The silence of the lambs.
Payment for carnivore conservation and sheep farming

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Abstract

During the last few decades the number of big carnivores (wolf, bear, lynx and wolverines) has increased significantly in Scandinavia. As a result, the conflict with livestock farmers has deepened due to more predation and animal loss. This conflict is modeled using sheep farming as an example, and where the farmers are given compensation for the predation loss. The compensation scheme is composed of a fixed per animal loss value (*ex post*), but also a compensation just for the presence of the carnivores (*ex ante*). In the first part of the paper, the stocking decision of a group of farmers acting as a single agent, without and with compensation, is analyzed. In a next step, the Directorate for Natural Resource Management (*DNRM*), managing the carnivores and compensation scheme, is introduced. The strategic interaction between the sheep farmers and *DNRM* is modelled as a Stackelberg game with *DNRM* as the leader. We find that it does no pay for *DNRM* to use *ex post*, but only *ex ante* compensation. The solution of this game is compared to the social planner solution where it is shown that the carnivore becomes too small and the sheep stock too large in the Stackelberg solution. However, we find the efficiency loss to be small.

Keywords: Carnivore conservation, sheep farming, compensation, Stackelberg game

JEL code: Q20, Q18

1. Introduction

In many instances, wild animals provide benefits for humans. However, often we also find that wild animals incur economic costs. Large herbivores, for example, may cause grazing or browsing damage, but on the other hand provide value through hunting and trapping (e.g., Zivin et al. 2000). Nuisance may also be channeled through ecological interaction when, say, big carnivores prey upon livestock or large herbivores, or it can be grazing competition between wildlife and livestock. The outcomes are often property and grazing right conflicts (see, e.g., Skonhoft 2006, Zabel and Holm-Müller 2008, Zabel et al. 2011). A conflict of this type where wild carnivores are preying upon livestock, exemplified by sheep farming in Scandinavia, is studied in this article. In Norway sheep graze on public and private land during the summer season, but because of the presence of grey wolf, brown bear, lynx and wolverine farmers often experience predation and loss of animals. In areas where big carnivores are prevalent it is hence conflicts between sheep farming and the political goal of keeping sustainable big carnivore populations. In total there are about 2.3 million summer grazing livestock in Norway (cattle, goats, horses and sheep), of which there are about 2.1 million sheep. Yearly about 40,000-50,000 of these animals, ewes, but mostly lambs, are killed during the summer grazing due to predation (Ekspertutvalget 2011). In economic terms this predation loss is modest, but certain farmers and certain areas are severely exposed. These losses are subject to be fully compensated by the State by its slaughter value (Ekspertutvalget 2011).

This paper studies this sheep - carnivore conflict and analyzes how the stocking decision by the farmers is influenced by the presence of carnivores and compensation for animal loss. Two types of compensations are considered. Firstly, we include the existing scheme where the farmers are paid according to the verified sheep loss number caused by the big carnivores accounted at the end of the summer grazing season. This is the *ex post* compensation scheme. Secondly, it is also assumed that the farmers can be compensated merely by the presence of carnivores. This scheme is used in the Saami reindeer herding in Sweden (see, e.g., Direktoratet 2011, Zabel et al. 2014), and is based on the estimated number of big carnivores in the actual area before the grazing season starts. For this reason it is called an *ex ante* compensation scheme. Such a scheme is also proposed implemented in the Saami reindeer herding in Norway, and has also been considered to be implemented in sheep farming (Ekspertutvalget 2011).

In a recent paper by Zabel et al. (2011) studying tiger conservation in India, the working of these two types of conservation schemes are analyzed. They find that the livestock holders have no incentives to protect the livestock from carnivores under the *ex post* scheme, while the opposite happens when the *ex ante* scheme is present. See also Zabel and Holm-Müller (2008). Our model has some similarities with Zabel et al. (2011), but one important difference is that while they keep the livestock and harvest numbers fixed, these will be influenced by the degree of predation and compensation in our reasoning;

that is, predation and compensation influence the stocking decision of the farmers. At least in a Scandinavian setting, including this mechanism strengthen the realism of the analysis. Another difference is that carnivore harvest, or poaching, by the farmers is neglected in our model. This fits well the reality in Norway where illegal hunting is small and negligible (Ekspertutvalget 2011). As in Zabel et al. we study the stocking problem and predation in ecological equilibrium and any dynamic considerations are hence outside the scope of the present analysis. Changing land use and habitat loss are not issues in Zabel et al. (2011) and in our study, but are taken up in Bulte and Rondeau (2005). See also Schulz and Skonhoft (1996).

