turunen et al., 2009; Tveraa et al., 2003).

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 Kojola, 2003; Albon et al., 2017 Bårdsen and Tveraa, 2012 Pettorelli et al., 2005 Tveraa et al., 2013) and reproductive success (Aikio and Kojola, 2003). On the other hand, delayed autumnal frost may cause mold formation and waters to freeze later, making migration to winter grazing areas more difficult (Furberg et al., 2011 Rasmus et al., 2018).

Through its impact on grazing opportunities and availability, climate change could affect the harvesting profit in reindeer herding through animal weights and stock dynamics. This paper examines possible consequences of climate change for harvesting profit in Saami reindeer herding 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 climate-weight and climate-population relationships. Bioeconomic models are used to study economic optimal use of biological resources and include a description of the ecological and economic parts included in the system. The level of details included in the present model is restricted relative to reality but fits well with the data sources used to analyze possible economic effects climate changes. We estimate the climate-weight relationships using historical data on reindeer weights and weather conditions. We then insert the estimates into the bioeconomic model to solve for the minimum economic loss of climate change and apply the model to simulate possible future economic effects in reindeer herding using data on future weather conditions from existing climate projections from the CMIP6 multi-model dataset (Eyring et al., 2016).

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 increase 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 leading to more than a 4 °C increase in global mean temperature by the end of the century (Riahi et al., 2017 Lee et al., 2021). These will now be called the Paris-scenario, the intermediate scenario, and the business-as-usual (BAU) scenario, respectively. To the best of our knowledge, no other studies that combine historical weather conditions and projected future climate for both summer and winter weather conditions, exist for reindeer herding.

Related bioeconomic modeling contributions include Pekkarinen et al. (2022), who analyzed possible effects of changing winter climate conditions on the economics of reindeer herding in Finland using historical knowledge from reindeer herders to predict future frequency, causes and consequences of difficult winter conditions. However, previous studies have not examined the combined economic consequences of changes in winter and summer grazing conditions. In the present, we analyze how climate change affecting both winter and summer grazing conditions impact animal weights, population sizes and economic return in Saami reindeer herding. We do so under different assumptions regarding expectations and adjustments to climate change. Furthermore, because climate projections predict changes that vary across geographical areas, we present economic illustrations for different regions in Norway and Sweden.

The rest of the paper is organized as follows. Section 2 gives a brief overview of Saami reindeer herding in Norway and Sweden. Section 3 presents a bioeconomic optimization model where the objective is to maximize net present profits in reindeer herding. Section 4 presents data on historical weather, climate projections, and reindeer weights, and estimates 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 is done under various assumptions about herders' information about future climate scenarios and how they may adjust to these scenarios. 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. Norwegian and Swedish governments provide Saami reindeer herders user rights to grazing land and roughly 40% of the mainland in Norway and Sweden is designated reindeer pasture (Moen, 2008 Tyler et al., 2007). The tradition of natural seasonal migration of reindeer between winter and summer grazing areas is largely maintained, although distances may vary across reindeer herding regions (Henden et al., 2014).

2.1. Saami reindeer herding in Norway

In Norway, 3300 people are involved in reindeer herding and organized in 540 reindeer herding units (Norwegian Reindeer Herding Administration (NRHA), 2022). 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 reindeer population (Norwegian Reindeer Herding Administration (NRHA), 2022). The reindeer herding regions cover a total of 70 reindeer herding districts (Norwegian Reindeer Herding Administration (NRHA), 2022). The total reindeer population counts some 220,000 animals (Norwegian Reindeer Herding Administration (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 to 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 the northernmost part of the blue area in Fig. 1). Here, herds migrate from 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 forage (Tveraa et al., 2007 Weladji and Holand, 2003). Reindeer herding in Trøndelag in mid Norway (dark green area in Fig. 1) is more stationary with some populations having winter and summer pasture within the same geographical area, and some populations doing shorter migrations 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, some of which are used throughout the year, while some herds migrate to mountain areas during spring

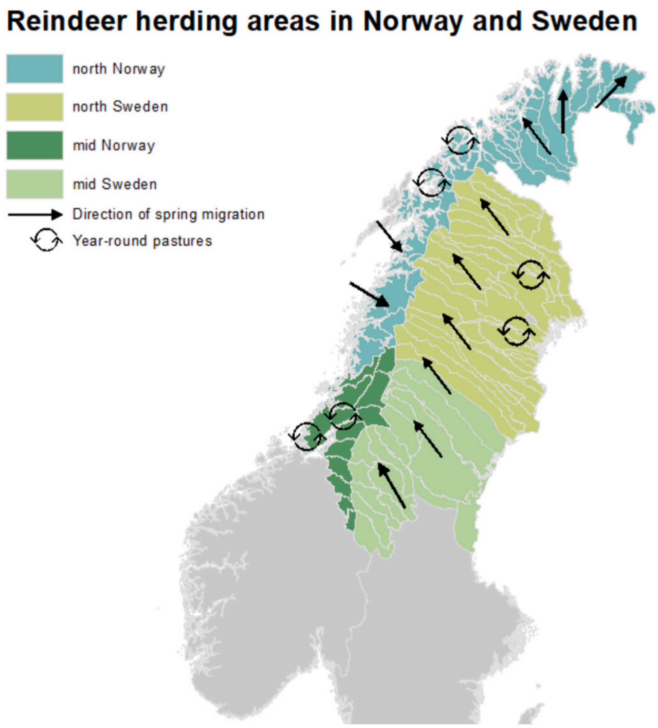

Fig. 1. Reindeer herding regions and reindeer herding communities in Norway and Sweden, respectively. The colors indicate the four simulation areas. Arrows indicate spring migration and year-round pastures (Source: Pape and Löeffler, 2012).

(Risvoll and Hovelsrud, 2016 Tveraa et al., 2007 Weladji and Holand, 2003).

Reindeer productivity, measured by slaughter weights, and income varies substantially across regions, with mid Norway (Trøndelag, dark green area in Fig. 1) being among the best performing areas over time (Norwegian Reindeer Herding Administration (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).

2.2. Saami reindeer herding in Sweden

In Sweden, about 4600 people are involved in reindeer herding (Sametinget, 2023). Saami reindeer herding takes place in four regions (counties), from Dalarna in mid Sweden to Norrbotten in north. The reindeer herding regions are divided into a total of 51 Saami villages, herby referred to as Reindeer herding communities, a management unit level approximately corresponding to a reindeer herding district in Norway. The total reindeer population counts about 250,000 to 300,000 animals (Sametinget, 2021).

Reindeer herding may be conducted all year round in the counties of Norrbotten, Västerbotten (lime colored area in Fig. 1), Jämtland and Dalarna (the light green areas in Fig. 1). In winter, reindeer herding may also be conducted in the coastal areas of Norrbotten and Västerbotten. Reindeer herders from Sweden may, in accordance with Norwegian law, also conduct reindeer herding in the summer in certain areas on the Norwegian side that are established in a convention between Sweden and Norway.

33 of the 51 reindeer herding communities are mountain Saami communities (Sametinget, 2021). In this type of Saami community, the reindeer herds are migratory and 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. In contrast, there are 10 forest Saami communities (Sametinget, 2021). Similar to Trøndelag in Norway, the reindeer herds are more stationary in these communities and graze in the forestland all year round. Finally, concession reindeer herding is a form of reindeer herding that is only conducted in the easternmost part of Norrbotten. There are eight concession Saami reindeer herding communities, and they typically have small reindeer herds (Sametinget, 2021).

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 but expand the model by including climate-weight and climate-population relationships. 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. Modeling only two year-classes (calves and adults) is a simplification compared to Pekkarinen et al. (2022) but is in accordance with the available data in Norway and Sweden.

The sequences over the year as described in the model are illustrated in Fig. 2. The reindeer population is counted in spring just before calving. The animals gain weight during spring, summer and early autumn, and the weight gain is affected by weather 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). The winter grazing conditions impact natural mortality both directly, and indirectly through the weight impact. The former accounts for the notion that extreme and difficult winters may increase mortality through winter starvation, even if weights in the autumn are high. Finally, climate conditions affect recruitment indirectly through the weight of female adults.

The use of supplementary feeding is ignored in this model but see Pekkarinen et al. (2015) for a model of reindeer herding in Finland including supplementary feeding. In Finland, supplementary feeding is used regularly throughout the winter (Åhman et al., 2022) but this is

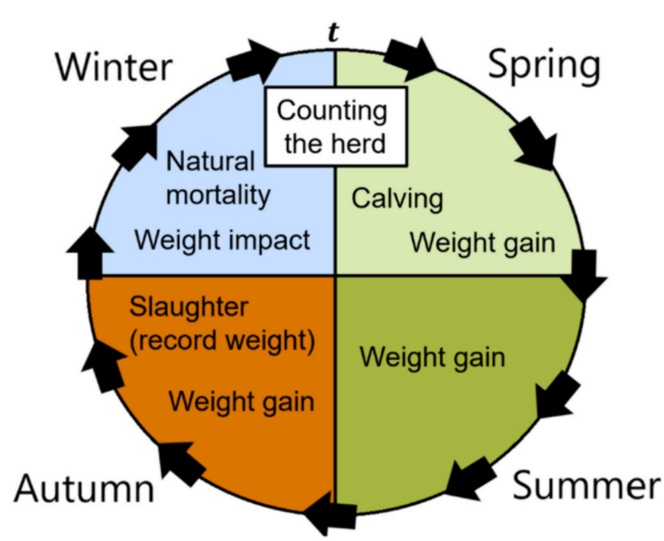

Fig. 2. A representation of yearly cycle for reindeer growth and herd changes as implemented in the model.

rarer in Norway and Sweden. While reindeer herders in Norway and Sweden may use supplementary feeding during events of (extreme) food limitation, many herders are reluctant to incorporate supplementary feeding as part of their regular practice because they see it as contrary to the traditional way of practicing Saami reindeer herding. Some are even prepared to quit reindeer herding if feeding becomes regular practice (Sandorf et al., 2024). We therefore neglect supplementary feeding in this paper and focus instead on adjustments in herd size and herd composition as major strategies to cope with climate change.

