On the tragedy of the commons:
When predation and livestock loss may improve the economic lot of herders

Anders Skonhoft

Anne B. Johannesen

and

Jon Olaf Olaussen

Norwegian University of Science and Technology, Trondheim Norway

Abstract

This paper studies the practice of semi-domestic reindeer (*Rangifer t. tarandus*) herding in Finnmark county in northern Norway. In this area, the Saami reindeer herders compete for space and grazing areas and keep large herds, while at the same time, the reindeer population is heavily exposed to carnivore predation by the lynx, the wolverine, and the golden eagle. It is demonstrated that predation actually may improve the economic lot of livestock holders in this unmanaged local common setting. There are ecological as well as economic reasons as to why this happens. The ecological reason is that predation compensates for natural mortality; that is, increased predation reduces natural mortality, indicating that the net loss due to predation actually may be quite small. When predation reduces livestock density, the feeding conditions of the animals will improve, resulting in increased livestock weight and higher per animal slaughter value. At the same time, a smaller stock reduces the operating costs of the herders.

Key words: Commons, Livestock, predation, food limitation, ecological and economic compensation mechanisms

Introduction

Common property resources are resources in which property rights exist, though members of a group exercise the property rights collectively. There is also rivalry concerning the consumption of the resource within the group; that is, an increase in the amount consumed by one individual reduces the amount remaining for others to consume. This is usually referred to as a reciprocal negative external effect. A common resource can be defined as a local common resource if the number of members in the specified group is small. In most developing countries, irrigation, grazing on pastures, in-shore fisheries, among others, are local commons, where the access to the resource is usually restricted to small local communities. Some of these resources are common resources for practical and economic reasons, others for cultural and institutional reasons (Ostrom 1990). A local common can be said to be *managed* if the exploitation of the common is executed in some cooperative manner among its owners, whereby reciprocal externalities are taken into account. On the other hand, a local common is *unmanaged* if no such cooperation is present. Under an unmanaged scheme, each owner typically follows his narrow self-interest and maximizes his private gain while neglecting the external cost of utilizing the common resource base.

Much of the discussion of the problems of unmanaged local commons can be traced back to Hardin's (1968) famous allegory of 'the tragedy of the commons'. Hardin studied a system of communally owned grazeland and privately owned livestock. He assumed that the exploitation was steered by the self-interests of the livestock owners, with the consequences of having excess livestock and the issue of overgrazing. His famous conclusion, while being widely criticized (see, e.g., Dasgupta 1982, Ch. 2), was that “each man is locked into a system that compels him to increase the herd without limits – in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interests in a society that believes in the freedom of the commons. Freedom in a common brings ruin to all” (Hardin 1968, p. 1244). Various aspects of common property and common property exploitation have been analyzed by, among others, Ostrom (1990), Bromley (1991), Seabright (1993), Baland and Platteau (1995), and Dasgupta and Mäler (1995).

In this paper, a similar type of system of communally owned pasture and privately owned livestock is analyzed. Our case study is semi-domestic reindeer (*Rangifer t. tarandus*) herding in Finnmark county, which is located in the far northern part of Norway (see Figure 1). In this area, conflicts are prevalent over the use of grazing land (Johannesen and Skonhoft 2009). Although previous studies show that herders cooperate in so-called herding groups through the sharing and exchange of labor (e.g., Johannesen and Skonhoft 2009, Naess et al. 2010), the utilization of grazing land is, to a large extent, characterized by mismanagement, in the sense that they fail to internalize the external costs. Conflicts are accompanied by high animal density and low animal weights. At the same time, the reindeer population is exposed to predation; thus, they are thus prone to the risk of being killed by predators such as the lynx (*Lynx lynx*), wolverine (*Gulo gulo*), and golden eagle (*Aquila chrysaetos*) (Tveraa et al. 2003). Small and weak animals, especially calves, are most vulnerable to predators (see Linnell et al. 1995). The research question we raise is to what extent livestock herders are negatively affected by predation within this system. Our main result is that we find that predation actually may improve the economic lot of the livestock holders. There are ecological as well as economic reasons as to why this happens. The ecological reason is that predation compensates for natural mortality; that is, increased predation reduces natural mortality, indicating that the net loss due to predation actually may be quite small. When predation reduces livestock density, the feeding conditions of the animals will improve, resulting in increased livestock weight and higher per animal slaughter value. At the same time, a smaller stock reduces the operating costs of the herders.

Figure 1 about here

The rest of the paper is structured as follows. In the Materials and method section, we start by giving a brief background of Saami reindeer herding in Norway and the prevailing problems related to food shortage and predation in our study area, western Finnmark, or only Finnmark for short. Next, we formulate a reindeer population model. As the various categories of the reindeer population are differently exposed to predation, the model is specified with different age classes. The model is structured in three classes, where the weight-mortality and weight-fecundity relationships are included. The effect of carnivore predation on total mortality is also introduced here. The reindeer population consists of several flocks owned by different herders, or groups of herders, competing for space and grazing areas, and the economic benefit and cost functions for these herders are formulated in the last part of this main section. The Numerical results section presents numerical results under the considered 'tragedy of the commons' scenario, and the biological and economic effects of predation are demonstrated. The results are also compared with reindeer herding in Nord-Trøndelag county (Figure 1). This county is located in the southern/middle part of Norway, identified as 'South', and is characterized by higher slaughter rates and significantly lower population density. In this area, we find that predation worsens the economic conditions of the livestock holders. The Discussion and conclusions section summarizes and discusses the results.

Materials and methods

Ecological and economic background

The interactions between carnivores and livestock take place under widely different ecological and economic circumstances. As the degree of food limitation may significantly influence the effects of predation, this relationship has received considerable attention in the ecological literature (e.g., Sinclair and Pech 1996; Boyce et al. 1999; Ballard et al. 2001; Tveraa et al. 2003; Vucetic et al. 2005; Wilmers et al. 2007). In general, it is more likely that predation is followed by density-dependent reductions in natural mortality and improved recruitment (fertility) when ungulate density is high. On the other hand, predation is more likely to limit ungulate populations when pastures are plentiful. See, e.g., Ballard et al. (2001) who studied wild ungulates in North America and found that ungulate density reduced the relative importance of predation and food availability as factors limiting ungulate populations. In light of this, the significance of food limitation depends on whether predation comes in addition to natural mortality (*additive* loss), or to some degree compensates for natural mortality (*compensatory* loss).