Included in our model is a group of sheep farmers acting as a single agent and a government agency, the Directorate for Natural Resource Management (*DNRM*). *DNRM* is the conservation authority and controls the carnivore population and it also manages the compensation scheme. The sheep farmers are assumed to maximize profit while the *DNRM* aims to maximize the conservation benefit minus the compensation payment to the farmers. These agents interact strategically through a Stackelberg game mechanism with *DNRM* as the leader and the farmers as the follower. A Stackelberg game seems most realistic when a government agency is included (see, e.g., the classical Schelling 1960). All the time complete and symmetric information are assumed. In section 2 we start by giving a brief background picture of the Nordic carnivore – sheep conflict. The stocking problem of the sheep farmers is studied under various assumptions about predation and compensation in section 3. In section 4 we consider the problem of *DNRM*, composed of setting the compensation scheme and managing the carnivore stock, and the Stackelberg game is solved. In section 5 the social planner solution is analyzed and compared with the game solution. Section 6 presents a numerical illustration, while section 7 concludes the paper.

2. Ecological and economic background

The big carnivore species in Scandinavia include the grey wolf (*canis lupus*), the brown bear (*ursus arctos*), the lynx (*lynx lynx*) and the wolverine (*gulo gulo*). In the middle of the 1960's the grey wolf was regarded as functionally extinct, and in the last part of the 1970's the first confirmed reproduction in 15 years was recorded. Since this first reproduction in northern Sweden, all new reproductions have been located to the southern-central parts of the Scandinavian Peninsula (Wabakken et al. 2001). The wolf population in Scandinavia now counts some 80 - 90 individuals which live in small family groups in the western-central part of Sweden and along the border area between Norway and Sweden. Figure 1 shows the last year's population evolvement.

Figure 1 about here

The bear, lynx and wolverine populations were also small and threatened in the 1960's. However, due to changing attitudes among people, an institutional change was taking place, and the wolf, but also the other big carnivores, were preserved by the state in Norway in 1972. The existence value of these species was also institutionalized through various international conventions and legal provisions, and Norway became a signatory member to the Bern-convention in 1986. Following the Bern-convention Norway, among others, is committed to keep viable populations of the wolf and the other big carnivores (Ekspertutvalget 2011). There is a short hunting season on lynx where the hunting is immediately stopped when the hunting quota is reached. The wolves, wolverines and bear populations are controlled to get rid of certain 'problem' animals in areas with especially high reported sheep (and also reindeer) losses. Additionally, there is some hunting to keep the stock sizes in accord with the political determined conservation measures (Ekspertutvalget 2011).There are reported some illegal hunting, but especially in the more southern parts of Scandinavia, where sheep farming is prevalent, the illegal hunting is considered to be small.

Although the big carnivore populations are small in number, these populations are associated with several conflicts. The most important is related to predation on livestock, and particularly on sheep. However, carnivore conservation is also seen as a conflict between center and periphery, or as a conflict between the 'local rural people' and the 'well-educated conservation people' living in the cities (Skogen et al. 2012). The conflicts have therefore clear similarities with the conflicting view of wildlife conservation that is present in many developing countries (see, e.g., Johannesen and Skonhoft 2005, Zabel et al. 2011).

While sheep farming in total is a small economic activity, it is an important source of income in many rural communities, and altogether there are approximately 13,000 sheep farms in Norway counting about 2.1 million animals during the outdoors grazing season (Ekspertutvalget 2011). This number has been quite stable since the middle of the 1980's. Norwegian farms are located close to mountain areas and other sparsely populated areas, or along the coast. The main product is meat, which accounts for about 80% of the average farmer's income. The remainder comes from wool, because sheep milk production is virtually nonexistent today. Housing and indoor feeding is required throughout winter because of snow and harsh weather conditions. In Norway, winter feeding typically consists of hay grown on pastures close to farms. The spring lambing scheme is controlled by the farmers because of the In Vitro Fertilization protocol used to time the lambing to fit current climatic conditions. In late spring and early summer, the animals usually graze on fenced land close to the farm at low elevations, typically in the areas where winter food for the sheep is harvested during summer. When weather conditions permit sheep are released into rough grazing areas in the valleys and mountains. Natural mortality, also including accidents and various types of diseases, takes basically place during the summer grazing season. The outdoors grazing season ends between late August and the middle of September. The length of the outdoor grazing season is relatively fixed. After the grazing season, the animals are mustered and the wool is shorn. Slaughtering takes place immediately or after a period of grazing on the farmland (more details are provided in Austrheim et al. 2008).