Because calves are born in the spring, the fertility rate (number of calves per female) depends on female weight the previous year and just before calving (Johannesen and Skonhoft, 2009). The number of calves (recruitment) in year t is then give as:

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

where $f_t > 0$ and follows the same functional form as in Johannesen and Skonhoft (2009). However, the present also accounts for the negative impact on recruitment of any weight loss of females during winter. When defining $C_{W,t-1}$ as a variable capturing winter weather conditions in year *t-1* and α_{Wf} as a winter effect parameter, we specify the fertility function as:

$$f_t = \bar{f}\left(\left(w_{f,t-1} + \alpha_{Wf}C_{W,t-1}\right)/\overline{w}_f\right)^a \tag{2}$$

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

The natural survival rates $0 < s_{i,t} < 1$ are assumed to depend on pasture conditions through the weights in year t and are generally different for the different age classes. We apply the same functional forms as Johannesen and Skonhoft (2009) and specify the survival rate of category i as:

$$s_{i,t} = \bar{s}_i\left(\left(w_{i,t} + \alpha_{W,i}C_{W,t}\right)/\overline{w}_i\right)^{b_i} - \Omega_{i,t}(C_{W,t}); i = c, f, m \tag{3}$$

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.[2] Winter weather conditions in year t affect survival in year t indirectly through the impact on animal weights (first term in Eq. (3)) and directly through $\Omega_{i,t}(C_{W,t})$. This is a function representing the direct negative effect of difficult winter conditions, such as ice locked pastures and starvation, on survival. This direct shock effect is typically larger for calves, and weak old animals (Solberg et al., 2001, Chan et al., 2005, Gaillard et al., 2000). Lower survival rates will all else equal lead to smaller herd sizes, but the magnitude of the effect will depend on herders' harvesting adaptation. Modeling the direct shock as additive is a simplification of reality as it is likely that the impact of difficult winter conditions interacts with reindeer density and competition over limited available food. The functional form of $\Omega_{i,t}(C_{W,t})$ is specified in the numerical analysis, Section 5.1.

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. Because the population is counted in spring and weight is measured during slaughter in the autumn, the autumn weight of adult animals in year t ($w_{i,t}$ for $i = f, m$) depends on summer weather conditions in year t ($C_{S,t}$) and winter weather 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 at the time of calving (i.e., slaughter weight plus any impact of the winter just prior to calving) (Tveraa et al., 2003).

The weight-density relationships are specified as sigmoidal functions where $w_{iX_t} \leq 0$, see Fig. 3 (Mysterud et al., 2001, Nilsen 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. This is a simplification which obviously may not hold but see Section 4.3 for a discussion and how we treat this in the empirical analysis. Therefore:

$$w_{i,t} = \frac{\overline{w}_i}{1 + (X_t/K)^\beta} + \alpha_{S,i}C_{S,t} + \alpha_{W,i}C_{W,t-1}; i = f, m \tag{4}$$

and

$$w_{c,t} = \frac{\overline{w}_c}{1 + (X_t/K)^\beta}\left(\frac{w_{f,t-1} + \alpha_{Wf}C_{W,t-1}}{\overline{w}_f}\right) + \alpha_{S,c}C_{S,t} \tag{5}$$

Previous studies suggest that more favorable summer weather conditions have a positive impact on weights ($\alpha_{S,i} > 0$) whereas less favorable winter conditions have a negative impact ($\alpha_{W,i} < 0$) (Aikio and Kojola, 2003 Albon et al., 2017 Bårdsen and Tveraa, 2012 Furberg et al., 2011 Pettorelli et al., 2005 Tveraa et al., 2013). The parameters $\alpha_{S,i}$ and $\alpha_{W,i}$ are estimated in Section 4 using historical data on animal and weather factors in Norway and Sweden.

Fig. 3 illustrates the weight-density relationship where the 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 (i.e., where $\alpha_{S,i}C_{S,t} + \alpha_{W,i}C_{W,t} < 0$) 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 thus limit the weight reduction by a movement upwards the new weight-density curve.

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 ($i = c, f, m$), the change in the size of the female and male population over time is written as:

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

and

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

3.2. Economic model

The economic effects of climate change are studied by considering

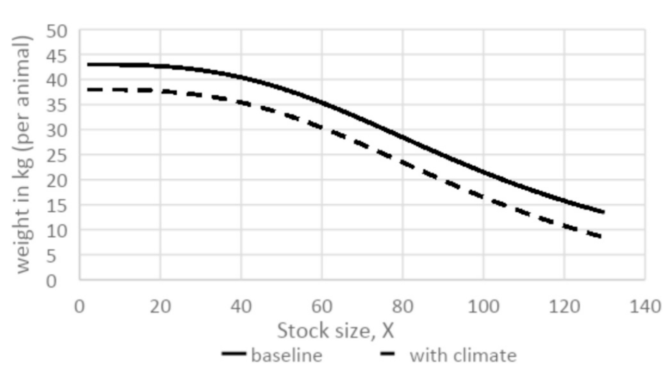

Fig. 3. Climate and slaughter weight - density relationship, baseline parameter values for adult females (see Table 5) and net negative climate effect.

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

[2] Similarly, $s_t = 1$, if $w_{i,t} > \overline{w}_i$

optimal herd management, as in Johannesen et al. (2019), Pekkarinen et al. (2015, 2022) 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 the cultural values inherent in Saami reindeer herding. Still, this simplification enables us to highlight the impact of climate change on productivity and, hence, harvesting profits.

We consider a reindeer herding area where the number of animals slaughtered in year t is given by $H_t = \sum_{i\in(c,f,m)} h_{t,i}X_{t,i}$. Thus, the current income from slaughtering may be written as.

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

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% of the domestic production of red meat in Norway. 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:

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

The cost function is typically strictly concave for rather small stock sizes before it becomes fairly linear, (NRHA, 2021). Following Johannesen et al. (2019) we assume constant marginal costs, i.e., $C' > 0, C'' = 0$. Climate change and weather conditions may affect herding costs, e.g. difficult winters require more intense herding, while delayed onset of winter may interrupt migration routes (Furberg et al., 2011). However, ignoring any (direct) impact of climate conditions on costs enables a strict focus on how relative changes in winter and summer weather affect animal weights and survival and thereby the economic return in reindeer herding.

The optimization problem of a unified reindeer manager is to determine the harvesting rates of calves, adult females and adult males that maximizes present value profits, i.e., $p\left(w_{c,t}h_{c,t}X_{c,t} + w_{f,t}h_{f,t}X_{f,t} + w_{m,t}h_{m,t}X_{m,t}\right) - C\left(X_{c,t} + X_{f,t} + X_{m,t}\right)$, subject to Eqs. (1), (6), and (7), and an upper constraint on the harvest of adult males. ρ is the discount factor. It follows that the only possible adaptation strategy to a changing climate in this model is to adjust harvest rates, and thus the herd size and its composition.

The model is analyzed in Section 5, where we start by assuming that reindeer herders have complete knowledge about future climate changes and hence, the optimization problem is solved as deterministic. Complete knowledge is obviously a simplified assumption which is discussed in Section 5 where we also provide alternative assumptions for how future climate scenarios are treated in the optimization problem.

Finally, the assumption of a unified manager implies that any internal externalities between individual herders in the utilization of common pastures are ignored in the present (but see Johannesen and Skonhoft (2009)). That is, we do not allow for externalities to affect adjustments to climate change.

4. Data and estimation

The climate-weight relationships are now estimated using historical data on herd sizes and slaughter weights (Norwegian Reindeer Herding Administration (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. The data also include information on the total number of reindeer in each district (i.e., lower-level reindeer herding administrative units, see Section 2.1). The dataset covers 67 of the reindeer herding districts in Norway. For Sweden, we have country level average slaughter weights for the period 1997 to 2020, and average number of reindeer per reindeer herding community. 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 Norway, see Table 1. 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.

4.2. Weather data and climate projections

The weather variables of focus in this paper include the onset of spring, snow depth, and weather conditions predicting icing. The paper utilizes weather data for two purposes: Section 4.3 uses historical weather data to estimate the climate-weight relationship, and Section 5 uses data on future climate projections to simulate possible future effects of climate change based on the bioeconomic model. For both purposes we use multi-model ensemble data from the sixth phase of the Coupled Model Intercomparison Project (CMIP6). These are considered global climate models with a grid-level of 250 to 100 km, and thus the data and our analysis ignore some of the local details in weather conditions that could impact reindeer herding. Although more detailed datasets, such as the ERA5 reanalysis data for historical data, and the regional climate models from the CORDEX project, allows for a finer granularity of the weather data, we have chosen to keep one data source for both time periods. Also, at the time the dataset was constructed, the regional climate models lacked suitable information on snow depth. Furthermore, we have chosen reindeer herding regions (rather than districts) as the level of aggregation since reindeer often migrate across huge areas and hence are exposed to weather conditions outside their reindeer herding districts.[3] For the numerical illustrations in Section 5 the data are further aggregated into four geographical areas.

To construct the final dataset, we use daily data on temperature and total precipitation, and monthly data on 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).[4] For all scenarios, we have used the available

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	28
Reindeer per district	3000	3998	23	34,639

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

[4] 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.

models to calculate multi-model ensemble means.[5] To illustrate the variation and uncertainty related to climate projections, we also consider the upper- and lower bound of the relevant variables. Although a 95% confidence interval would be preferable, not all area-period combinations are represented by enough models to calculate this. We consider year to year weather variations, instead of the standard 30-year climate mean, to capture and study how any increased variation and extreme weather conditions may impact the economics of reindeer herding.

Panel A in Table 2 presents descriptive statistics on the historical weather data, covering the entire study area for the 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. Fig. 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 is 4.7 days per year in the historical data set, with some regions having experienced extreme years with up to 24 days with icing conditions. Spatially disaggregated descriptive statistics can be seen in Appendix A.1.

Table 2
Descriptive statistics of historical climate 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	127.8
B. Paris scenario (SSP 1–1.9)	Start of spring (#days since 1. Jan.)	115.02	6.05	94.02	131.90
	#days with icing Nov-Mar	10.64	3.31	3.44	24.85
	Mean snow depth Dec-Jan (cm)	29.34	4.89	17.97	45.03
	Mean snow depth Feb-Mar (cm)	49.13	6.31	33.31	67.05
C. Intermediate scenario (SSP 2–4.5)	Start of spring (#days since 1. Jan.)	103.37	10.30	76.73	127.44
	#days with icing Nov-Mar	23.79	7.52	9.25	42.74
	Mean snow depth Dec-Jan (cm)	20.21	5.02	7.46	38.31
	Mean snow depth Feb-Mar (cm)	37.13	7.28	16.18	60.95
D. BAU scenario (SSP 5–8.5)	Start of spring (#days since 1. Jan.)	45.85	40.44	1.00	128.64
	#days with icing Nov-Mar	30.53	15.06	0.00	77.00
	Mean snow depth Dec-Jan (cm)	7.41	8.79	0.00	39.04
	Mean snow depth Feb-Mar (cm)	14.52	16.31	0.00	71.55

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 (shared socioeconomic 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 the fossil fuel driven business-as-usual scenario with an increase in global mean temperature above 4 °C (BAU) (SSP 5–8.5) (Eyring et al., 2016; Riahi et al., 2017, Lee et al., 2021). The SSP scenarios are climate change scenarios that incorporate how global trajectories in socioeconomic variables, such as population growth, economic development, inequality, and climate policies, affect the trajectory of greenhouse gas- emissions and concentration, and thus changes in global mean temperature (IPCC, 2023). It is well established that climate change and an increase in global mean temperature will affect different regions of the world differently, and while the global climate models used in this paper to some extent account for varying effects across geographical regions, they are not as detailed as the regional climate models. Thus, the projections in Table 2, which are based on 250–100 km grids, may not be considered local projections. In particular, local weather is influenced by altitude and proximity to the ocean which cannot be appropriately accounted for in larger grids.

