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On the tragedy of the commons:

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When predation and livestock loss may improve the economic lot of herders

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11 **Abstract**

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

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

28

29 **Introduction**

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

45

46 Much of the discussion of the problems of unmanaged local commons can be traced back to
47 Hardin's (1968) famous allegory of 'the tragedy of the commons'. Hardin studied a system of
48 communally owned grazeland and privately owned livestock. He assumed that the
49 exploitation was steered by the self-interests of the livestock owners, with the consequences
50 of having excess livestock and the issue of overgrazing. His famous conclusion, while being
51 widely criticized (see, e.g., Dasgupta 1982, Ch. 2), was that "each man is locked into a system
52 that compels him to increase the herd without limits – in a world that is limited. Ruin is the
53 destination toward which all men rush, each pursuing his own best interests in a society that
54 believes in the freedom of the commons. Freedom in a common brings ruin to all" (Hardin
55 1968, p. 1244). Various aspects of common property and common property exploitation have
56 been analyzed by, among others, Ostrom (1990), Bromley (1991), Seabright (1993), Baland
57 and Platteau (1995), and Dasgupta and Mäler (1995).

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

79 Figure 1 about here

80

81 The rest of the paper is structured as follows. In the Materials and method section, we start
82 by giving a brief background of Saami reindeer herding in Norway and the prevailing
83 problems related to food shortage and predation in our study area, Finnmark. Next, we
84 formulate a reindeer population model. As the various categories of the reindeer population
85 are differently exposed to predation, the model is specified with different age classes. The
86 model is structured in three classes, where the weight-mortality and weight-fecundity
87 relationships are included. The effect of carnivore predation on total mortality is also

88 introduced here. The reindeer population consists of several flocks owned by different
89 herders, or groups of herders, competing for space and grazing areas, and the economic
90 benefit and cost functions for these herders are formulated in the last part of this main
91 section. The Numerical results section presents numerical results under the considered
92 ‘tragedy of the commons’ scenario, and the biological and economic effects of predation are
93 demonstrated. The results are also compared with reindeer herding in Nord-Trøndelag
94 county (Figure 1). This county is located in the southern/middle part of Norway, identified as
95 ‘South’, and is characterized by higher slaughter rates and significantly lower population
96 density. In this area, we find that predation worsens the economic conditions of the
97 livestock holders. The Discussion and conclusions section summarizes and discusses the
98 results.

99

100 **Materials and methods**

101 *Ecological and economic background*

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

115 A similar relationship has also been demonstrated in semi-domestic reindeer herding in
116 Norway (Tveraa et al. 2003). Because reindeer graze on natural pastures throughout the

117 year, they are prone to the risk of being killed by predators. Predation is significant, and this
118 problem has accentuated during the last two to three decades because of growing carnivore
119 populations, as Norway has the goal of keeping 'sustainable' carnivore populations (see, e.g.,
120 <http://www.roviltportalen.no/content/2704/Bestandsmal>, Ekspertutvalget 2011)¹. In our
121 study area, Finnmark, reindeer predation is particularly related to the lynx and wolverine,
122 but also the golden eagle (Tveraa et al. 2014). Small and weak reindeer, especially calves,
123 are more vulnerable to predators than other animals in good condition (Tveraa et al. 2003).
124 Figure 2, panel (c) shows that the loss of calves to predators per km² has increased
125 substantially over the past few years in our study area, Finnmark, while it has remained
126 stable and at a significantly lower level in the southern part of Norway. The losses reported
127 here are those claimed by the herders. These are probably larger than the actual losses as
128 the prevailing monetary compensation scheme gives incentives to overstate losses. Losses
129 actually compensated are, however, likely to underestimate real losses because
130 compensation relies on the ability to document losses, which may be difficult, especially for
131 losses of calves (Tveraa et al. 2014). In the numerical analysis in section five, the average
132 between the claimed and compensated losses is used as the baseline predation pressure.
133 For further information, see the Appendix.

134

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

143

144 Reindeer husbandry is a traditional and culturally based livelihood of the Saami people in
145 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).