A similar relationship has also been demonstrated in semi-domestic reindeer herding in Norway (Tveraa et al. 2003). Because reindeer graze on natural pastures throughout the year, they are prone to the risk of being killed by predators. Predation is significant, and this problem has accentuated during the last two to three decades because of growing carnivore populations, as Norway has the goal of keeping 'sustainable' carnivore populations (see, e.g., http://www.rovviltportalen.no/content/2704/Bestandsmal, Ekspertutvalget 2011)[1]. In our study area, Finnmark, reindeer predation is particularly related to the lynx and wolverine, but also the golden eagle (Tveraa et al. 2014). Small and weak reindeer, especially calves, are more vulnerable to predators than other animals in good condition (Tveraa et al. 2003). Figure 2, panel (c) shows that the loss of calves to predators per km^2 has increased substantially over the past few years in our study area, Finnmark, while it has remained stable and at a significantly lower level in the southern part of Norway. The losses reported here are those claimed by the herders. These are probably larger than the actual losses as the prevailing monetary compensation scheme gives incentives to overstate losses. Losses actually compensated are, however, likely to underestimate real losses because compensation relies on the ability to document losses, which may be difficult, especially for losses of calves (Tveraa et al. 2014). In the numerical analysis in section five, the average between the claimed and compensated losses is used as the baseline predation pressure. For further information, see the Appendix.

Although differences in carnivore density may explain some of the variation in claimed losses between Finnmark and the South, Tveraa et al. (2014) demonstrated that various indicators of food limitation (i.e., reindeer density, climate, and plant productivity) are the most prominent factors explaining the differences in predator losses. Furthermore, when combined with the previous findings showing that predators tend to kill weak animals (Tveraa et al. 2003), these researchers claim that losses to predators in Finnmark are highly compensatory. Food limitations also have important economic consequences, as the weight and slaughter value of the livestock may be severely influenced.

Reindeer husbandry is a traditional and culturally based livelihood of the Saami people in Norway, Sweden, Finland, and Russia, and can be traced back to the fifteenth century, when

[1] Because of the conflicts between carnivores and livestock holding (and especially sheep farming), the term 'sustainable' carnivore populations has widely different content among different stakeholders (see, e.g., Ekspertutvalget 2011).

the Saami people domesticated entire reindeer herds, leading a considerable number of Saami people to become herding nomads (e.g., Riseth 2006). This tradition has been preserved until today. Saami reindeer herding in Norway takes place in Finnmark, Troms, Nordland, Nord-Trøndelag, Sør-Trøndelag, and Hedmark counties (Figure 1), and is an exclusive right of the Saami people in these counties (Johannesen 2014). It is a small economic activity, comprising some 530 herding units that keep a total of 230,000 animals (NRHA 2014). The industry produces about 2,000 tons of reindeer meat yearly, which amounts to 1-2 percent of the total production of red meat in Norway (NRHA 2013b). Although small on a national scale, reindeer husbandry is of great importance to the Saami people, both culturally and economically (Bostedt 2005, Johannesen and Skonhoft 2009). 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 as the income opportunities the industry provides (Johannesen and Skonhoft 2009). Therefore, not surprisingly, a large number of herders emphasize that herd size is important as a part of the cultural valuation, as well as providing insurance against unfavorable environmental conditions (Johannesen and Skonhoft 2011).

Reindeer graze on natural pastures throughout the year and the pastures are utilized as common properties. The largest herding area in Norway is found in our study area, Finnmark County, and constitutes about 70 % of the total Norwegian reindeer population (NRHA 2014). Until the 1970s, the reindeer herders in Finnmark held a relatively stable number of reindeer, but the number increased substantially during the 1990s and onwards (Riseth and Vatn 2009). Previously, herders utilized the grazing land according to traditional rules of allocation and respected the prevailing informal rules transferred through generations (Riseth and Vatn 2009). At that time, reindeer herding proved sustainable, and the utilization of the grazing land was characterized as a managed common property. However, the social structure in reindeer herding in Finnmark changed and eroded with technological improvements, access to external markets, centralized settlements, and the establishment of external regulations from the Norwegian government (Riseth and Vatn 2009). Over the past decades, many herding communities in Finnmark have been characterized by internal conflicts and strong competition over access to pastures (Johannesen and Skonhoft 2009, Riseth and Vatn 2009). This perceived lack of cooperation and coordination has resulted in low slaughter rates, thus leading to increased reindeer density, and subsequent pasture degradation (Johansen and Karlsen 2005). The situation shows clear signs of ‘tragedy of the commons’ exploitation.

High reindeer density and food shortages have, in turn led to low animal weights in parts of Finnmark compared to previous years. Figure 2, panels (a) and (b), compare the situation in Finnmark and South, where the reindeer herding areas in South have much higher slaughter rates. The reindeer density in Finnmark is currently more than twice the density in South, and irrespective of the fact that the carrying capacity per area unit is generally higher in Finnmark, the average slaughter weight here is significantly lower.

In South, pastures are utilized as common property as well. However, here the herders have managed to coordinate their activity and restrict the reindeer density so as to avoid pasture degradation. As stated by Riseth and Vatn (2009), a reason for this difference between South and Finnmark is that Finnmark is characterized by open landscapes with few natural borders. Moreover, the number of herders is much smaller in South, and hence coordination may be easier.

The high population density in Finnmark and the low weights have also worked in the direction of reduced natural survival rates, especially for calves (Tveraa et al. 2014). Because females with lower weights are less likely to reproduce, lower fertility rates have been observed (Tveraa et al. 2003, Bårdsen et al. 2010).

Figure 2 about here

Population model

The total reindeer population for the herders in our study area at the time (year) t is structured in three stages: calves $X_{c,t}$ ($yr < 1$), adult females $X_{f,t}$ ($yr \geq 1$), and adult males

$X_{m,t}$ ($yr \geq 1$). The population is measured in the spring, just before calving. When we neglect summer mortality and assume predation takes place after winter natural mortality; the events over the yearly cycle are then calving, slaughtering (which takes place in September – October), winter natural mortality (diseases, accidents, starvation), and predation[2]. Within the range of the actual reindeer densities, the sex composition seems to play a negligible fecundity role, and recruitment is steered only by the number of adult females. This implies that there are always enough males to reproduce the stock. Therefore, the number of calf (recruitment) is first governed by:

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

where $f_t > 0$ is the fertility rate (number of calves per female).

With $0 < s_{i,t} < 1$ as the natural survival rate, $0 \leq m_{i,t} < 1$ as the predation rate associated with carnivores, $0 \leq h_{i,t} < 1$ as the harvest (or slaughter) rates ($i = c, f, m$), which typically are low in our study area (details below), and ψ as the fraction of female calves (usually about 0.5), the abundance of adult females and males may next be written as:

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

and

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

respectively. Both fertility and survival rates depend on food conditions and food shortages approximated by the (average) animal weights. The weight of the animals, on the other hand, depends on food availability and the grazing pressure during the summer and fall, approximated by the total number of grazing animals (Tveraa et al. 2003). See Figure 3, panel (a). Therefore, natural survival rates and fertility rates reduce with animal density (Figure 3, panel b and c; also see the Appendix for more details). The survival rates are

[2] In reality, there is a spring and summer mortality, especially for calves (Bårdsen at al. 2011), and predation and natural mortality generally take place simultaneously. However, by sequencing the events over the annual cycle the model becomes analytically and numerically traceable. We have also studied the model when predation takes place before natural mortality. This causes a change in the distribution of losses from natural mortality to predation mortality, but has a negligible impact on the remaining results, as long as (slaughter) weights, and hence, the fertility rate and natural survival rates, depend on the autumn stock size.

assumed similar for the adults, and are higher for adults than for calves at all population levels, $s_{m,t} = s_{f,t} > s_{c,t}$.