As seen in Fig. 4, already in the Paris scenario there is a slight shift in the trends of onset of spring and the occurrence of icing, relative to the historical dataset, but both variables fluctuate around extremes we have seen historically. Both the Intermediate and BAU scenario depict a much stronger trend in earlier spring and increase in the number of days with icing. The main difference is that the trend in both variables appears to flatten after 2050 in the Intermediate scenario, while the steep change continues in the BAU scenario. Figs. A1 and A2 in Appendix A.1 illustrates variables disaggregated by area, and includes the mean, upper- and lower bound estimates for onset of spring and icing days.[6] In general, the southern areas will experience an earlier onset of spring, but none of the variables exhibit any clear difference between the geographical areas. However, if we consider the upper and lower bound estimates in Figs. A1 and A2, north Norway has a greater occurrence of potentially late onset of spring. While both north and mid Norway also have much higher upper bounds, up to 150 days, for the number of days with conditions for icing. It may also be seen that the upper and lower bounds of the different scenarios quite often overlap.

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 weather variables. The first column reports the results from a regular OLS, while the second column also includes reindeer herding district 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

[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] Descriptive statistics disaggregated by the four simulation areas can be seen in Appendix A.1.

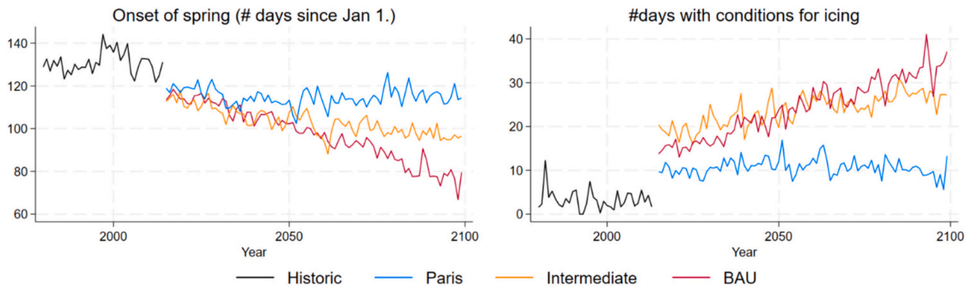

Fig. 4. Past and projected onset of spring and number of days with conditions for icing.

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: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

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 effect on slaughter weights, which confirms the density dependence of slaughter weights. However, the effect size is 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 g, 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 g higher than average. This is a 0.09% increase in the average slaughter weight of adult females. One more day with icing, compared to the average number of icing days, is related to a decrease in slaughter weights of 67 g. This is a reduction of 0.22% compared to the average. As mentioned in Section 3.1, 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 any supplementary feeding that may have occurred during the study period, and thus mitigated the impact of icing, the true effect 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 increased 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).

While the continuous specification of start of spring allows for convenient comparison of our two main weather 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 plant biomass and productivity of a pasture of fixed size may not be linearly increasing in an earlier onset of spring. In fact, specifying a limit to the productivity of a pasture of fixed size where the impact of an even earlier onset of spring is negligible may be more realistic. Furthermore, the relationship may even change in sign as an earlier onset of spring may be related to an earlier start of summer and more drought degrading the pasture too early. Secondly, even with high productive pastures there is a limit to how much the reindeer can consume and gain in weight.

Therefore, specifying the relationship between onset of spring and slaughter weights as linear must be seen as a simplification. This simplification is 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 where “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.[7] 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

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

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. However, 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.

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. The bioeconomic model is solved for the three future climate scenarios, the Paris, Intermediate, and BAU-scenarios, and for four simulation areas, mid and northern Norway, and mid and northern Sweden. For comparison, we also present a benchmark scenario without any climate effect ($C_{S,t} = C_{W,t} = 0$). The benchmark scenario is treated as equal for all simulation areas, which enables a comparison of future scenarios across areas caused by climate changes alone.

As mentioned in Section 3, the model is first optimized under the assumption that the unified reindeer herders can predict future climate changes perfectly. We therefore derive a first-best adaptation to future climate changes, which can also be interpreted as the minimum economic loss of climate change. This assumption is then relaxed by assuming that reindeer herders adjust to an expected trend in the climate variables. We then compare the impact on the economics of reindeer herding in the two situations, before considering some cases where there is mismatch between the expectations, and thus harvest rates, of reindeer herders and the climate projections they face.

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

Variables	(1) Slaughter weight female	(2) Slaughter weight male	(3) 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: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

5.1. Parameter values

To account for the spatial heterogeneity in climate within and across countries, we consider four geographical areas, denoted as mid Norway (Trøndelag, dark green area in Fig. 1), north Norway (Nordland, Troms and Finnmark, blue area in Fig. 1), mid Sweden (Jämtland, light green area in Fig. 1) and north Sweden (Norrbotten and Västerbotten, lime colored area in Fig. 1). We start out with identical weights, stock size and stock composition across areas to focus on how the climate impact differs across geographical areas due to variation in climate projections. Hence, the model is specified with the same baseline parameter values for all areas. This is of course a simplification as productivity and stock sizes vary across areas due to e.g., vegetation and topographical dissimilarities, but it enables us to identify future geographical differences caused by climate changes alone (see e.g., Section 2.1 and Skonhoft et al., 2017).

The baseline parameter values are presented in Table 5. Most of the parameters are based on Johannesen et al. (2019) but have been further calibrated to the current model. Present maximum slaughter weights are updated based on maximum observed weights in the historical dataset. As in Johannesen and Skonhoft (2011), baseline carrying capacity of pastures is set to 100 animals per 10 km^2, the price for calf and adult meat is considered equal, and the per animal maintenance cost is assumed constant.

The initial number of reindeer is set to 15 for each category, which sums up to 45 animals per 10 km^2. This is just below the average allowable upper limit for reindeer herding districts as set by the management authorities in Sweden and Norway. The tradition of reindeer herding has continued for multiple centuries and the aim is for it to continue for centuries more. Accordingly, in the theoretical setup in Section 3.2 net present value is maximized over an infinite time. As the climate projection data are limited to 2100, simulations are run over 76 years where the last 10 years are excluded from the figures below to mimic the steady state solution of an infinite time horizon.[8] Moreover, because many reindeer herders have already noticed the effect of climate change, it is of interest to start the simulation with projections from 2023 to study possible adaptation strategies in the present and near future.

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” reported in Table 4.

In the case where herders have perfect information about future climate predictions, $C_{S,t}$ and $C_{W,t}$ represent the yearly projected onset of spring and number of days with icing conditions as constructed from the CMIP6 multi-model ensemble (see Section 4.2). When we relax the assumption of perfect information, $C_{S,t}$ and $C_{W,t}$ represent the trend in each of these variables. The trends are generated by fitting a linear regression model to the weather variables. These are illustrated in Fig. A3 in Appendix A.1.

When it comes to the functional form of the survival functions, there is little empirical evidence on how icing affects survival. Most studies compare mortality in years with icing conditions with mortality in years without icing, without stating the level of icing required for a year to be considered as a year with icing. Bartsch et al. (2010) suggested that icing

[8] With a finite time horizon, and no scrap value, it will always be optimal to slaughter and sell all animals in the last time periods. Thus, it is common practice to exclude the last ten years when illustrating an infinite time horizon problem with a finite numerical illustration.

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	Norwegian Reindeer Herding Administration (NRHA) (2014)
Parameter fertility rate	a	0.4		Johannesen et al. (2019).
Maximum weights	$\overline{w}_c, \overline{w}_f, \overline{w}_m$	28, 44, 55	Kg/ animal	Directorate 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	Johannesen et al. (2019)
Meat price	p	7	EUR/kg	Norwegian Reindeer Herding Administration (NRHA) (2020)
Maintenance cost	c	10.5	EUR/ animal	Johannesen et al. (2019).
Discount rate[a]	δ	0.03		Assumed
Male harvest constraint	$\bar{h}_m$	0.7		Skonhoft et al. (2017)
Initial herd size	$X_{f,0}, X_{m,0}, X_{c,0}$	15,15,15		Assumed
Summer/spring weather coefficient	$\alpha_{S,f}, \alpha_{S,m}$	[0.616, −0.809], [0.838, −1.276]		Estimated
Winter weather coefficient	$\alpha_{W,f}, \alpha_{W,m}$	−0.0602, −0.0581		Estimated
Yearly projected onset of spring (dummies for early/late spring)/trend	$C_{S,t}$			Projected data (Norwegian Reindeer Herding Administration (NRHA), 2021)
Assumed trend in/Yearly projected number of days with icing conditions/ trend	$C_{W,t}$		Number of days per year	Projected data (Norwegian Reindeer Herding Administration (NRHA), 2021)
Icing induced increase in mortality	m	0.5		Assumed

[a] Sensitivity analysis is conducted with a 0% discount rate.

led to a 25% reduction in the population, while Helle and Kojola (2008) reported a 50% increase in mortality rate in years with icing. Thus, we apply a simplified approach where mortality increases with 25 or 50% relative to the benchmark mortality rate if the number of days with icing exceeds 4.7, that is, the average number of days with icing conditions in the historical data set (1984–2014). The benchmark mortality rate, $s_i^{benchmark}$ is the steady state mortality rate, for each of the stage classes from the benchmark scenario without climate effects. As such, the negative shock function in (3) is specified as $\Omega_{i,t}(C_{W,t}) = m(1 - s_i^{benchmark})$ if $C_{W,t} > 4.7$, where m is icing-induced increase in mortality. Because benchmark mortality differs across stage classes, this formulation will also account for the fact that icing affects the survival of calves to a greater degree than adults. We use $m = 0.5$ as the baseline parameter value and conduct sensitivity with $m = 0.25$. From Fig. 4 and Table A1 in the Appendix it is clear that the negative shock will enter our model every year in the BAU and Intermediate scenario, and most years in the Paris scenario, when considering the multi-model ensemble means of the climate projections.[9] When considering the lower-bound projections there is more variation in the number of years with conditions for icing exceeding 4.7 days and hence, the number of years with the negative climate shock reduces. This could increase herd size, depending on the response of herders, but it would definitely lessen the negative impact of climate change. Another alternative is to use a step-wise function with different cutoff and magnitudes for the shock, however there is as far as we know, no empirical indication of what this function would look like.