146 the Saami people domesticated entire reindeer herds, leading a considerable number of
147 Saami people to become herding nomads (e.g., Riseth 2006). This tradition has been
148 preserved until today. Saami reindeer herding in Norway takes place in Finnmark, Troms,
149 Nordland, Nord-Trøndelag, Sør-Trøndelag, and Hedmark counties (Figure 1), and is an
150 exclusive right of the Saami people in these counties (Johannesen 2014). It is a small
151 economic activity, comprising some 530 herding units that keep a total of 230 000 animals
152 (NRHA 2014). The industry produces about 2000 tons of reindeer meat yearly, which
153 amounts to 1-2 percent of the total production of red meat in Norway (NRHA 2013b).
154 Although small on a national scale, reindeer husbandry is of great importance to the Saami
155 people, both culturally and economically (Bostedt 2005, Johannesen and Skonhoft 2009). For
156 many herders, cultural values are important when choosing to make a living through
157 reindeer husbandry, and these values seem to be valued just as highly as the income
158 opportunities the industry provides (Johannesen and Skonhoft 2009). Therefore, not
159 surprisingly, a large number of herders emphasize that herd size is important as a part of the
160 cultural valuation, as well as providing insurance against unfavorable environmental
161 conditions (Johannesen and Skonhoft 2011).

162

163 Reindeer graze on open natural pastures throughout the year and the pastures are utilized
164 as common properties. The largest herding area in Norway is found in our study area,
165 Finnmark County, and constitutes about 70 % of the total Norwegian reindeer population
166 (NRHA 2014). Until the 1970s, the reindeer herders in Finnmark held a relatively stable
167 number of reindeer, but the number increased substantially during the 1990s and onwards
168 (Riseth and Vatn 2009). Previously, herders utilized the grazing land according to traditional
169 rules of allocation and respected the prevailing informal rules transferred through
170 generations (Riseth and Vatn 2009). At that time, reindeer herding proved sustainable, and
171 the utilization of the grazing land was characterized as a managed common property.
172 However, the social structure in reindeer herding in Finnmark changed and eroded with
173 technological improvements, access to external markets, centralized settlements, and the
174 establishment of external regulations from the Norwegian government (Riseth and Vatn
175 2009). Over the past decades, many herding communities in Finnmark have been
176 characterized by internal conflicts and strong competition over access to pastures

177 (Johannesen and Skonhoft 2009, Riseth and Vatn 2009). This perceived lack of cooperation
178 and coordination has resulted in low slaughter rates, thus leading to increased reindeer
179 density, and subsequent pasture degradation (Johansen and Karlsen 2005). The situation
180 shows clear signs of ‘tragedy of the commons’ exploitation, especially in the eastern parts of
181 Finnmark (NRHA 2014).

182

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

190

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

197

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

202

203 Figure 2 about here

204

205 *Population model*

206 The total reindeer population for the herders in our study area at the time (year) t is
 207 structured in three stages: calves $X_{c,t}$ ($yr < 1$), adult females $X_{f,t}$ ($yr \geq 1$), and adult males
 208 $X_{m,t}$ ($yr \geq 1$). The population is measured in the spring, just before calving. When we neglect
 209 summer mortality and assume predation takes place after winter natural mortality; the
 210 events over the yearly cycle are then calving, slaughtering (which takes place in September –
 211 October), winter natural mortality (diseases, accidents, starvation), and predation². Within
 212 the range of the actual reindeer densities, the sex composition seems to play a negligible
 213 fecundity role, and recruitment is steered only by the number of adult females. This implies
 214 that there are always enough males to reproduce the stock. Therefore, the number of calf
 215 (recruitment) is first governed by:

$$216 \quad (1) \quad X_{c,t} = f_t X_{f,t},$$

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

218

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

$$223 \quad (2) \quad X_{f,t+1} = \psi(1 - h_{c,t})X_{c,t}s_{c,t}(1 - m_{c,t}) + (1 - h_{f,t})X_{f,t}s_{f,t}(1 - m_{f,t})$$

224 and

$$225 \quad (3) \quad X_{m,t+1} = (1 - \psi)(1 - h_{c,t})X_{c,t}s_{c,t}(1 - m_{c,t}) + (1 - h_{m,t})X_{m,t}s_{m,t}(1 - m_{m,t}),$$

226 respectively. Both fertility and survival rates depend on food conditions and food shortages
 227 approximated by the (average) animal weights. The weight of the animals, on the other
 228 hand, depends on food availability and the grazing pressure during the summer and fall,
 229 approximated by the total number of grazing animals (Tveraa et al. 2003). See Figure 3,
 230 panel (a). Therefore, natural survival rates and fertility rates reduce with animal density

² In reality, there is a spring and summer mortality, especially for calves (Bårdsen et 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.