The predation rates also differ between sexes and age classes and are lower for adults than calves, $m_{c,t} > m_{f,t} \neq m_{m,t}$ (Tveraa et al. 2003). We assume that the predation rates are independent of the reindeer density. There may be feedback effects, where the size of the reindeer population influences the growth of the predator population; however, we neglect these because the number of carnivores is regulated with certain population goals for the lynx and wolverine (again, see (http://www.rovviltportalen.no/content/2704/Bestandsmal, and Ekspertutvalget 2011)[3]. The carnivore natural growth and population sizes are thus assumed independent of the size of the reindeer population, and the predation rates are exogenous in the model.

Figure 3 about here

In our population model, predation and natural mortality are interacting. This is because higher predation reduces the number of animals; therefore, the animal weights increase with the amount of predation. This again feeds into higher natural survival rates. As a result, predation mortality generally compensates for natural mortality; that is, higher predation pressure shifts up the natural survival rates. This compensatory effect will typically be stronger in the presence of a severe food shortage, as well as in situations where weights are more sensitive to changes in animal density (Figure 3). There is also a compensating effect present through the fertility rate, and higher predation pressure therefore increases the fertility rate.

We also consider the compensatory effects in terms of morality rates. With natural mortality in the number of animals of category i, given as $N_{i,t} = (1-h_{i,t})X_{i,t}(1-s_{i,t})$, and predation in

[3] See also e.g., Nilsen et al. (2005) and Boman et al. (2003) for related discussions in other ecological settings in Scandinavia.

number of animals defined by $M_{i,t} = (1-h_{i,t})X_{i,t}s_{i,t}m_{i,t}$, because predation is assumed to take place after natural mortality, the total mortality of category i becomes $N_{i,t} + M_{i,t} = (1-h_{i,t})X_{i,t}(1-s_{i,t}) + (1-h_{i,t})X_{i,t}s_{i,t}m_{i,t}$. The total mortality rate may therefore be written as $(N_{i,t} + M_{i,t})/(1-h_{i,t})X_{i,t} \equiv g_{i,t} = (1-s_{i,t}) + s_{i,t}m_{i,t}$. Changing mortality rates due to increased predation now reads $\partial g_{i,t}/\partial m_{i,t} = s_{i,t} - (1-m_{i,t})(\partial s_{i,t}/\partial m_{i,t})$, with $\partial s_{i,t}/\partial m_{i,t} \geq 0$. The first order effect is therefore captured by the term $s_{i,t}$. The second order effect is captured by $-(1-m_{i,t})(\partial s_{i,t}/\partial m_{i,t})$, and hence this represents the compensatory effect.

Because of strong density-dependent effects in our population model, we find that the total population size stabilizes quite quickly with fixed slaughter rates. Figure 4 illustrates the transitional dynamics with the baseline slaughter and predation rates and baseline parameter values (the Appendix provides details about the data and the functional forms). This figure clearly indicates that the dynamic is ergodic; that is, a unique steady state is approached under the two different initial situations of low and high animal density. The low *fixed* slaughter rates included here, $h_c = 0.20$, $h_f = 0.05$ and $h_m = 0.21$ (the time notation is omitted), are in accordance with the present management situation in our study area (see also Tables 1 and 2). Therefore, the high steady state total stock density, about 70 (# of animals/10 km^2), reflects today's 'tragedy of the commons' situation, and is, as previously mentioned, significantly higher than in the southern part of Norway (Figure 2 above). The time-invariant predation rates represented here, $m_c = 0.27$, $m_f = m_m = 0.04$, are the average of current claimed and compensated losses and reflect our baseline predation scenario. In the numerical analysis below, only equilibrium, or steady state, is considered.

Figure 4 about here

Cost and benefit functions

In the present study, we are only concerned with the net income from slaughtering, considering the harvesting value, slaughtering costs, and the operating costs with respect to the animals. Therefore, any positive stock value related to status, insurance or cultural identity (see section two above) is not taken into account in the present exposition. Compensation for the predation loss is neither taken into account[4]. Because natural mortality and predation are assumed to take place during the late fall and winter, after slaughtering, the number of animals removed through slaughtering in year t is simply defined by $H_{i,t} = h_{i,t} X_{i,t}$ ($i = c, f, m$). The current slaughter value, or meat value, for our group of herders, is accordingly:

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

where p is the net meat value (NOK/kg), i.e., the slaughter value corrected for slaughter costs. The meat value is thus assumed to be fixed and similar for all categories of animals.

The operating costs are generally different between the winter and summer seasons. There are also costs included in moving the animals from the winter grazing to the summer grazing area, and *vice versa*. There may also be cost variations between the various herders. However, such differences are neglected, and we simply relate the variable operating costs to the total size of the summer stock:

(5) $$C_t = C(X_{c,t} + X_{f,t} + X_{m,t}) = C(X_t),$$

with $C' > 0$ and and $C(0) = 0$. In addition, there are fixed costs, but they are not included as these have no influence of the solution of the model. The cost function may be convex, or concave-convex. As a compromise and simplification, it is assumed to be linear, $C'' = 0$. However, in the sensitivity analysis, we have also included a convex function. As any possible protective effort with respect to predation is also neglected here, Eq. (5) indicates the total variable costs. The current net benefit, or profit, for our considered group of herders is thus defined by:

(6) $$\pi_t = I_t - C_t.$$

[4] Including compensation will obviously increase the profitability of the scenarios where predation is present. Compensation may also influence the behavior of the herders. See Skonhoft (2016) for an analysis of carnivore conservation, predation, and sheep farming.

Numerical results: the cost and benefit of predation

We now present our numerical steady state results under the ‘tragedy of the commons’ management situation in our study area in Finnmark, which is characterized by low slaughter rates and high population density. We consider three predation scenarios with the baseline scenario reflecting the average between today’s claimed and compensated loss. Additionally, we study the effects of zero predation as well as high predation. The last scenario is characterized by a somewhat higher calf predation rate than in the baseline scenario, while the adult rates are just slightly higher (see Table 1, and also the Appendix). In these first scenarios, the slaughter rates are kept fixed and thus any possible harvest control response to the changing predation pressure is not taken into account.

The main biological results are first considered (see Table 1). Increased predation pressure reduces the total stock (column one) and the predation losses increase for all animal categories (column six). However, the ecological compensation effect, when working through increased natural survival rates (column four), reduces natural mortality (column five) and dampens the effect on total mortality (column seven). Indeed, the compensation effect is so strong that the total mortality for adult animals is actually lower under the baseline predation scenario than under the no predation scenario (column seven). Therefore, we find that the second order effect in the population model dominates the first order effect for these two stages (see the above Materials and methods section). The natural mortality compensation mechanism is also strong for the calf population, although not sufficient to offset the increased predation loss. The total mortality hence increases slightly when moving from the no predation scenario to the baseline predation scenario. When moving further from the baseline to the high predation scenario, much of the same picture emerges, and the total mortality rates are lower for both categories of adult animals when the predation pressure is high.