5.2. Results

As mentioned above, the bioeconomic model is first solved under the assumption that reindeer herders have perfect information about future climate conditions and can adjust the number and composition of slaughtered animals optimally, as such this represents the minimum economic loss of climate change. While this is far from realistic, it is a useful thought experiment, which could reveal some tendencies, and serve as a hypothetical best-case and comparison for alternative setups. This will be referred to as the perfect information case. We then solve the model under the assumption that the future climate variables follow a trend and where herders expect the climate to follow this trend. This case is referred to as the trend case. Fig. 5 reports optimal paths for slaughter weights, herd size, total animals slaughtered and current value profits (with total NPV in the legend), for all three climate scenarios. Here we present only the case of north Sweden, while the other geographical areas are presented in appendix A.2. This is done because the difference between areas is relatively small, and we prioritize exploring the difference between climate change scenarios instead. The solid lines indicate the optimal path in the case of perfect information, whereas the dashed lines indicate the optimal path in the trend cases.

The initial herd size is close to the optimal herd size without any climate effects (w/o climate), and thus it only takes a few years for this scenario to reach its steady state. In the perfect information climate change cases, the climate variables act as yearly shocks to the slaughter weights and survival rates, preventing the system from reaching a steady state. For all geographical areas, the perfect information solution fluctuates around the optimal path in the trend case in both the Paris and Intermediate scenarios. The somewhat greater deviation between the perfect information and trend solutions in the BAU scenario highlights that climate change also increases the variation in the weather conditions.

In all climate scenarios it is optimal to keep a smaller reindeer population relative to the benchmark scenario with no climate effect. This increases slaughter weights as competition over grazing resources reduces, but not enough to offset the reduction in profits that follow from a lower total harvest rate coupled with the smaller herd. Due to the instability of the perfect information paths, it is difficult to determine any optimal adaptation strategy. However, given the baseline parameter values, it is always optimal to harvest the maximum number of adult males (i.e. = 0.7), to harvest females but not to harvest calves. Thus, Fig. 5 only illustrates the harvest rate of females. As expected, icing negatively impacts natural survival, which also contributes to a smaller reindeer population when climate is included. In this model the increased mortality from icing *(m)* must reach 1.45 before it is optimal to harvest calves instead of adult females in the intermediate and BAU scenario in mid Norway and Sweden. At $m = 1.8$ harvest of calves is

[9] In the Paris scenario there are four years in northern Sweden and two years in mid Sweden in which the shock does not enter.

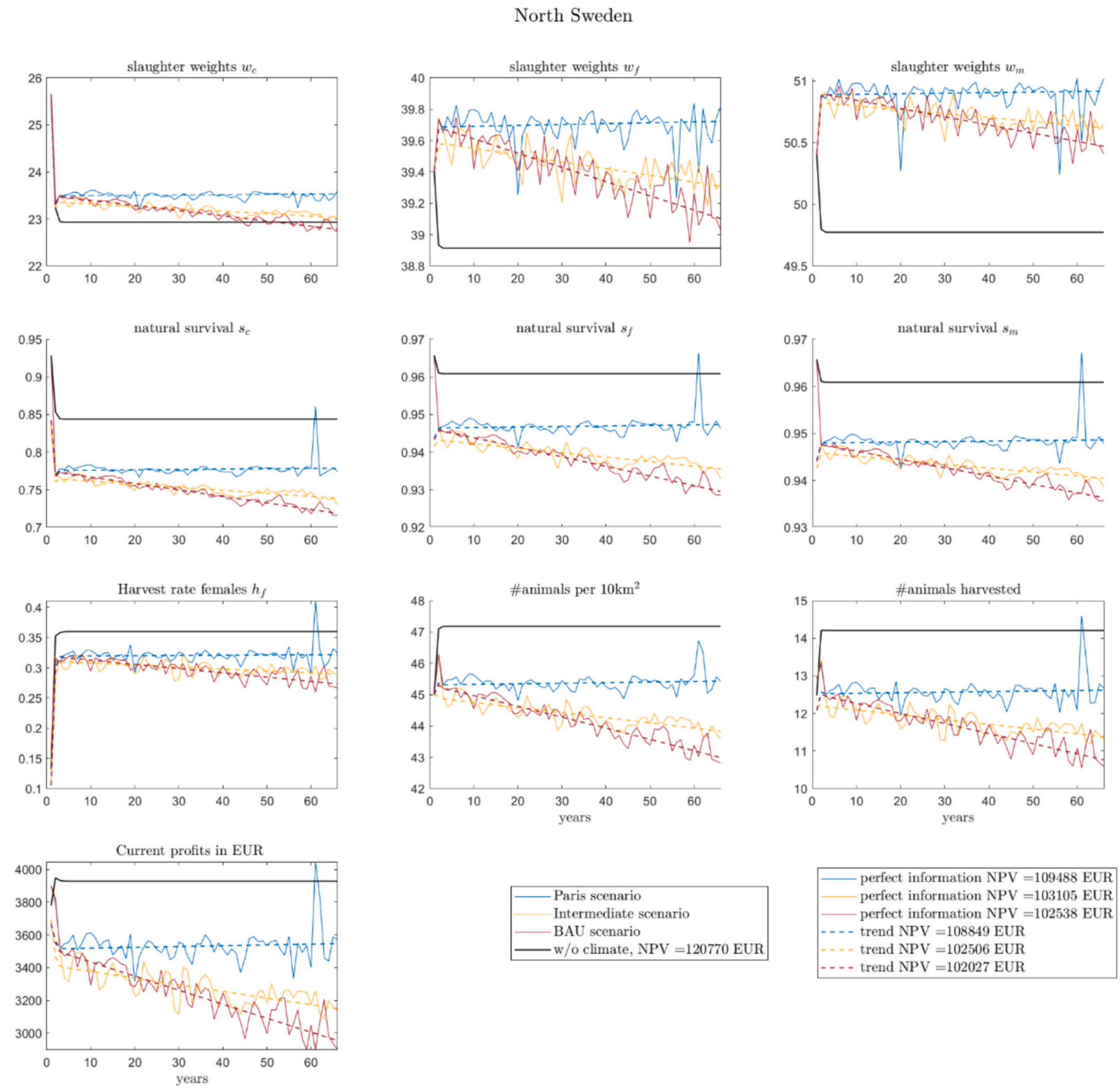

Fig. 5. Optimal paths for the perfect information and trend case for all climate change scenarios in north Sweden, baseline parameter values.

optimal for the majority of area-scenario combinations. See also Section 6. Thus, most of the adaptation arises from changes in the harvest rate of adult females, and with more severe climate change scenarios it is optimal to reduce the harvest rate of females compared to the benchmark scenario with no climate change.

In both the Paris and Intermediate scenarios, the perfect information case fluctuates around the trend case. In contrast, there is no overlap between the optimal adaptation strategy with full information and the trend adaptation strategy in the BAU-scenario. It is also evident from Fig. 5 that the optimal herd sizes and weights are relatively similar in the Intermediate and BAU scenarios and that the difference to the Paris scenario increases over time.

The combined effect of climate change and adaptations generates a perfect information NPV that is between 9 and 15% less than the benchmark scenario without climate effects, and a trend NPV which is between 10 and 29% less than benchmark. Column one in Table 6 reports the difference in NPV between the benchmark scenario without climate and the perfect information case for all areas and scenarios. All areas experience a loss in NPV from climate change, which implies that the increase in the number of days with icing conditions outweighs any positive impact from earlier spring. Mid Norway faces the greatest potential loss from climate change, relative to the benchmark. In all areas except north Norway there is little to gain, relative to the BAU scenario, from limiting climate change to the intermediate scenario. The reason is that the projected number of days with icing in the intermediate and BAU scenario are quite overlapping in all areas, as seen in Fig. 4. Fig. 4 also shows that while the change in icing days is steeper for the BAU scenario, the first years of our simulation has more icing days in the intermediate scenario, before they cross around 2050. With a positive discount rate, the first years in our optimization receive higher weights

Table 6
Percentage change in NPV profits for different cases of information, all areas and climate change scenarios.

Area	Scenario	Perfect information, deviation from benchmark	Simulated, deviation from perfect information	No adjustment (relative to perfect information)	Best-case expectation, worst case realization (relative to having perfect information)	Worst-case expectation, best case realization (relative to having perfect information)
North Norway	Paris	−11%	−0.05%	−4%	−0.9%	−1%
	Intermediate	−21%	−0.09%	−16%	−33%	−12%
	BAU	−16%	−0.04%	−8%	−28%	−62%
North Sweden	Paris	−9%	−0.04%	−3%	−44%	−14%
	Intermediate	−15%	−0.05%	−7%	−52%	−25%
	BAU	−15%	−0.03%	−7%	−50%	−32%
Mid Norway	Paris	−14%	−0.09%	−6%	−3%	−2%
	Intermediate	−29%	−0.33%	−33%	−48%	−30%
	BAU	−29%	−0.16%	−30%	−22%	−64%
Mid Sweden	Paris	−11%	−0.05%	−4%	−48%	−16%
	Intermediate	−18%	−0.08%	−11%	−52%	−30%
	BAU	−19%	−0.06%	−12%	−50%	−30%

than the last. Therefore, we run sensitivity analysis with a 0 % discount rate (see Table A3 in Appendix A.4). In that case, for all areas except north Norway, the percentage loss in NPV, relative to the benchmark is 2 percentage points greater for the BAU scenario compared to the intermediate scenario. For north Norway, there is a slight decrease in the deviation between the two scenarios. Without discounting it is optimal to keep a slightly larger herd, which leads to lower slaughter weights and survival rates. The harvest rates are slightly higher and thus the total number of animals harvested is very similar in the two discount rate scenarios (see Figs. A7 to A10 in Appendix A.4).

We also run simulations for a lower mortality rate from icing. When reducing the icing induced mortality parameter from 0.5 to 0.25, the number of animals increases. This in turn, reduces slaughter weights. Still, the current value profit increases for all scenarios and areas, and the average yearly current profit is 6 to 8% higher when icing increases the mortality rate by 25%, compared to 50%.

So far, we have assumed that reindeer herders adjust perfectly to the projected climate scenarios or to an expected climate trend. In Fig. 6 we allow for deviations between climate expectations and climate projections. That is, we allow for herders to continue with the harvest strategy as derived from the optimization with an expected trend but simulate the model with a stochastic climate. See also column two in Table 6. This approach gives a smoother current value profit path than in the perfect information case and a slightly lower NPV compared to the perfect information case. Thus, the results suggest that the loss in NPV due to imperfect information is small when herders adjust to a reasonable expectation about the climate. In reality, some herders may value the lower variability in yearly current profits in the simulated case, and hence prefer to adjust according to an expected trend over the perfect information adjustment. NPV is higher in the simulated case than the trend case. While this may seem surprising, for instance in relation to Pekkarinen et al. (2022), this is partly because there are slightly more years where the trend overestimates the number of days with icing, than when it underestimates icing occurrences. As such, in the stochastic realization herders are more often exposed to years that are better than expected, compared to years that are worse than expected. This is not the case in Pekkarinen et al. (2022) who construct future climate projections based on what herders have reported as historical climate conditions and not on the SSP climate projections as in the present.