231 (Figure 3, panel b and c; also see the Appendix for more details). The survival rates are
232 assumed similar for the adults, and are higher for adults than for calves at all population
233 levels, $s_{m,t} = s_{f,t} > s_{c,t}$.

234

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

242 The carnivore natural growth and population sizes are thus assumed independent of the size
243 of the reindeer population, and the predation rates are exogenous in the model.

244 Figure 3 about here

245

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

255

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

256 We also consider the compensatory effects in terms of mortality rates. With natural mortality
 257 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
 258 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
 259 place after natural mortality, the total mortality of category i becomes
 260 $N_{i,t} + M_{i,t} = (1-h_{i,t})X_{i,t}(1-s_{i,t}) + (1-h_{i,t})X_{i,t}s_{i,t}m_{i,t}$. The total mortality rate may therefore be
 261 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
 262 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
 263 first order effect is therefore captured by the term $s_{i,t}$. The second order effect is captured
 264 by $-(1-m_{i,t})(\partial s_{i,t} / \partial m_{i,t})$, and hence this represents the compensatory effect.

265

266 Because of strong density-dependent effects in our population model, we find that the total
 267 population size stabilizes quite quickly with fixed slaughter rates. Figure 4 illustrates the
 268 transitional dynamics with the baseline slaughter and predation rates and baseline
 269 parameter values (the Appendix provides details about the data and the functional forms).
 270 This figure clearly indicates that the dynamic is ergodic; that is, a unique steady state is
 271 approached under the two different initial situations of low and high animal density. The low
 272 *fixed* slaughter rates included here, $h_c = 0.20$, $h_f = 0.05$ and $h_m = 0.21$ (the time notation is
 273 omitted), are in accordance with the present management situation in our study area (see
 274 also Tables 1 and 2). Therefore, the high steady state total stock density, about 70 (# of
 275 animals/10 km²), reflects today's 'tragedy of the commons' situation, and is, as previously
 276 mentioned, significantly higher than in the southern part of Norway (Figure 2 above). The
 277 time-invariant predation rates represented here, $m_c = 0.27$, $m_f = m_m = 0.04$, are the average
 278 of current claimed and compensated losses and reflect our baseline predation scenario. In
 279 the numerical analysis below, only equilibrium, or steady state, is considered.

280 Figure 4 about here

281

282 *Cost and benefit functions*

283 In the present study, we are only concerned with the net income from slaughtering,
 284 considering the harvesting value, slaughtering costs, and the operating costs with respect to
 285 the animals. Therefore, any positive stock value related to status, insurance or cultural
 286 identity (see section two above) is not taken into account in the present exposition.
 287 Compensation for the predation loss is neither taken into account⁴. Because natural
 288 mortality and predation are assumed to take place during the late fall and winter, after
 289 slaughtering, the number of animals removed through slaughtering in year t is simply
 290 defined by $H_{i,t} = h_{i,t} X_{i,t}$ ($i = c, f, m$). The current slaughter value, or meat value, for our
 291 group of herders, is accordingly:

$$292 \quad (4) \quad I_t = p(w_{c,t} h_{c,t} X_{c,t} + w_{f,t} h_{f,t} X_{f,t} + w_{m,t} h_{m,t} X_{m,t}),$$

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

295

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

$$301 \quad (5) \quad C_t = C(X_{c,t} + X_{f,t} + X_{m,t}) = C(X_t),$$

302 with $C' > 0$ and $C(0) = 0$. In addition, there are fixed costs, but they are not included
 303 as these have no influence of the solution of the model. The cost function may be convex, or
 304 concave-convex. As a compromise and simplification, it is assumed to be linear, $C'' = 0$.
 305 However, in the sensitivity analysis, we have also included a convex function. As any possible
 306 protective effort with respect to predation is also neglected here, Eq. (5) indicates the total

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 Skonhøft (2016) for an analysis of carnivore conservation, predation, and sheep farming.

307 variable costs. The current net benefit, or profit, for our considered group of herders is thus
308 defined by:

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

310

311 **Numerical results: the cost and benefit of predation**

312 We now present our numerical steady state results under the ‘tragedy of the commons’
313 management situation in our study area in Finnmark, which is characterized by low slaughter
314 rates and high population density. We consider three predation scenarios with the baseline
315 scenario reflecting the average between today’s claimed and compensated loss.