Table 1 about here

Table 2 demonstrates the accompanying cost and benefit results of predation. It is first observed that the number of animals slaughtered decreases when the predation pressure shifts up (column two), simply because of reduced stock sizes (cf. Eq. 4). On the other hand, the slaughter weights increase (column three), though not sufficiently to offset the income effect through the reduced number of slaughtered animals. The total biomass slaughtered and the slaughter income is therefore reduced, but only by 2.5 % when moving from no predation to the baseline predation scenario (12,422 vs. 12,106 NOK/10 km^2). However, when also taking into account lower effort and lower operating cost following the reduced flock size, the economic compensation effect through increased weights is strong enough to make the herders economically better off with predation. Indeed, profit increases by as much as 24 % (5,257 vs. 4,236 NOK/10 km^2). When predation is increased to a higher level, profit increases even further.

Table 2 about here

Our 'tragedy of the commons' outcomes in Finnmark may be compared with possible outcomes in the herding areas in southern Norway. As mentioned previously, in the South (again, see Figure 1), herders have managed to coordinate their activity and restrict the reindeer density so as to avoid pasture degradation. Therefore, the slaughter rates are significantly higher, the animal density is lower, and the animal weights are higher in the South compared to Finnmark (Figure 2 above). In turn, higher weights lead to smaller predation loss in the South. Using the same price and cost parameters as in our study area of Finnmark, but with actual slaughter rates in the South based on data from Nord-Trøndelag County (NRHA 2014), we accordingly find that the slaughter income is higher, with the operating cost lower than in Finnmark under both the zero and baseline predation scenarios (again, see Table 2). More importantly, we find that the introduction of predation in the South results in losses to the herders. Therefore, carnivores and livestock predation work as a nuisance in this area. The high predation scenario is not included in this comparison because it, when combined with the high slaughter rates, leads to depletion of the population in the South.

The slaughter rates have been kept fixed under the different predation scenarios presented so far. In Figure 5 we have relaxed this assumption. We find here that when higher predation pressure is accompanied by lower slaughter rates, the profit reduces compared to the previous situation where the slaughter rates were kept fixed. On the contrary, when higher predation pressure is accompanied by higher slaughter rates, the profitability improves compared to the fixed slaughter rates situation. It is also noted that the profit with zero predation and baseline slaughter rates results in more or less the same amount of profit as in the baseline and high predation scenario, but with lower slaughter rates.

Figure 5 about here

Discussion and conclusions

Under the present management situation in our study area of Finnmark, characterized by low slaughter rates, high animal density, competition for grazing areas, and overgrazing, the numerical analysis demonstrates the paradoxical result that higher predation pressure and higher animal loss due to predation may improve the economic lot of our group of reindeer herders. Therefore, although reindeer herders perceive predation as a negative effect of the public goal of keeping sustainable carnivore populations in Norway, this policy may be beneficial for the herders under our model and parameter value assumptions. This paradoxical effect exists under the current 'tragedy of the commons' situation, in which the lack of coordinated management implies low and fixed slaughter rates and too many grazing animals, as well as slaughtering rates that do not respond to shifting ecological conditions. We have also highlighted some scenarios where the slaughter rates respond to changing predation pressures. We find that higher slaughter rates accompanying higher predation pressure improve profitability compared to the fixed slaughter rate situation. Additionally, our results for Finnmark have been compared with the well-managed grazing areas in the southern part of Norway, characterized by high slaughter rates and low animal densities, where we find that higher predation pressure actually imposes an economic cost to the herders.

The three predation scenarios considered in Finnmark conditioned upon identical low and fixed slaughter rates have also been studied under a different set of parameter values. While more valuable meat and a higher slaughter price scale up the moderate income loss following higher predation pressure, higher operating cost works in the opposite direction. Therefore, when keeping the unit operating cost parameter fixed while increasing the slaughter price in Eq. (4) by 8 %, up from 53.7 NOK/kg to 58.0 NOK/kg (see Appendix), the zero predation pressure and baseline scenario yield identical profit. Moreover, when keeping the slaughter price fixed while reducing the unit operating cost parameter in the linear specified cost function (5) by about 12 %, from 97.3 NOK/animal to 85.2 NOK/animal (see Appendix), we also find that the profit in these two scenarios just breaks even. These parameter values are therefore crucial for our main conclusion. While the baseline meat price data is reliable, the value of the operating cost parameter is much more uncertain (see Appendix). We have also done some sensitivity analysis by assuming increasing marginal operating costs. When specifying the convex cost function so as to yield the same baseline scenario, as previously stated, the impact of a changing predation pressure on profit is actually strengthened.

Additionally, we have obtained sensitivity results under shifting biological conditions, where we find that a higher value of the parameter governing density dependence in the recruitment function (parameter a; see Eq. (A1) and Table A1 in the Appendix) reduces profitability under all predation pressure scenarios, but does not change the quantitative effect of increased predation pressure on profitability. The same picture emerges when increasing the natural survival density dependence for the calf population (parameter b_c; see Eq. (A2) and Table A1). Changing other biological parameters does not change the quantitative effects of increased predation pressure; that is, higher predation pressure still results in higher profit. Finally, we have included scenarios with even higher predation rates than the high level considered above, and these scenarios demonstrate that profit may be reduced under our baseline parameter values when the predation pressure becomes very high.

More broadly, the main finding in this paper is that a negative external impact through ecological and economic compensation mechanisms may actually improve the economic lot of livestock holders in a situation with overgrazing and mismanagement. Such a result may be replicated under other economic and ecological settings where an exploitation scheme of the ‘tragedy of the commons’ type prevails. Another example may be that of common property grazing systems where livestock is subject to predation, but also illegal harvesting, although we are not aware of any studies on this. The ecological and economic compensation mechanisms studied in our paper may also be explored further when considering other predator-prey type interactions, where feedback effects, or numerical responses, are included, or when management of competing grazing animals is considered. To the best of our knowledge, these possible economic compensation mechanisms have been neglected in the literature.

References

Ballard, W. B., D. Lutz, T. W. Keegan, L. H. Carpenter, and J. C. deVos, Jr. 2001. Deer-predator relationships: a review of recent North American studies with emphasis on mule and black-tailed deer. *Wildlife Society Bulletin* 29: 99-115.

Baland, J. M. and J.P. Platteau 1996. Halting Degradation of Natural Resources. FAO, Rome.

Boman, M., G. Bostedt and J. Persson 2003. The bioeconomics of the spatial distribution of an endangered species. The case of the Swedish wolf population. *Journal of Bioeconomics* 5: 55 – 74.

Bostedt, G. 2005. Pastoralist economic behavior: Empirical results from reindeer herders in Northern Sweden. *Journal of Agricultural and Resource Economics* 30: 381-396.