Still, column three highlight the importance of making precise expectations about climate conditions over time and being able to adjust harvesting strategies accordingly. It presents the difference in NPV relative to the benchmark case, but where the reindeer herders make no adjustment in the harvesting strategy, i.e., they have no information about future climate conditions and set harvest rates equal to those in the benchmark case. We see that herders in all areas are worse off when not adjusting their harvest rates to climate changes, implying that the cost in terms of lower NPV of not being able to adjust optimally may be significant. Here, the optimal benchmark harvest rate for adult females is 0.36, whereas the optimal harvest rate in the perfect information and trend case varies between 0.31 and 0.24, depending on the area and scenario. While higher benchmark harvesting rates lead to higher slaughter weights it is not enough to offset the negative impact on profits of a smaller herd.

As mentioned, there is uncertainty related to the climate projection data. We have therefore used the lower- and upper-bound projections (see Section 4.2) of each scenario to generate so-called best- and worst-case realizations of the climate change scenarios. The best-case realization of a climate change scenario is the combination of minimum number of icing days and earliest possible spring, whereas the worst-case realization is the combination of the maximum amount of icing days and the latest possible spring. Table A2 in Appendix A.3 reports the loss in NPV, relative to the benchmark, for the perfect information case of the best- and worst-case realizations. Considering these bounds, the impact of climate change on the slaughter profits from reindeer herding could range from an 8% improvement to an 84% loss, relative to the

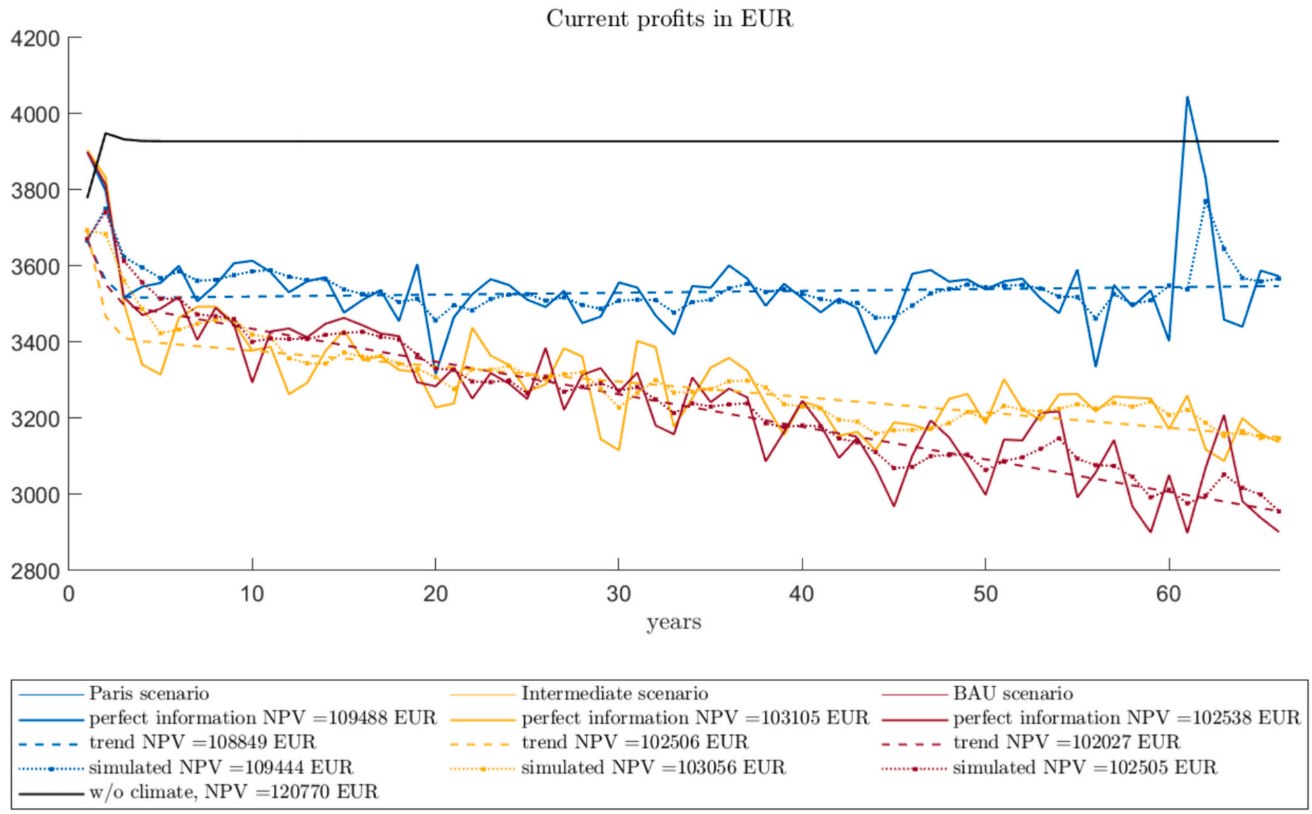

Fig. 6. Current profits for the perfect information, trend, and simulated case for all three climate change scenarios in north Sweden, baseline parameter values.

benchmark.

The uncertainty in climate change projection data highlights the difficulty in forming an accurate expectation for reindeer herders. Column four of Table 6 presents the NPV loss when reindeer herders form their expectation and harvesting strategy according to the best-case realization of a climate scenario, when the reality in the simulated case is the worst-case realization. The losses are reported relative to the case where herders have perfect information about the worst-case realization. Expecting the best-case when the reality is the worst-case leads to harvest rates that are much higher than optimal. This, in combination with lower survival rates, leads to a smaller herd. Due to the reduced herd size, slaughter weights are higher, but not enough to offset the impact on NPV. Column five reports the reversed situation. Expecting the worst-case realization when the opposite is true generates lower than optimal harvest rates, a larger herd and lower slaughter weights than the perfect info case.

6. Discussion and 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 during winter. Climate change and yearly weather conditions affect the model through its impact on slaughter weights and survival rates. 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 bio-economic 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 several 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, we have ignored parasites, insect harassment and wildfires as additional stressors that increase with a warmer climate (Mallory and Boyce, 2018). Reindeer may respond to such stressors seeking relief on windy hilltops, snowy patches, and other unproductive areas (Hagemoen and Reimers, 2002 Mallory and Boyce, 2018). Such behavioral responses may be necessary for survival but can have negative implications for summer reindeer body mass growth but has not been included in the model. If such events are not related to the onset of spring, we may have overestimated the summer climate effect on weights. If so, reindeer herders will be even worse off than calculated in this paper.

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, northern Norway and mid Sweden, mid Norway will experience the greatest loss in NPV across all climate change scenarios. North Sweden is the least affected area but will still face a loss of between 9 and 15%. This is mainly due to a difference in the number of days with icing, which appear to be the greatest for mid Norway. 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 decreasing harvesting rates. Throughout most simulations it is optimal to harvest adult males and females but no calves. The latter contrasts actual harvesting practices with larges fractions of calves (Norwegian Reindeer Herding Administration (NRHA), 2022). One reason may be that we ignored any slaughtering subsidies aiming to stimulate slaughtering of calves (Norwegian Reindeer Herding Administration (NRHA), 2022b). Furthermore, we have ignored predation and losses to carnivores, which is found to stimulate harvesting of calves as calves are particularly vulnerable to predation (Johannesen et al., 2019).

The model is first solved under the assumption of perfect information, which provides a first-best minimum economic loss of climate change. Because it is unreasonable to expect herders to have perfect information about future stochastic weather conditions, the paper also explores the economic loss of adapting according to imperfect information. As expected, herders are always worse off when they are unable to perfectly predict future weather conditions. However, the loss can be mitigated if herders form a reasonable expectation and adapt accordingly. In a situation where herders lack perfect knowledge but have a well-informed expectation about the trend in climate changes and are exposed to the stochastic weather conditions, their NPV is only between 0.04 and 3.05% less than if they had perfect information. However, if they are too optimistic or pessimistic in their expectations the mismatch between the chosen harvest strategy and the optimal harvest strategy can lead to a NPV that is 74% less than in the case of perfect information. Thus, the paper clearly highlights the importance of information about future weather conditions and the ability to adjust to a changing climate. While this study has used relatively coarse data on climate projections, it does suggest that reindeer herders throughout Norway and Sweden would benefit from access to high quality long-term local weather forecasts.

The economic part of the model presents a simplified version of reality. One limitation of the economic set up 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. Finally, reindeer herding 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 herding, and these values seem to be just as high, and probably higher, than the income opportunities the industry provides (Bostedt and Lundgren, 2010 Johannesen and Skonhoft, 2009). With a changing climate, herders may have to change reindeer herding practices, for instance by increasing the use of supplementary feeding and restricting traditional nomadic practices. Such changes may further reduce the welfare of Saami reindeer herding communities. Thus, while inherently difficult to quantify and include, it is important to note that the exclusion of cultural values may underestimate the impact that climate change will have on reindeer herding.

CRediT authorship contribution statement

Irmelin Slettemoen Helgesen: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Anne Borge Johannesen:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization. **Göran Bostedt:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization. **Erlend Dancke Sandorf:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Goran Bostedt and Anne Borge Johannesen report financial support was provided by European Biodiversity Partnership.

Data availability

Data will be made available on request.

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Appendix A. Appendix

A.1. Summary statistics

Table A1
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[a]	
	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.)	119.39	113.03	116.86	110.80
		(4.61)	(6.25)	(3.81)	(5.31)
	#days with icing Nov-Mar	10.95	14.15	7.94	9.53
		(2.09)	(3.31)	(1.73)	(2.20)
	Mean snow depth Dec-Jan (cm)	32.85	28.62	29.99	25.92

(continued on next page)

Table A1 (*continued*)

	Variables	Norway		Sweden[a]	
		North	Mid	North	Mid
		(4.97)	(5.11)	(3.23)	(3.16)
	Mean snow depth Feb-Mar (cm)	53.45	48.27	50.70	44.12
		(5.12)	(6.69)	(4.15)	(4.97)
C. Intermediate scenario (SSP 2–4.5)	Start of spring (#days since 1.Jan.)	110.04	90.90	109.55	103.01
		(6.88)	(6.66)	(6.54)	(7.22)
	#days with icing Nov-Mar	24.02	34.06	16.29	20.79
		(2.74)	(4.38)	(3.54)	(4.05)
	Mean snow depth Dec-Jan (cm)	17.69	18.21	24.24	20.69
		(3.31)	(5.32)	(3.75)	(4.61)
	Mean snow depth Feb-Mar (cm)	33.42	35.27	43.59	36.26
		(4.63)	(8.38)	(4.69)	(6.30)
D. BAU scenario (SSP 5–8.5)	Start of spring (#days since 1.Jan.)	49.87	38.81	50.85	43.89
		(42.40)	(36.94)	(40.89)	(40.39)
	#days with icing Nov-Mar	30.22	31.91	30.32	29.65
		(10.76)	(10.78)	(20.58)	(15.85)
	Mean snow depth Dec-Jan (cm)	6.34	5.92	10.14	7.26
		(7.49)	(8.62)	(9.87)	(8.44)
	Mean snow depth Feb-Mar (cm)	12.54	12.49	19.69	13.32
		(13.49)	(17.45)	(17.63)	(15.33)

[a] 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).