316 Additionally, we study the effects of zero predation as well as high predation. The last
317 scenario is characterized by a somewhat higher calf predation rate than in the baseline
318 scenario, while the adult rates are just slightly higher (see Table 1, and also the Appendix). In
319 these first scenarios, the slaughter rates are kept fixed and thus any possible harvest control
320 response to the changing predation pressure is not taken into account.

321

322 The main biological results are first considered (see Table 1). Increased predation pressure
323 reduces the total stock (column one) and the predation losses increase for all animal
324 categories (column six). However, the ecological compensation effect, when working
325 through increased natural survival rates (column four), reduces natural mortality (column
326 five) and dampens the effect on total mortality (column seven). Indeed, the compensation
327 effect is so strong that the total mortality for adult animals is actually lower under the
328 baseline predation scenario than under the no predation scenario (column seven).

329 Therefore, we find that the second order effect in the population model dominates the first
330 order effect for these two stages (see the above Materials and methods section). The natural
331 mortality compensation mechanism is also strong for the calf population, although not
332 sufficient to offset the increased predation loss. The total mortality hence increases slightly
333 when moving from the no predation scenario to the baseline predation scenario. When
334 moving further from the baseline to the high predation scenario, much of the same picture

335 emerges, and the total mortality rates are lower for both categories of adult animals when
336 the predation pressure is high.

337 Table 1 about here

338

339 Table 2 demonstrates the accompanying cost and benefit results of predation. It is first
340 observed that the number of animals slaughtered decreases when the predation pressure
341 shifts up (column two), simply because of reduced stock sizes (cf. Eq. 4). On the other hand,
342 the slaughter weights increase (column three), though not sufficiently to offset the income
343 effect through the reduced number of slaughtered animals. The total biomass slaughtered
344 and the slaughter income is therefore reduced, but only by 2.5 % when moving from no
345 predation to the baseline predation scenario (12,422 vs. 12,106 NOK/10 km²). However,
346 when also taking into account lower effort and lower operating cost following the reduced
347 flock size, the economic compensation effect through increased weights is strong enough to
348 make the herders economically better off with predation. Indeed, profit increases by as
349 much as 24 % (5,257 vs. 4,236 NOK/10 km²). When predation is increased to a higher level,
350 profit increases even further.

351 Table 2 about here

352

353 Our 'tragedy of the commons' outcomes in Finnmark may be compared with possible
354 outcomes in the herding areas in southern Norway. As mentioned previously, in the South
355 (again, see Figure 1), herders have managed to coordinate their activity and restrict the
356 reindeer density so as to avoid pasture degradation. Therefore, the slaughter rates are
357 significantly higher, the animal density is lower, and the animal weights are higher in the
358 South compared to Finnmark (Figure 2 above). In turn, higher weights lead to smaller
359 predation loss in the South. Using the same price and cost parameters as in our study area of
360 Finnmark, but with actual slaughter rates in the South based on data from Nord-Trøndelag
361 County (NRHA 2014), we accordingly find that the slaughter income is higher, with the
362 operating cost lower than in Finnmark under both the zero and baseline predation scenarios
363 (again, see Table 2). More importantly, we find that the introduction of predation in the

364 South results in losses to the herders. Therefore, carnivores and livestock predation work as
365 a nuisance in this area. The high predation scenario is not included in this comparison
366 because it, when combined with the high slaughter rates, leads to depletion of the
367 population in the South.

368

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

377 Figure 5 about here

378

379 **Discussion and conclusions**

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

393 our results for Finnmark have been compared with the well-managed grazing areas in the
394 southern part of Norway, characterized by high slaughter rates and low animal densities,
395 where we find that higher predation pressure actually imposes an economic cost to the
396 herders.

397

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

414

415 Additionally, we have obtained sensitivity results under shifting biological conditions, where
416 we find that a higher value of the parameter governing density dependence in the
417 recruitment function (parameter a ; see Eq. (A1) and Table A1 in the Appendix) reduces
418 profitability under all predation pressure scenarios, but does not change the quantitative
419 effect of increased predation pressure on profitability. The same picture emerges when
420 increasing the natural survival density dependence for the calf population (parameter b_c ; see
421 Eq. (A2) and Table A1). Changing other biological parameters does not change the
422 quantitative effects of increased predation pressure; that is, higher predation pressure still

423 results in higher profit. Finally, we have included scenarios with even higher predation rates
424 than the high level considered above, and these scenarios demonstrate that profit may be
425 reduced under our baseline parameter values when the predation pressure becomes very
426 high.