Boyce, M. S., A. R. E. Sinclair, and G. C. White 1999. Seasonal compensation of predation and harvesting. Oikos 87: 419-426.

Bromley, D. 1991. *Environment and Ecology. Property Rights and Public Policy*. Basil Blackwell, Oxford.

Bårdsen, B. J., T. Tveraa, P. Fauchald, and K. Langeland 2010. Observational evidence of risk-sensitive reproductive allocation in a long-lived mammal. *Oecologia* 162: 627-639.

Dasgupta, P. 1982. *The control of resources*. Harvard University Press, Cambridge US.

Dasgupta, P. and K. G. Mäler 1995. Poverty, institutions, and the environmental resource Base. In *Handbook of Development Economics*, Vol III, ed. J. Behrman and T. Srinivasan. Elsevier, Amsterdam.

Ekspertutvalget 2011. Innstilling fra ekspertutvalget vedrørende endringer I erstatningsordningen for rovviltskade på husdyr. Direktoratet for Naturforvaltning, Trondheim (in Norwegian).

Hardin, G. 1968. The tragedy of the commons. *Science* 162: 1243-1248.

Johannesen, A. B. 2014: Samisk reindrift. Ch. 9 in *Naturessursenes Økonomi*, ed. O. Flaaten and A. Skonhoft. Gyldendal, Oslo (in Norwegian)

Johannesen, A. B., J. O. Olausssen and A. Skonhoft 2016. Livestock and carnivores: Economic and ecological interactions. Working paper Department of Economics NTNU Trondheim.

Johannesen, A. B. and A. Skonhoft 2008. Culture, economy, and conflicts in reindeer herding. A descriptive analysis of Trøndelag and western Finnmark. SØF report 3, Center for economic research at NTNU, Trondheim (in Norwegian).

Johannesen, A. B. and A. Skonhoft 2009. Local common property exploitation with rewards. *Land Economics* 85: 637-654.

Johannesen, A. B. and A. Skonhoft 2011. Livestock as insurance and social status: Evidence from reindeer herding in Norway. *Environmental and Resource Economics* 48: 679-694.

Johansen, B. and S. R. Karlsen 2005. Monitoring vegetation changes on Finnmarksvidda, Northern Norway, using Landsat MSS and Landsat TM/ETM+ satellite images. *Phytocoenologia* 35: 969-984.

Linnell, J., R. Aanes and R. Andersen 1995. Who killed Bambi? The role of predation in the neonatal mortality of temperature ungulates. *Wildlife Biology* 1: 209 – 223.

Mysterud, A., N. G. Yoccoz, N. C. Stenseth and R. Langvatn 2001. Effects of age, sex and density on body weight of Norwegian red deer; evidence of density-dependent senescence. *Proc. R. Soc. London B* 268: 911 – 919.

Naess, M. V., B. J. Bårdsen, P. Fauchald and T. Tveraa 2010. Cooperative pastoral production –the importance of kinship. *Evolution and Human Behavior* 31: 246 – 258.

Nilsen, E., T. Pettersen, H. Gundersen, A. Mysterud, J. Milner, J., E. Solberg, H. Andreassen and N. C. Stenseth 2005. Moose harvesting strategies in the presence of wolves. Spatially structured populations. *Journal of Applied Ecology* 42: 389 - 399.

Norwegian Reindeer Husbandry Administration (NRHA) 2014. Ressursregnskap for reindriftsnæringen, Alta (in Norwegian).

Ostrom, E. 1990. *Governing the Commons*. Cambridge University Press, Cambridge.

Riseth, J. Å. 2006. Sami reindeer herd managers: Why do they stay in low-profit business? *British Food Journal* 108: 541 – 559.

Riseth, J. Å. and A. Vatn 2009. Modernization and pasture degradation: A comparative study of two Sami reindeer pasture regions in Norway. *Land Economics* 85: 87-106.

Seabright, P. 1993. Managing local commons. *Journal of Economic Perspectives* 7: 131 – 144.

Sinclair, A. R. E. and R. P. Pech 1996. Density dependence, stochasticity, compensation and predator regulation. *Oikos* 75: 164-173.

Skonhoft, A. 2016. The silence of the lambs: Payment for carnivore conservation and livestock farming under strategic behavior. *Environmental and Resource Economics* doi:10.1007/s10640-016-0011-9

Tveraa, T., P. Fauchald, C. Henaug, and N. G. Yoccoz 2003. An examination of a compensatory relationship between food limitation and predation in semi-domestic reindeer. *Population Ecology* 137: 370-376.

Tveraa, T., A. Stien, H. Brøseth, and N. G. Yoccoz 2014. The role of predation and food limitation on claims for compensation, reindeer demography and population dynamics. *Journal of Applied Ecology* 51: 1264-1272.

Vucetic, J. A., D. W. Smith, and D. R. Stahler 2005. Influence of harvest, climate and wolf predation in Yellowstone elk 1961-2004. *Oikos* 111: 259-270.

Wilmers, C. C., E. Post, A. Hastings 2007. The anatomy of predator-prey dynamics in a changing climate. *Journal of Animal Ecology* 76: 1037-1044.