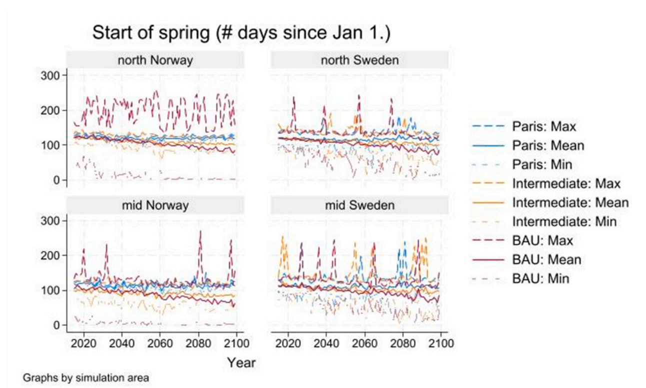

Fig. A1. Max, mean and min projected start of spring for all climate change scenarios, by area.

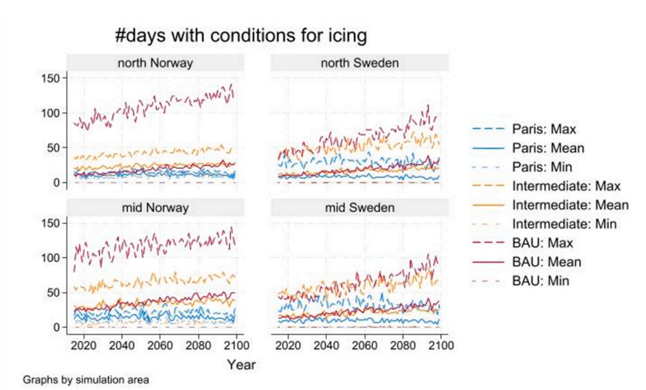

Fig. A2. Max, mean and min projected number of days with conditions for icing for all climate change scenarios, by area.

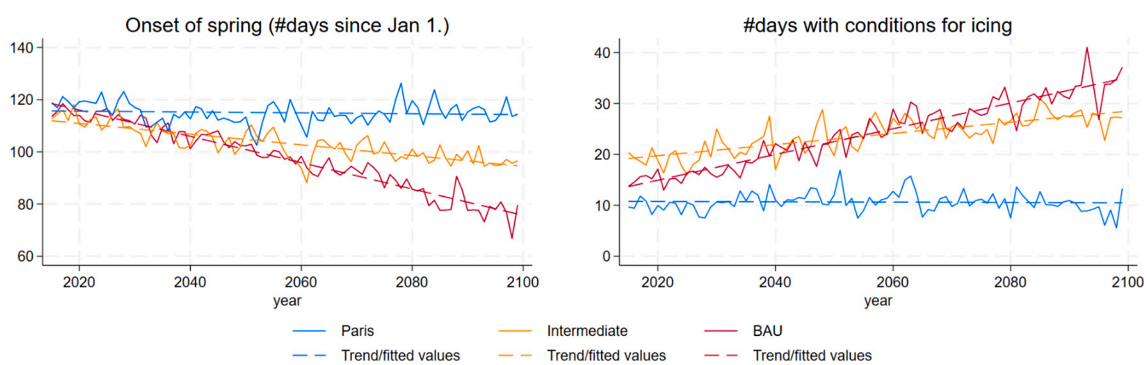

Fig. A3. Projected onset of spring and number of days with conditions for icing, year-to-year data and linear trend.

A.2. Simulation results for all areas

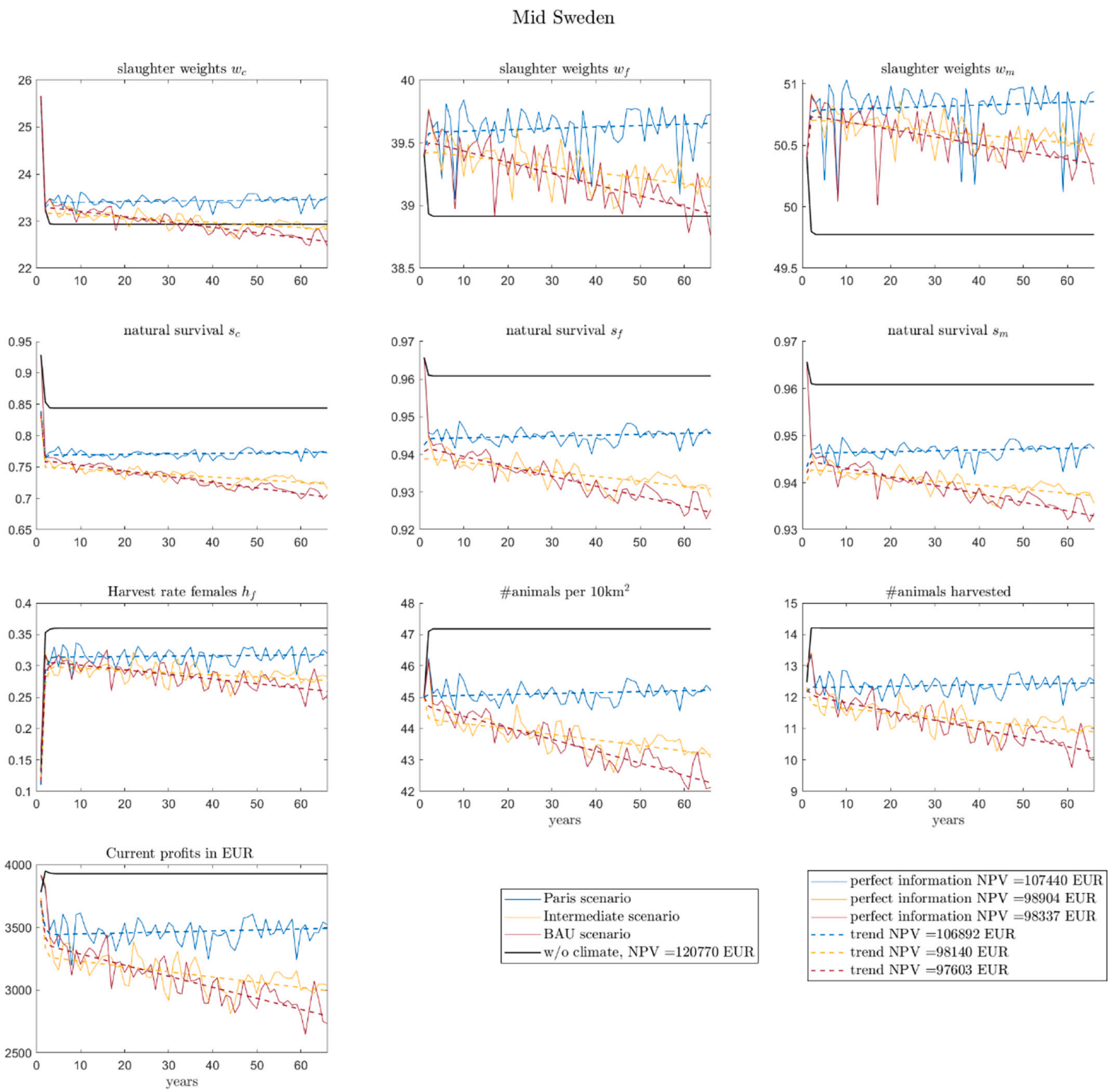

Fig. A4. Optimal paths for the perfect information and trend case for all climate change scenarios in mid Sweden, baseline parameter values.

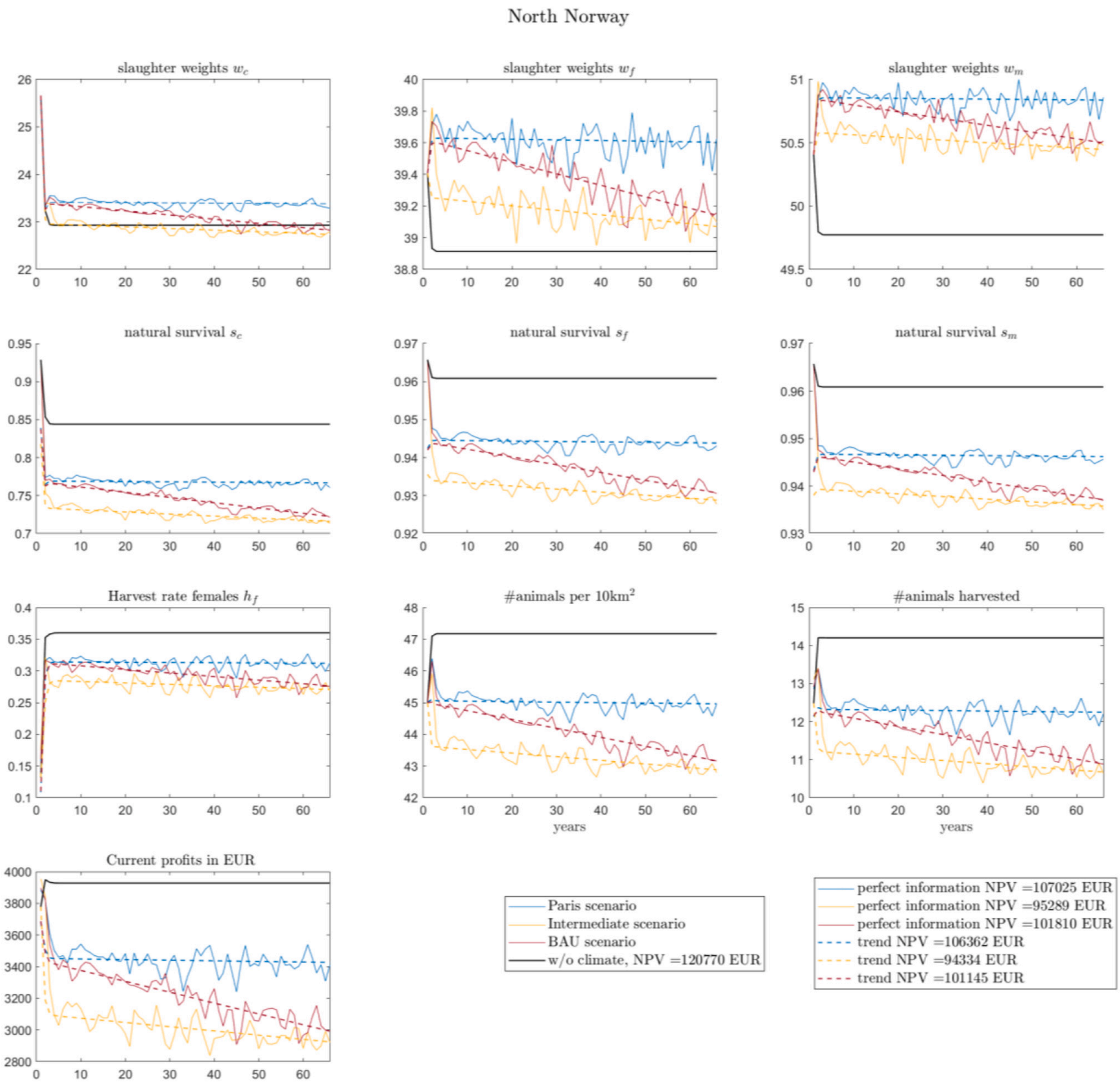

Fig. A5. Optimal paths for the perfect information and trend case for all climate change scenarios in north Norway, baseline parameter values.