In the last few years about 125,000 animals has been reported lost during the summer grazing season. It is estimated that about one third of this total loss, or about 40,000 – 50,000 animals, is due to predation caused by the four big carnivores. The rest is loss related to accidents and diseases (the so called 'normal loss', Ekspertutvalget 2011). While predation takes place during the whole rough grazing period, there are some certain different patterns among the four carnivores. Most notably is the killing by the wolverine, basically taking place late summer or early fall and just before slaughtering. The geographical predation pattern is distinct and where lynx is most important in the south-eastern part of Norway while wolverine is most important in the northern part. The predation loss in the south-western part of Norway is small and negligible, simply due to the more or less non-existence of carnivores, while it is important in certain regions in the southern-central and northern-central parts of the country.

Figure 2 about here

Figure 2 demonstrates the losses, in percentage of the total summer grazing animals, in the four counties with the most extensive predation pressure. Additionally, the national county average is depicted. While Hedmark and Oppland counties are located in the southern-central part of Norway Sør-Trøndelag and Nord-Trøndelag counties are found in the northern-central part. All these counties, expect of Oppland, are bordering Sweden. This figure clearly indicates the emerging predation problem during the last two decades. Until about 1990 with no predation, the loss (the 'normal loss') were more or less constant and in the range 3 – 4.5 % per year. From the beginning of the 1990's, the loss increased dramatically in these counties, especially in Hedmark where it has been above 10 % during the last few years. This indicates that the yearly predation loss in this county may be about 5 – 6 % of the summer grazing population while it may be about 3 % in Sør-Trøndelag county.

3. Livestock holding of the farmers

3.1. Livestock growth and equilibrium harvesting

We start to look at the stocking problem of our group of sheep farmers, with and without predation. The sheep growth model is formulated in discrete time, and where additions to the stock occur once in the year, in the spring, and where all natural mortality is assumed to take place during the outdoors grazing season. As mentioned, slaughtering also takes place once in the year, in September – October, after the end of the summer grazing season. We are using a biomass model and do not distinguish between different age classes of the sheep (but see Skonhoft 2008). The natural growth rate is assumed constant; a reasonable assumption with a domestic animal stock facing controlled breeding and maintenance. The growth of the sheep flock of the farmers in absence of predation is thus governed by:

(1) $X_{t+1} = X_t + rX_t - H_t = sX_t - H_t = s(1-h_t)X_t$,

where X_t is the number of animals in the beginning of year t and $r = (s-1) > 0$ is the constant natural growth rate. The natural growth rate comprises fertility and natural mortality during the outdoors grazing season ('normal' loss; section 2), but includes no carnivore predation. $H_t \geq 0$ is the slaughter (harvest) in number of animals, and $0 \leq h_t < 1$ is the slaughter rate. Because harvest takes place after natural growth, the harvest fraction is defined through $H_t = sX_t h_t$. In biological equilibrium with a stable population, $X_{t+1} = X_t$ and omitting the time subscript, the equilibrium harvest (slaughter) rate is:

(2) $h = (1-1/s)$.

With $0 \leq m_t < 1$ as the predation rate, the animal growth Eq. (1) changes to:

(3) $X_{t+1} = s(1-h_t)(1-m_t)X_t$

when predation is assumed to be purely additive to natural mortality, also a realistic assumption for a domestic animal stock. Predation occurs generally during the whole grazing season, but possible at a higher degree in late summer/early fall than in the beginning of the grazing season (section 2 above). In what follows, we assume that all predation takes place after natural growth, but before slaughtering. The predation loss in number of animals is then defined as $M_t = sX_t m_t$, while the number of animals slaughtered in presence of predation becomes $H_t = sX_t(1-m_t)h_t$. With a constant sheep population, and also a constant predation rate, the equilibrium harvest rate now reads:

(4) $h = 1-1/s(1-m)$.

Therefore, the higher predation rate, the fewer animals is left over for slaughtering to keep a fixed population size.