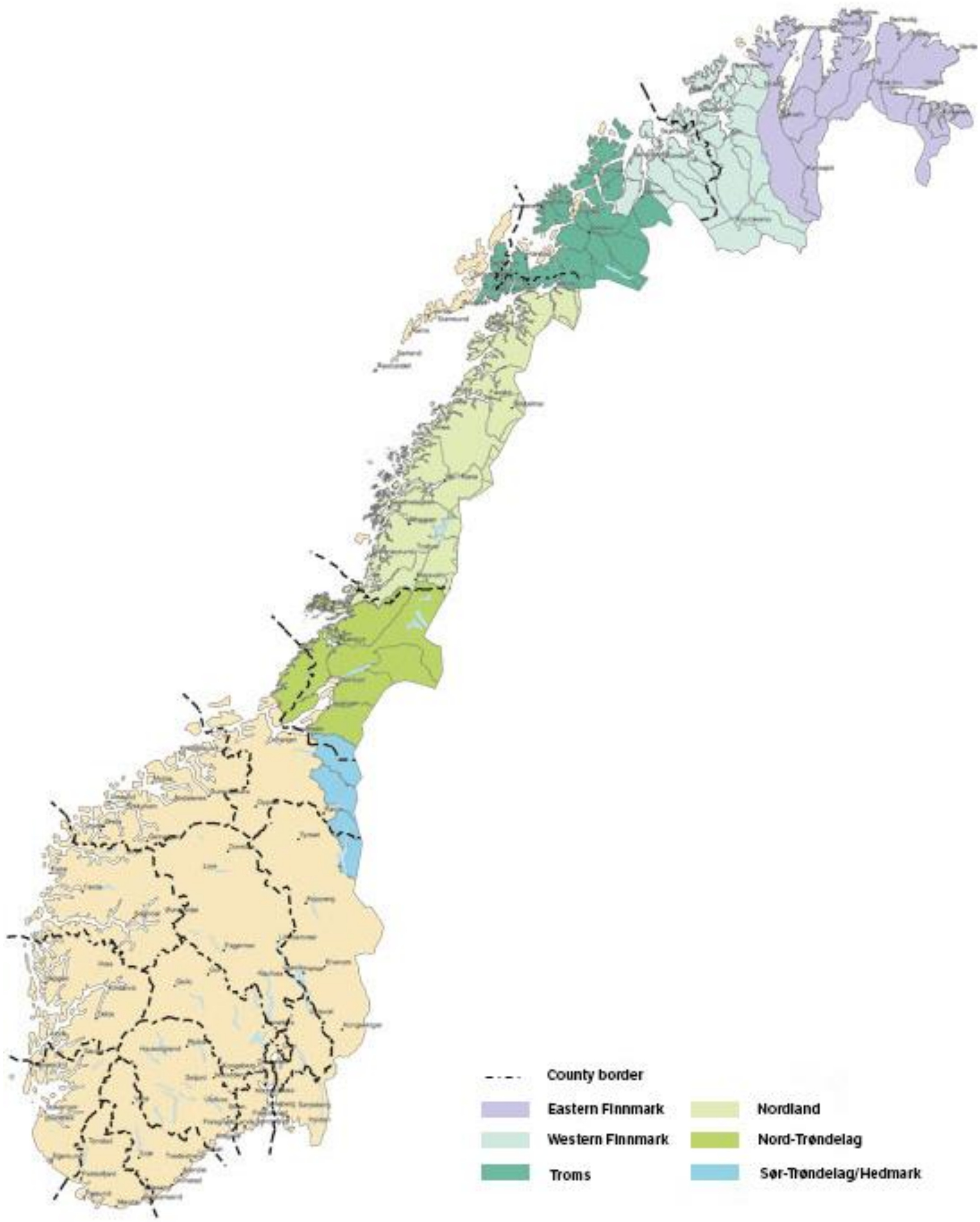


Figure 1. Reindeer herding districts in Norway (adopted from NOU 2007:13). Western Finnmark is the study area while Nord-Trøndelag is the district denoted as 'South'.

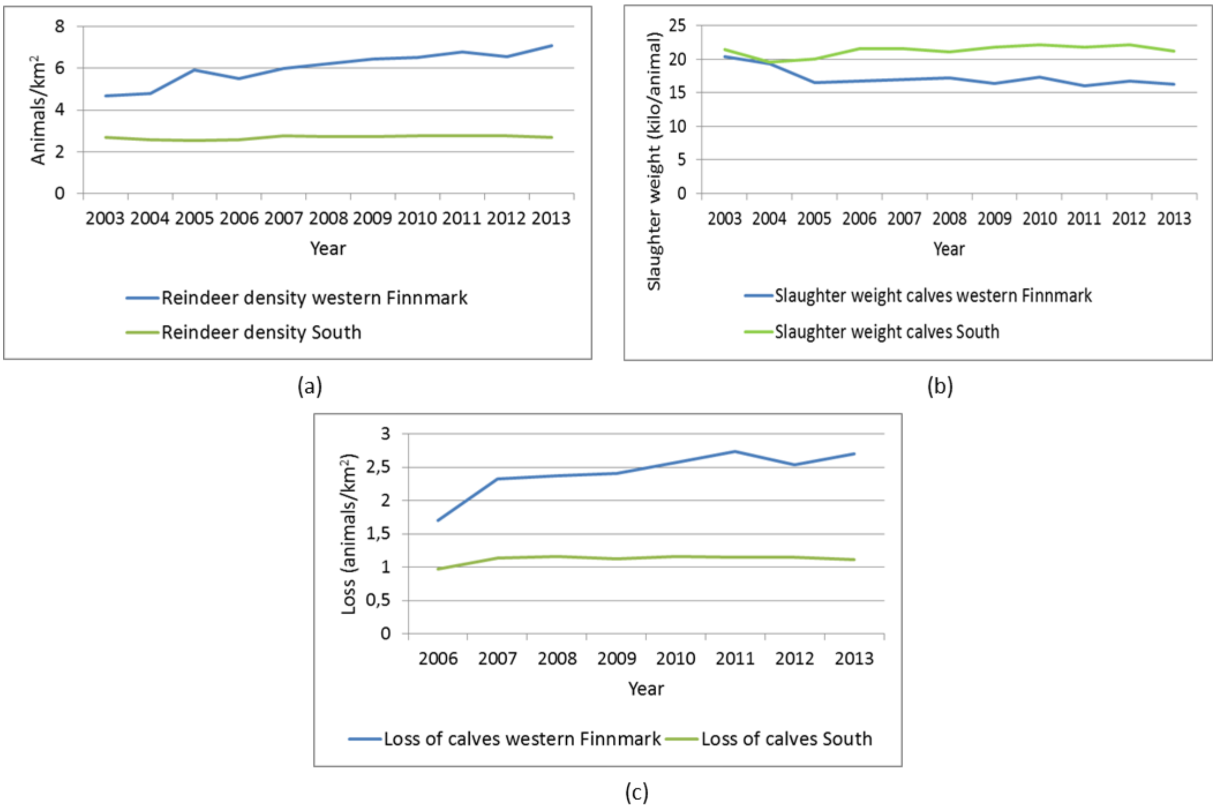
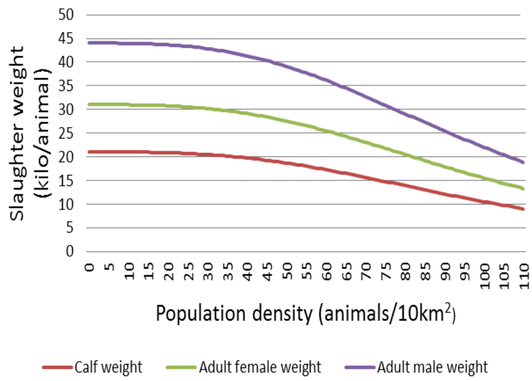
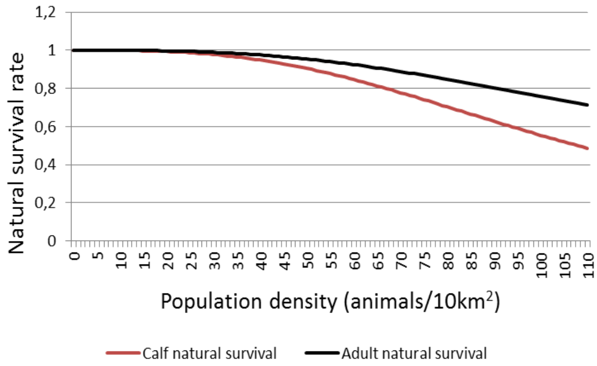


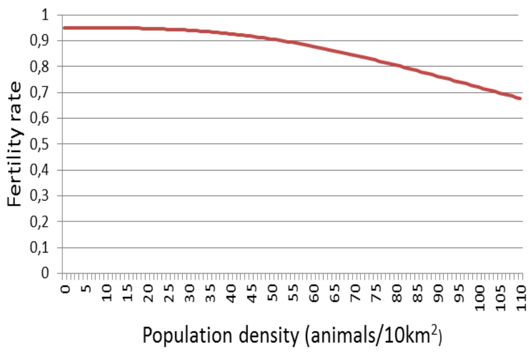
Figure 2. Reindeer density, weight of calves, and claimed losses of calves to predators from 2003 – 2013 (Source: http://www.reindrift.no and http://www.rovbase.no).