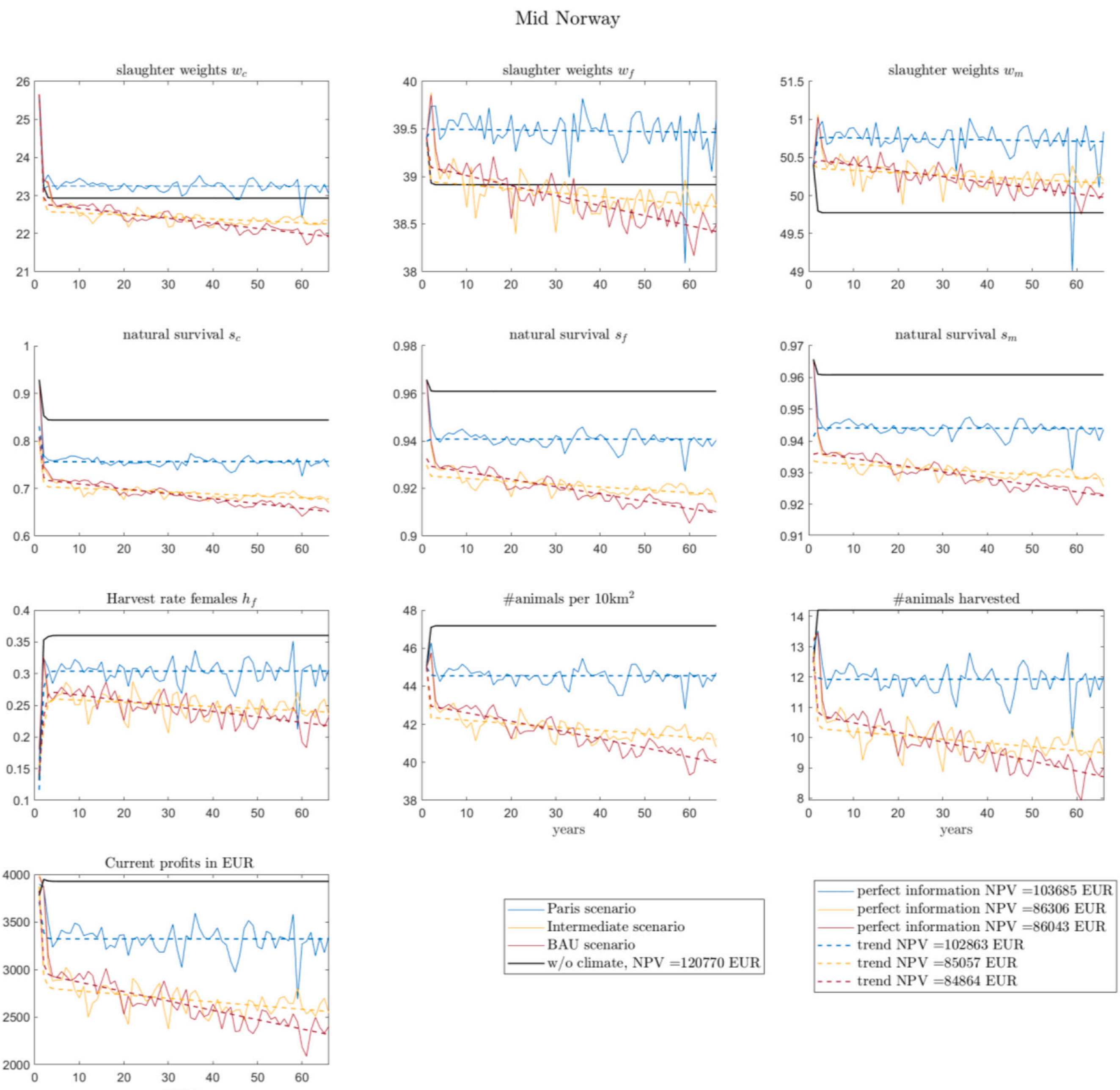

Fig. A6. Optimal paths for the perfect information and trend case for all climate change scenarios in mid Norway, baseline parameter values.

A.3. Best- and worst-case simulation results

Table A2
NPV in the best- and worst-case realization for the perfect information case, relative to the benchmark NPV.

Area	Scenario	Best-case realization	Worst-case realization
North Norway	Paris	−8%	−15%
	Intermediate	−12%	−41%
	BAU	8%	−81%
North Sweden	Paris	8%	−31%
	Intermediate	8%	−44%
	BAU	8%	−51%
Mid Norway	Paris	−9%	−21%
	Intermediate	−5%	−55%
	BAU	8%	−84%
Mid Sweden	Paris	8%	−33%
	Intermediate	8%	−49%
	BAU	8%	−49%

A.4. Discount rate sensitivity analysis

Table A3
Percentage change in NPV profits for perfect information and with a 0% discount rate.

Area	Scenario	Relative to benchmark,
North Norway	Paris	−12%
	Intermediate	−23%
	BAU	−19%
North Sweden	Paris	−10%
	Intermediate	−17%
	BAU	−19%
Mid Norway	Paris	−15%
	Intermediate	−31%
	BAU	−33%
Mid Sweden	Paris	−12%
	Intermediate	−20%
	BAU	−22%

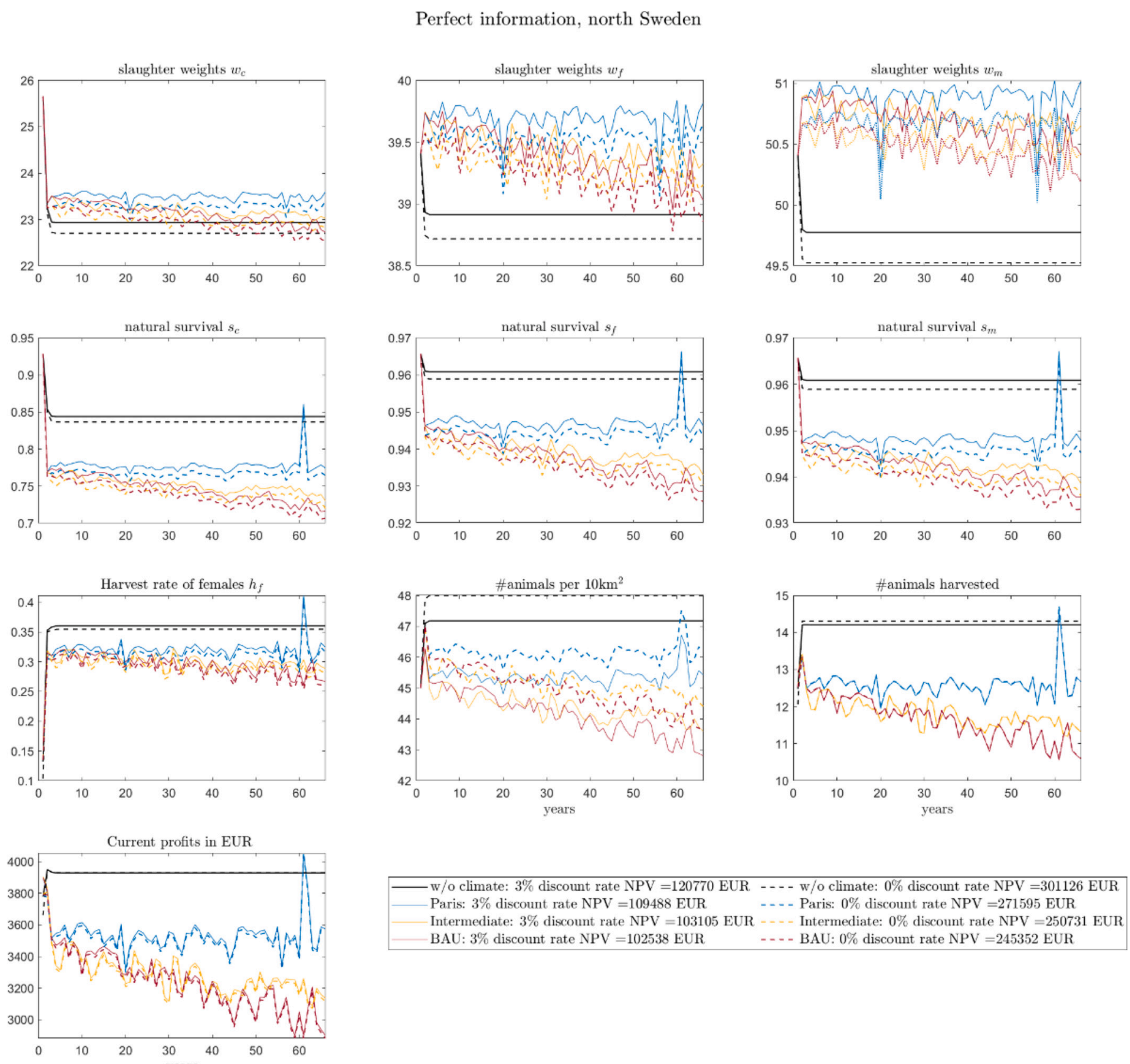

Fig. A7. Optimal paths for the case of perfect information for a 3% discount rate and a 0% discount rate, north Sweden.