427

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

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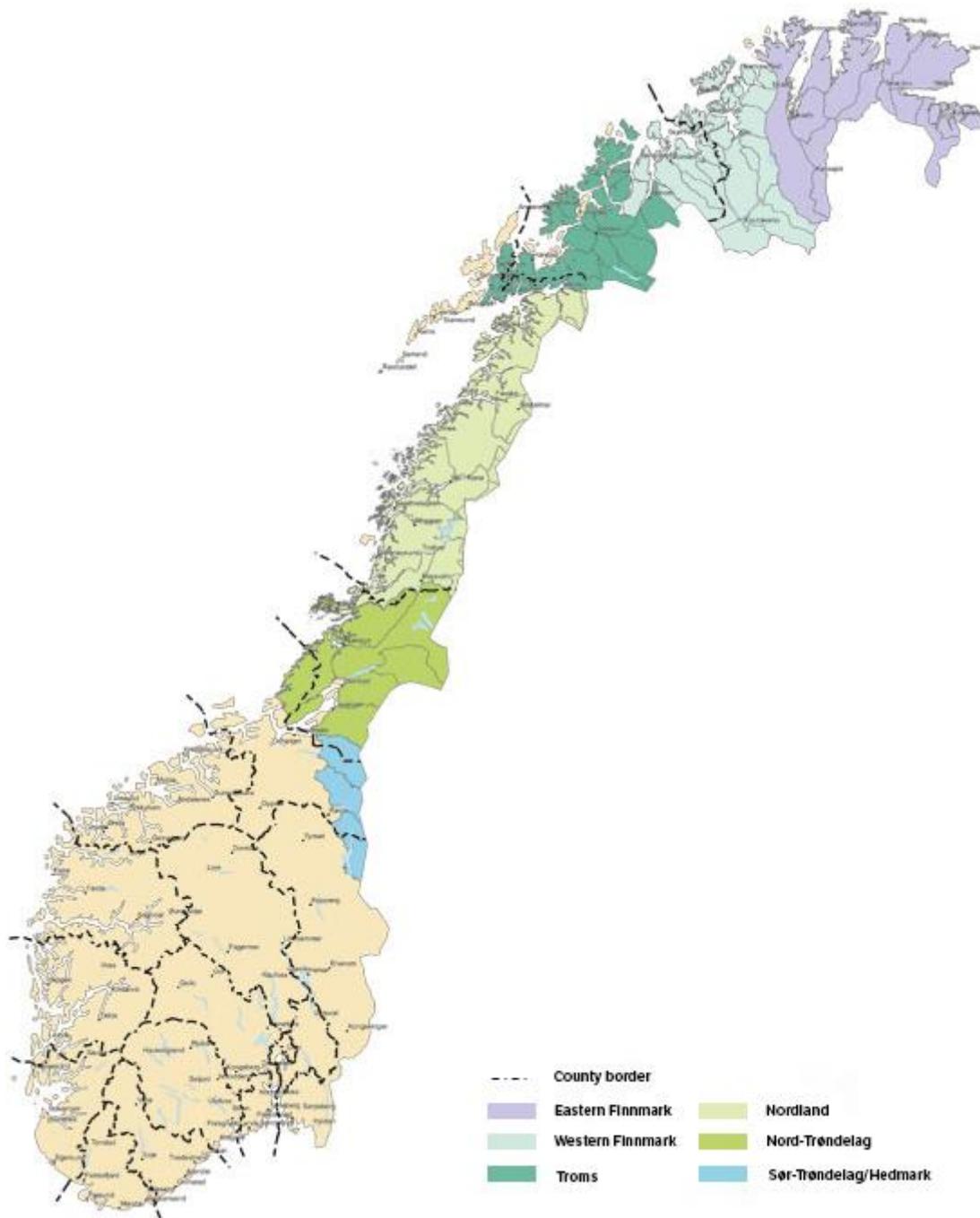
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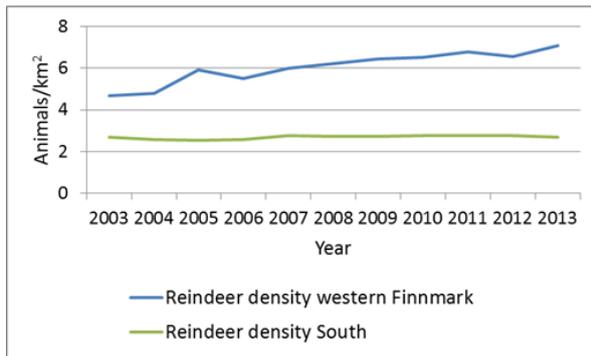
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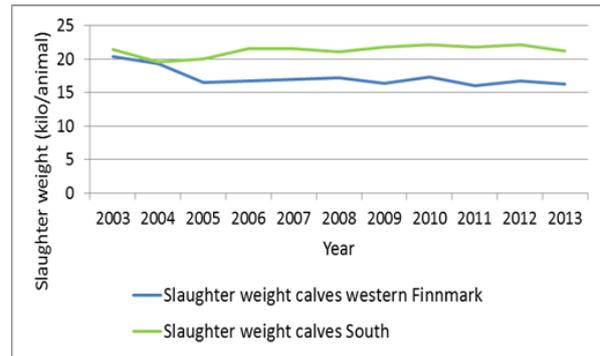
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525 **Figure 1.** Reindeer herding districts in Norway (adopted from NOU 2007:13). Western
 526 Finnmark is the study area while Nord-Trøndelag is the district denoted as 'South'.