(a)



(b)



(c)

Figure 3. Density dependent weight-, natural survival-, and recruitment functions. Baseline parameter values western Finnmark (see Table A1)

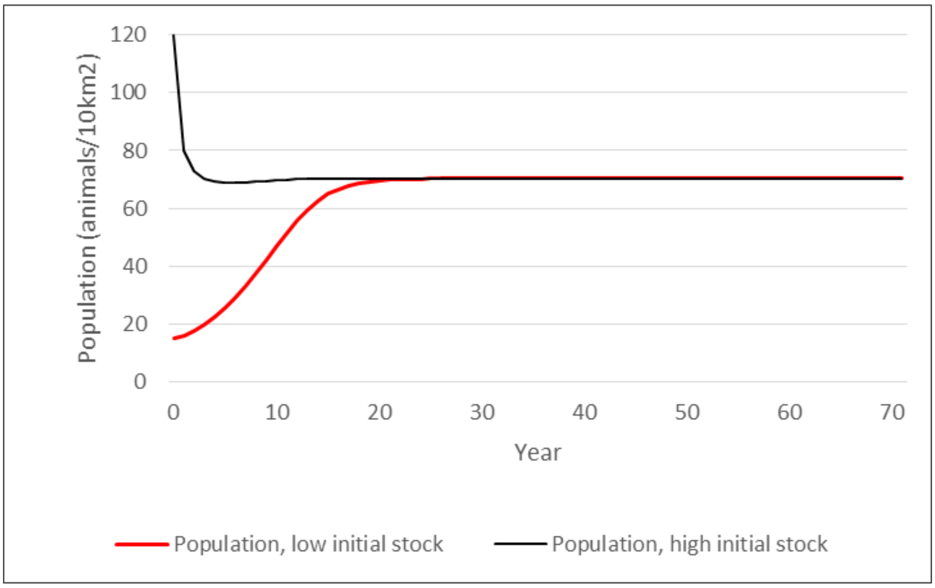


Figure 4. Population dynamics total stock, $X_t = (X_{c,t} + X_{f,t} + X_{m,t})$, with low initial population size $X_0 = 15$ and high, $X_0 = 120$. Present management situation and baseline predation rates in western Finnmark.

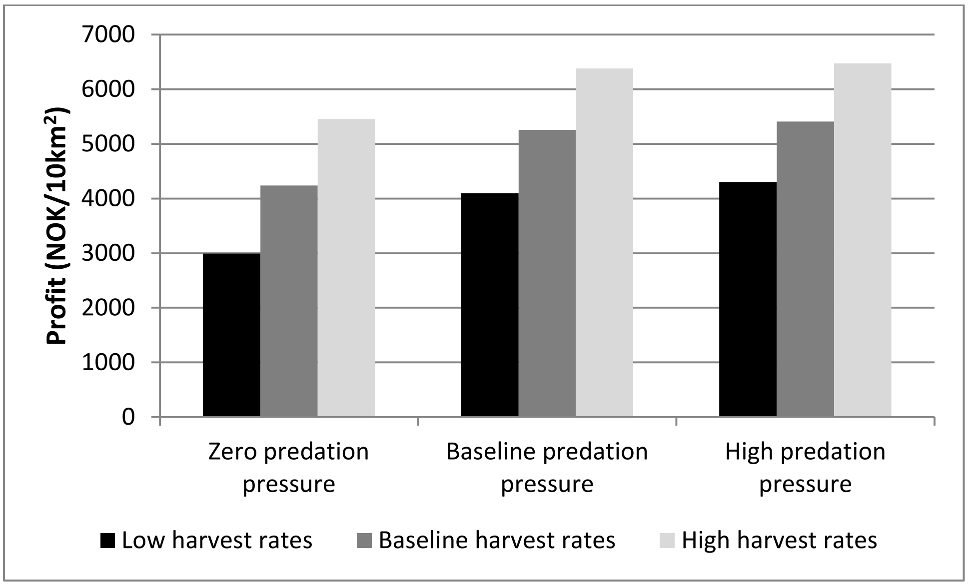


Figure 5. Steady state profit western Finnmark. Baseline parameter values, but shifting slaughter rates. Low harvest rates=0.9*Baseline harvest rates, High harvest rates=1.1* Baseline harvest rates. Baseline harvest rates, see Table 1.

Table 1: Steady state biological results under present management situation in western Finnmark; $h_c = 0.20$, $h_f = 0.05$, $h_m = 0.21$. Baseline parameter values.

	Animal density (# animals/10km^2)		Fertility rate	Survival rates	Mortality (# animals/10km^2)		
Predation pressure[1)]	X	X_c, X_f, X_m	f	s_c, s_f, s_m	Natural[2)]	Predation[3)]	Total
Zero	84.1	27.6, 35.0, 21.5	0.79	0.67, 0.83, 0.83	7.3, 5.7, 2.9	0.0, 0.0, 0.0	7.3, 5.7, 2.9
Baseline	70.4	24.5, 29.0, 16.9	0.84	0.78, 0.89, 0.89	4.3, 3.0, 1.5	4.1, 1.0, 0.5	8.4, 4.0, 2.0
High	65.7	23.2, 27.0, 15.5	0.86	0.81, 0.90, 0.90	3.6, 2.4, 1,2	5.1, 1.2, 0.6	8.7, 3.6, 1.8

Table notes: [1)] Baseline predation pressure; $m_c = 0.27$, $m_f = m_m = 0.04$. High predation pressure; $m_c = 0.34$, $m_f = m_m = 0.05$. [2)] Natural mortality equals $N_i = (1-h_i)(1-s_i)X_i$, $i = c, f, m$ (see main text). [3)] Predation loss equals $M_i = (1-h_i)s_i X_i m_i$, $i = c, f, m$ (see main text).

Table 2: Steady state economic results in western Finnmark and South (in brackets). Similar economic and biological parameter values (baseline parameter values). Slaughter rates western Finnmark; $h_c = 0.20$ **,** $h_f = 0.05$, $h_m = 0.21$. Slaughter rates South; $h_c = 0.57$, $h_f = 0.09$, $h_m = 0.28$.