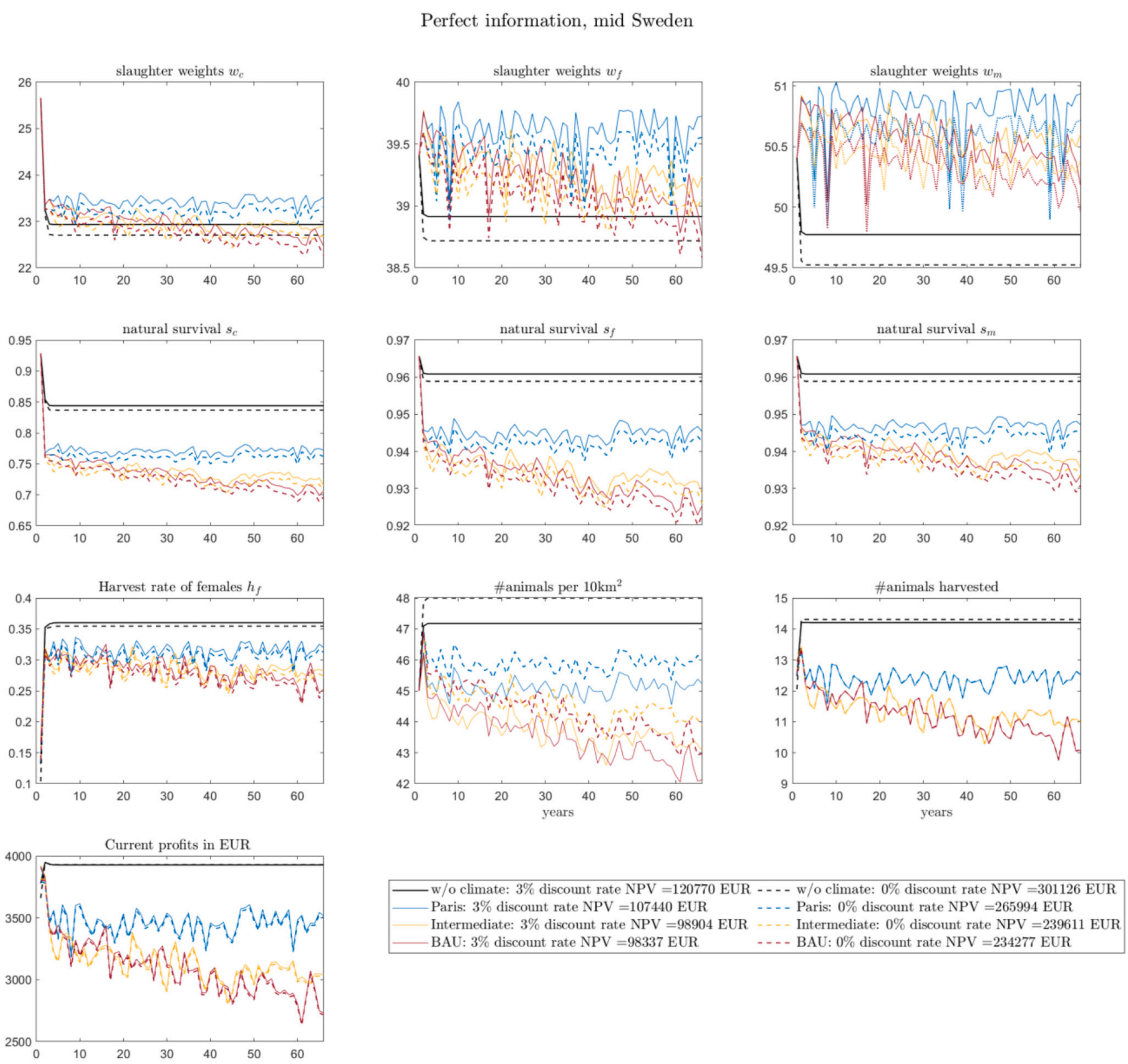

Fig. A8. Optimal paths for the case of perfect information for a 3% discount rate and a 0% discount rate, mid Sweden.

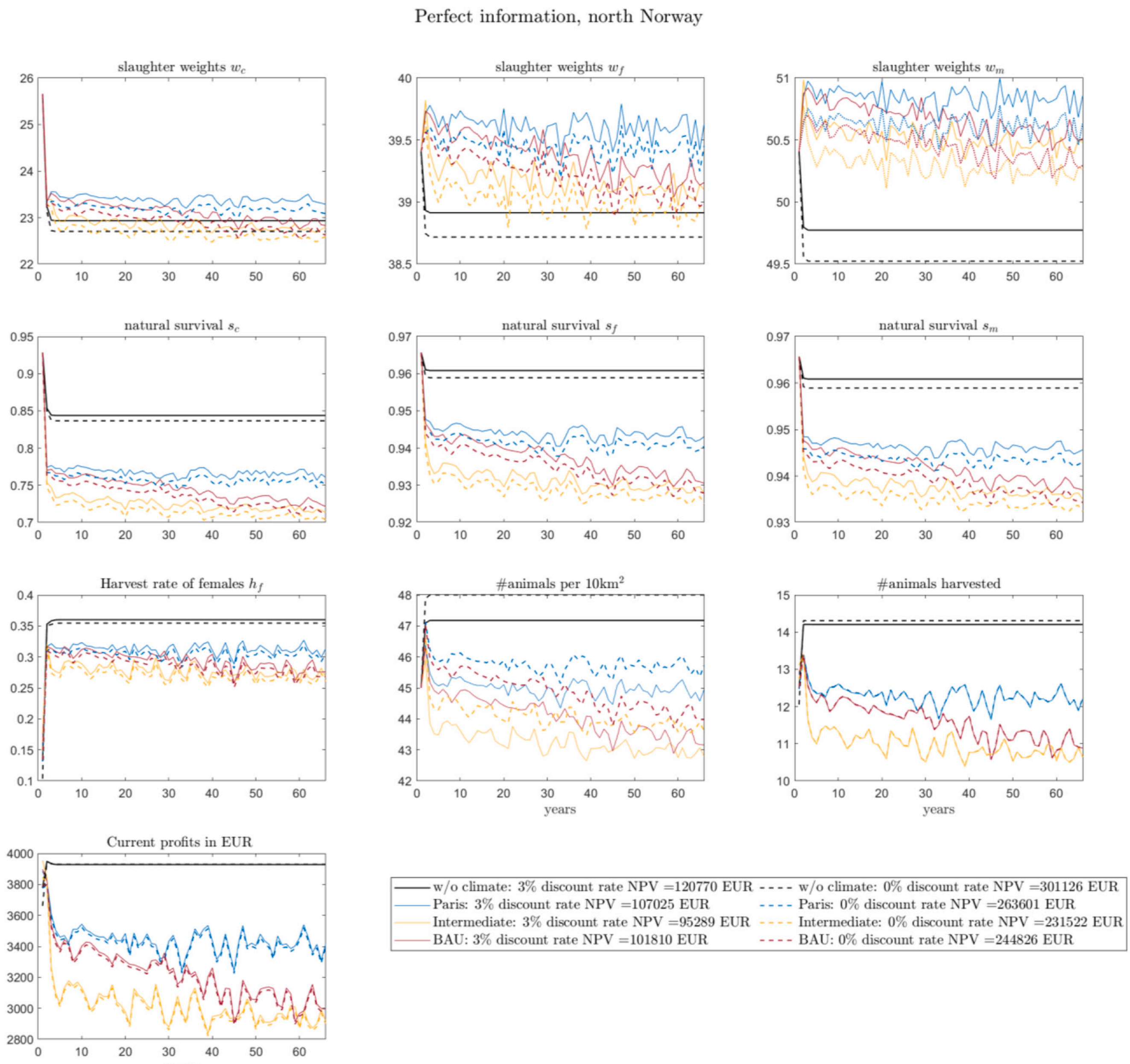

Fig. A9. Optimal paths for the case of perfect information for a 3% discount rate and a 0% discount rate, north Norway.

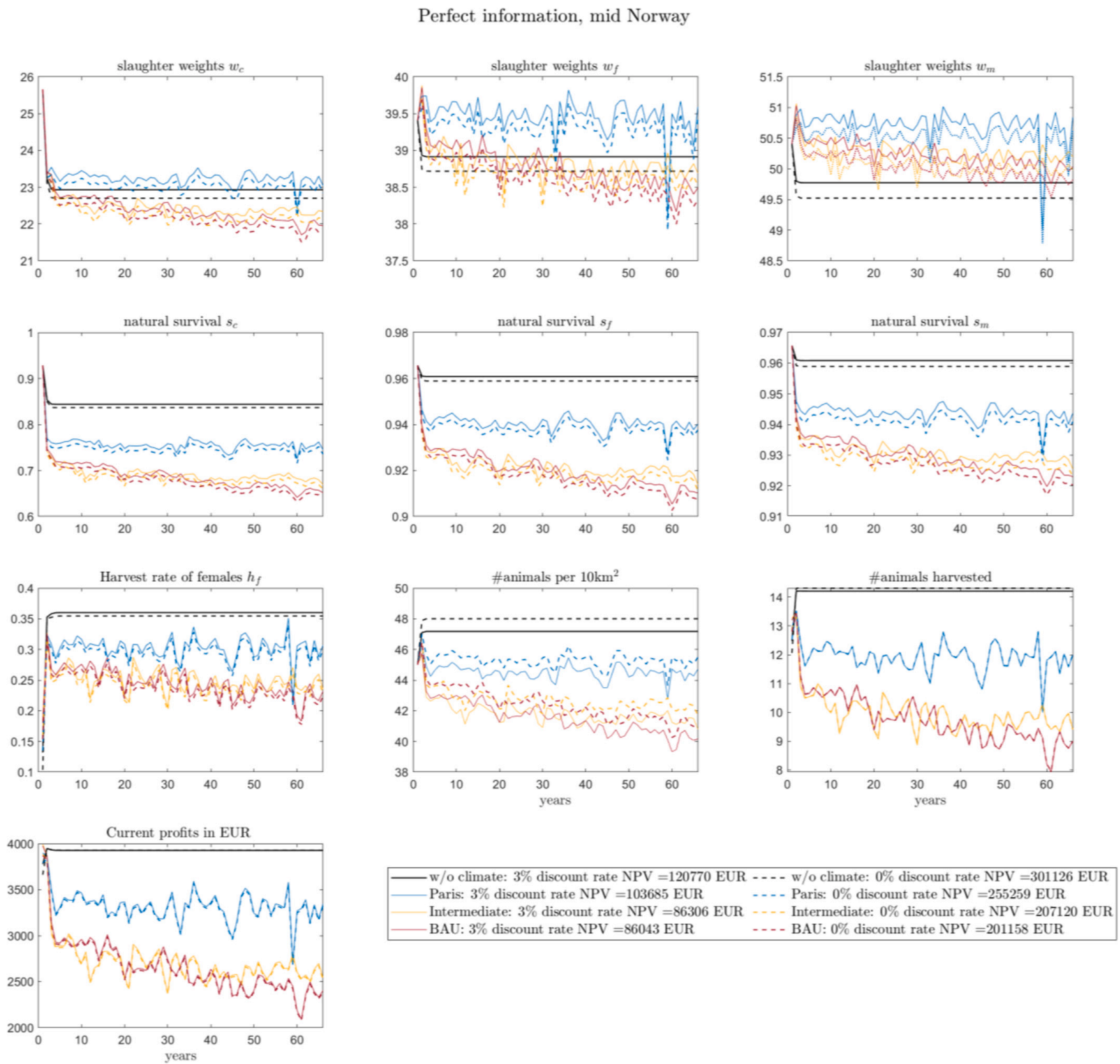

Fig. A10. Optimal paths for the case of perfect information for a 3% discount rate and a 0% discount rate, mid Sweden.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108227.

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