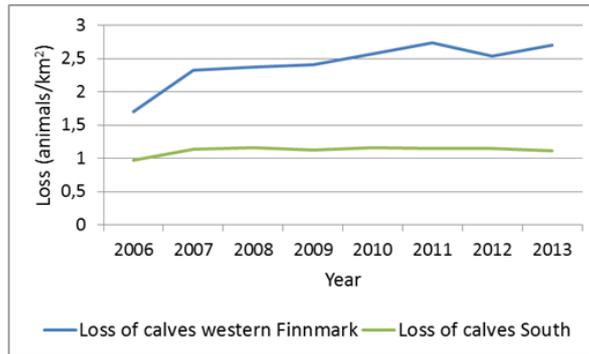
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(a)



(b)



(c)

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529 **Figure 2.** Reindeer density, weight of calves, and losses of calves to predators from 2003 –

530 2013 (Source: <http://www.reindrift.no> and <http://www.rovbase.no>).

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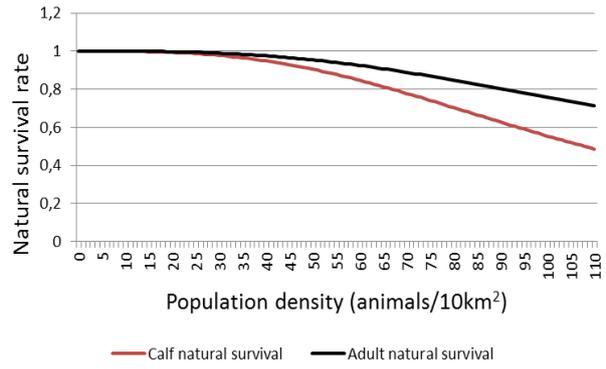
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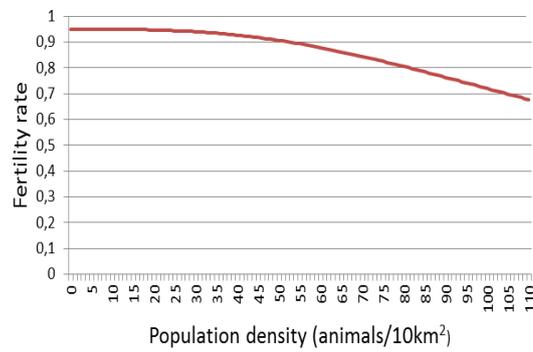
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544 **Figure 3.** Weight-, natural survival-, and recruitment functions. Baseline parameter values
545 (see Table A1)