Predation pressure[1)]	Animal density (# animals/ 10km^2) X	Harvesting[2)] H_c, H_f, H_m	Weight (kg/animal) w_c, w_f, w_m	Slaughter income (NOK/10km^2) I	Operating cost (NOK/10km^2) C	Profit (NOK/10km^2) π
Zero	84.1 (60.3)	5.5, 1.8, 4.5 (12.8, 2.3, 3.4)	13.2, 19.4, 27.6 (17.2, 25.4, 36.1)	12,422 (21,621)	8,186 (5,869)	4,236 (15,753)
Baseline	70.4 (35.3)	4.9, 1.5, 3.6 (7.9, 1.3, 1.8)	15.6, 23.0, 32.6 (20.1, 29.7, 42,1)	12,106 (14, 847)	6,849 (3,439)	5,257 (11,409)
High	65.7	4.6, 1.4, 3.2	16.4, 24.1, 34.3	11,808	6,398	5,410

Table note: 1) See note 1, Table 1

Appendix: Specific functional forms and parameter values

Specific functional forms

The fertility rate, increasing in the female weight, is specified as:

(A1) $f_t = \bar{f} \cdot (w_{f,t} / \bar{w}_f)^a$,

with $f_t = \bar{f}$ as the maximum fertility rate when the adult female weight reaches its maximum value, $w_{f,t} = \bar{w}_f$. The parameter $0 < a < 1$ indicates fertility as a concave function of the weight. The next equation:

(A2) $s_{i,t} = \bar{s}_i \cdot (w_{i,t} / \bar{w}_i)^{b_i}$; $i = c, f, m$

yields the same functional form for the natural survival rates. $\bar{s}_i$ is the maximum survival rate for animal category i, while the parameter $0 < b_i < 1$ generally differs among the various categories of animals.

The weight-density relationships, where weights decrease in the total number of animals, $X_t = X_{c,t} + X_{f,t} + X_{m,t}$, are specified as sigmoidal functions with an increasing degree of density dependence at high densities (Nielsen et al. 2005, Mysterud et al., 2001; see also Figure 3). The same functional form is assumed for all categories of animals:

(A3) $w_{i,t} = \dfrac{\bar{w}_i}{1 + (X_t / K)^\beta}$; $i = c, f, m$.

The parameter $K > 0$ represents the stock size for which the density-dependent weight effect is equal to the density-independent weight effect. This parameter scales the population sizes, and its value is contingent upon factors such as the size of the grazing area and the potential productivity of the grazing resources (i.e., lichen). The compensation parameter $\beta > 0$ indicates the extent to which density-independent factors compensate for changes in the stock size.

Combining Eqs. (A1) and (A3) yields $f_t = \bar{f} \cdot (\dfrac{1}{1 + (X_t / K)^\beta})^a$, while Eq. (A2) together with Eq. (A3) yield $s_{i,t} = \bar{s}_i \cdot (\dfrac{1}{1 + (X_t / K)^\beta})^{b_i}$. Therefore, both fertility and survival rates are sigmoidal functions of the total animal stock (see also Figure 3). With $b_f = b_m$ the ratio of the natural survival rates between the two adult categories of animals is then proportional to the maximum survival rates $\bar{s}_i$. Because $\bar{s}_f = \bar{s}_m$ (see Table A1), the natural survival rates of the adult categories are identical.

Finally, the operating cost function is specified linearly:

(A4) $C_t = cX_t$,

such that $c > 0$ is the constant marginal operating cost. In the sensitivity analysis, we have also applied a convex cost function, specified as:

(A5) $C_t = c_1 X_t + (c_2 / 2) X_t^2$,

with $c_1 > 0$ and $c_2 > 0$.

Parameter values, baseline predation rates and harvesting rates

Table A1 presents the baseline parameter values. The considered area in Finnmark comprises about 24,400 km^2. With about 170,000 grazing reindeers (summer 2012, NRHA 2014), the animal density is accordingly about 70 animals per 10 km^2. The main sources of information on predation loss are annual reports from herders to the government (NRHA 2014) and official statistics (www.rovbase.no). Our baseline predation rates are determined based on data on losses to predators, as reported by herders yearly when applying to the State for compensation losses due to predation. Because of certain characteristics of the compensation system, there is a tendency to overstate the predation losses and accordingly to understate losses due to natural mortality (see Tveraa et al. 2014). The baseline predation rates used represent the average of claimed and compensated losses in 2013. The baseline harvesting rates are identical with the current rates in our study area, Finnmark county.

Table A1 about here

We use the calving rate in the best performing reindeer herding area as a proxy for the maximum calving rate $\bar{f}$. The recruitment parameter a is calibrated to give a baseline calving rate similar or equal to the observed calving rate of 0.84 calves per female in Finmark (NRHA 2014). The maximum natural survival rate is assumed to be one. When determining the baseline survival parameters b_c, b_f, and b_m (Eq. A2), we assume that $b_f = b_m$ and that the survival rate of calves is more sensitive to changes in stock density; that is, $b_c > b_f = b_m$. Finally, b_c, b_f, and b_m are calibrated such that the steady state ecological values fit reasonably well with actual values. The slaughter weights in the best performing reindeer herding area in the southern part of Norway, where the vegetation cover is intact, are used as proxies for maximum weights. When using these values together with the baseline stock density in the weight functions, and when assuming that $\beta = 3$ and $K = 100$ (# of animals/10 km^2), the weights in the steady state (Table 2) correspond reasonably well with the actual weights observed in the northernmost part of Norway (NRHA 2014). The value of carrying capacity K also scales the model. The slaughtering price p is assumed to be 53.7 (NOK/kg), and coincides with the actual market price in 2012 (NRHA 2013b). Finally, the operating (herding) cost per animal c was calculated based on the current stock composition and slaughtering rates, and the estimated net herding income in Finnmark per 10km^2 in 2012 (NRHA 2013b) was also taken into account. The sensitivity analysis also applies the convex cost function (A5). Somewhat arbitrarily, we use $c_1 = 50$ (NOK/animal) and $c_2 = 2.77$ (NOK/animal^2) in a way that the total cost with this cost function equalizes the cost utilizing the linear cost function in the baseline scenario of Finnmark with an animal density of 70.4 (#animals/10km^2) (see Table 2).

Table A1: Baseline economic and ecological parameter values

Description	Parameter	Value	unit	Reference
Sex ratio	ψ	0.5		Assumed
Maximum fertility	$\bar{f}$	0.95	Calves/females	NRHA (2014)
Maximum weights	$\bar{w}_c$, $\bar{w}_f$, $\bar{w}_m$	21, 31, 44	kg/animal	NRHA (2014)
Parameter fertility	a	0.40		Calibrated
Maximum survival	$\bar{s}_c$, $\bar{s}_f$, $\bar{s}_m$	1, 1, 1		Assumed
Parameter survival	b_c, b_f, b_m	0.85,0.40,0.40		Calibrated
Weight parameter	β	3		Assumed
Carrying capacity	K	100	# of animals/10	Assumed
Predation rates	m_c, m_f, m_m	0.27,0.04,0.04		www.rovbase.no
Harvesting rates	h_c, h_f, h_m	0.20,0.05,0,20		NRHA (2014)
Meat price	p	53.7	NOK/kg	NRHA (2013b)
Unit operating cost	c	97.3	NOK/animal	Calibrated