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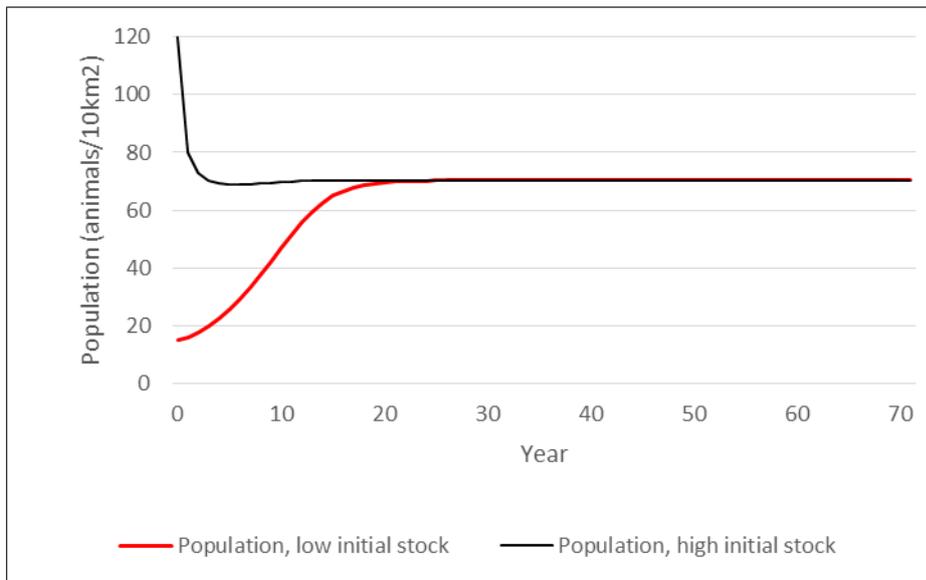
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554 **Figure 4.** Population dynamics total stock, $X_t = (X_{c,t} + X_{f,t} + X_{m,t})$, with low initial
 555 population size $X_0 = 15$ and high, $X_0 = 120$. Present management situation and baseline
 556 predation rates in Finnmark.

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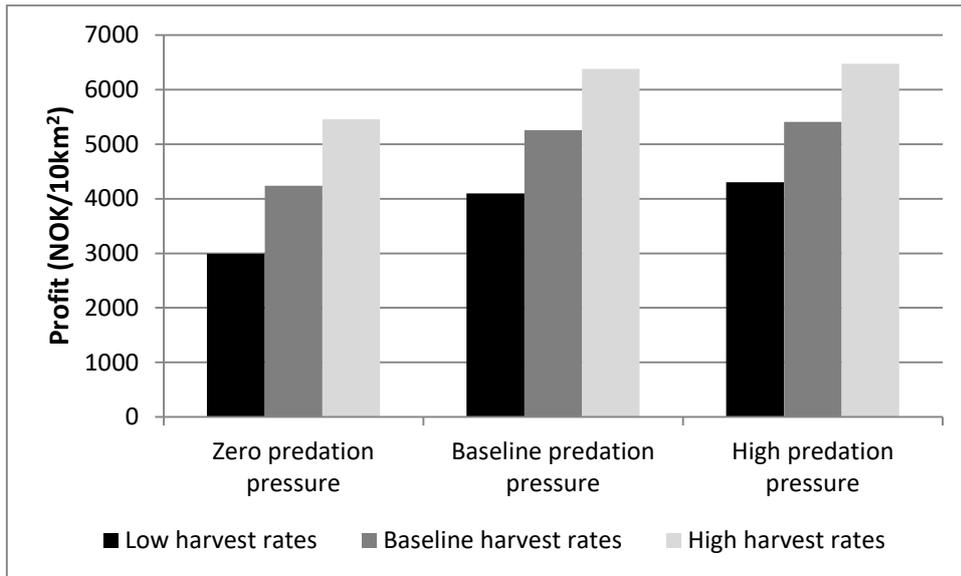
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566 **Figure 5.** Steady state profit Finnmark. Baseline parameter values, but shifting slaughter
 567 rates. Low harvest rates=0.9*Baseline harvest rates, High harvest rates=1.1* Baseline
 568 harvest rates. Baseline harvest rates, see Table 1.

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585 **Table 1:** Steady state biological results under present management situation in Finnmark;
 586 $h_c = 0.20$, $h_f = 0.05$, $h_m = 0.21$. Baseline parameter values.

Predation pressure ¹⁾	Animal density (# animals/10km ²)			Fertility rate	Survival rates	Mortality (# animals/10km ²)		
	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	

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

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606 **Table 2:** Steady state economic results in Finnmark and South (in brackets). Similar economic
 607 and biological parameter values (baseline parameter values). Slaughter rates Finnmark;
 608 $h_c = 0.20$, $h_f = 0.05$, $h_m = 0.21$. 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

609 Table note: 1) See note 1, Table 1

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624 **Appendix: Specific functional forms and parameter values**

625 *Specific functional forms*

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

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

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

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

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

635 The weight-density relationships, where weights decrease in the total number of animals,
636 $X_t = X_{c,t} + X_{f,t} + X_{m,t}$, are specified as sigmoidal functions with an increasing degree of
637 density dependence at high densities (Nielsen et al. 2005, Mysterud et al., 2001; see also
638 Figure 3). The same functional form is assumed for all categories of animals:

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

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

646 Combining Eqs. (A1) and (A3) yields $f_t = \bar{f} \cdot \left(\frac{1}{1 + (X_t / K)^\beta}\right)^a$, while Eq. (A2) together with Eq.

647 (A3) yield $s_{i,t} = \bar{s}_i \cdot \left(\frac{1}{1 + (X_t / K)^\beta}\right)^{b_i}$. Therefore, both fertility and survival rates are sigmoidal

648 functions of the total animal stock (see also Figure 3). With $b_f = b_m$ the ratio of the natural
649 survival rates between the two adult categories of animals is then proportional to the
650 maximum survival rates \bar{s}_i . Because $\bar{s}_f = \bar{s}_m$ (see Table A1), the natural survival rates of the
651 adult categories are identical.

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653 Finally, the operating cost function is specified linearly:

654 (A4) $C_t = cX_t,$

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

657 (A5) $C_t = c_1X_t + (c_2 / 2)X_t^2,$

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

659

660 *Parameter values, baseline predation rates and harvesting rates*

661 Table A1 presents the baseline parameter values. The considered area in Finnmark
662 comprises about 24,400 km². With about 170,000 grazing reindeers (summer 2012, NRHA
663 2014), the animal density is accordingly about 70 animals per 10 km². The main sources of
664 information on predation loss are annual reports from herders to the government (NRHA
665 2014) and official statistics (www.rovbase.no). Our baseline predation rates are determined
666 based on data on losses to predators, as reported by herders yearly when applying to the
667 State for compensation losses due to predation. Because of certain characteristics of the
668 compensation system, there is a tendency to overstate the predation losses and accordingly
669 to understate losses due to natural mortality (see Tveraa et al. 2014). The baseline predation
670 rates used represent the average of claimed and compensated losses in 2013. The baseline
671 harvesting rates are identical with the current rates in our study area, Finnmark county.

672 Table A1 about here

673 We use the calving rate in the best performing reindeer herding area as a proxy for the
674 maximum calving rate \bar{f} . The recruitment parameter a is calibrated to give a baseline
675 calving rate similar or equal to the observed calving rate of 0.84 calves per female in Finnmark
676 (NRHA 2014). The maximum natural survival rate is assumed to be one. When determining
677 the baseline survival parameters b_c , b_f , and b_m (Eq. A2), we assume that $b_f = b_m$ and that
678 the survival rate of calves is more sensitive to changes in stock density; that is, $b_c > b_f = b_m$.
679 Finally, b_c , b_f , and b_m are calibrated such that the steady state ecological values fit
680 reasonably well with actual values. The slaughter weights in the best performing reindeer
681 herding area in the southern part of Norway, where the vegetation cover is intact, are used
682 as proxies for maximum weights. When using these values together with the baseline stock
683 density in the weight functions, and when assuming that $\beta = 3$ and $K = 100$ (# of animals/10
684 km²), the weights in the steady state (Table 2) correspond reasonably well with the actual
685 weights observed in the northernmost part of Norway (NRHA 2014). The value of carrying
686 capacity K also scales the model. The slaughtering price p is assumed to be 53.7 (NOK/kg),

687 and coincides with the actual market price in 2012 (NRHA 2013b). Finally, the operating
688 (herding) cost per animal c was calculated based on the current stock composition and
689 slaughtering rates, and the estimated net herding income in Finnmark per 10km² in 2012
690 (NRHA 2013b) was also taken into account. The sensitivity analysis also applies the convex
691 cost function (A5). Somewhat arbitrarily, we use $c_1 = 50$ (NOK/animal) and $c_2 = 2.77$
692 (NOK/animal²) in a way that the total cost with this cost function equalizes the cost utilizing
693 the linear cost function in the baseline scenario of Finnmark with an animal density of 70.4
694 (#animals/10km²) (see Table 2).

695 **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	0.4		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, 0.4, 0.4		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,		www.rovbase.no
Harvesting rates	h_c, h_f, h_m	0.20, 0.05,		NRHA (2014)
Meat price	p	53.7	NOK/kg	NRHA (2013b)
Unit operating cost	c	97.3	NOK/animal	Calibrated

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