3.2 Stocking without predation

Our group of sheep farmers is assumed to act as a single agent aiming to maximize profit, and we start to look at the stocking problem without predation. The revenue is made up of just income from meat production as possible income from wool production is neglected. With $p > 0$ as the given slaughtering price (net of slaughtering costs) the current income of the farmers reads pH . The farm capacity is assumed fixed (but see Gauteplass and Skonhoft 2015), and the costs are thus only operating costs. These costs, which include labor costs (typically as an opportunity cost) in addition to fodder and veterinary costs, are related to the size of the animal stock, $C = C(X)$, and with $C' > 0$, $C'' \geq 0$ and $C(0) = 0$. The current profit of the farmers thus reads:

(5) $\pi = pH - C(X) = psXh - C(X)$.

In absence of predation, the problem of the farmers is $\max_{h,X} \pi = psXh - C(X)$, or

$\max_{X} \pi = psX(1-1/s) - C(X) = pX(s-1) - C(X)$ when inserting the harvest rate from Eq. (2). Maximizing yields $p(s-1) = C'(X)$, or $(s-1) = C'(X)/p$, indicating that the natural growth rate should equalize the marginal cost – income ratio in optimum. With a strictly convex cost function, the sufficiency condition is fulfilled, and in the subsequent analysis the cost function is specified as $C(X) = (c/2)X^2$, with $c > 0$. We then find the optimal stock size as:

(6) $X^I = (p/c)(s-1)$

(superscript ' I ' indicates the stock size without predation and without compensation). Furthermore, we find the number of animals slaughtered as $H^I = (p/c)(s-1)^2$ while the profit reads $\pi^I = (p^2/2c)(s-1)^2$. Therefore, in contrast to the standard biomass model (see, e.g., Clark 1990), the optimal stock size (or standing biomass) increases with a higher slaughter price, and reduces with higher costs. It is also seen that the slaughtering increases unambiguously with a higher price – cost ratio.

3.3 Stocking with predation, but without compensation

We then proceed to solve the stocking problem of the farmers with predation. A crucial question is whether the predation rate is related to the sheep density, or not. We assume that it is independent of the number of grazing animals which is consistent with the Lotka - Volterra predator – prey model (see, e.g., Clark 1990). With W_t as the number of carnivores, the sheep loss in number of animals due to predation then writes $M_t = \psi s X_t W_t$. $\psi > 0$ is a parameter indicating the strength of the predation pressure, depending on, among others, type and composition of predators in the considered area, alterative food sources for the carnivores, measures taken by the farmers to protect the livestock and how they organize the rough grazing period when the sheep stock is exposed for predation, and so forth. With the predation rate as $m_t = M_t / sX_t = \psi W_t$, independent of the number of grazing animals and proportional to the carnivores density we have:

(7) $$m = \psi W$$

for a fixed number of carnivores.

With predation included the current profit of the farmer is defined as:

(8) $$\pi = pH - C(X) = psX(1-\psi W)h - C(X).$$

The profit maximizing problem of the farmers with predation, but without any compensation, is now stated as $\max_{X,h} \pi = psX(1-\psi W))h - C(X)$, or $\max_{X} \pi = pX[s(1-\psi W)-1]-(c/2)X^2$ when inserting for the equilibrium condition (4) and the specified cost function. The optimal stock size becomes:

(9) $$X^{II} = (p/c)[s(1-\psi W)-1],$$

indicating that the number of carnivores must not exceed $W < (s-1)/\psi s$, or the predation rate must not exceed $m < (1-1/s)$, to secure a positive sheep stock (subscript '*II*' indicates solution with predation, but without compensation). The number of animals slaughtered and profit read $H^{II} = (p/c)[s(1-\psi W)-1]^2$ and $\pi^{II} = (p^2/2c)[s(1-\psi W)-1]^2$, respectively. The loss in number of animals in the presence of carnivores and predation is accordingly $(X^I - X^{II}) = (p/c)(s-1)-(p/c)[s(1-\psi W)-1] = (p/c)s\psi W \geq 0$, while $(\pi^I - \pi^{II}) = (p^2/2c)\{(s-1)^2 - [s(1-\psi W-1)]^2\} \geq 0$ indicates the profit loss. Therefore, with predation, the optimal sheep stock reduces proportionally with the predation rate and the number of carnivores. It is also seen that predation has a smaller profitability effect on the margin with a high than a low predation rate. Not surprisingly, we find that the economic loss increases with the market value of the animals as well as the animal productivity through the parameter s. The economic loss is made up of a direct effect related to the marginal revenue reduction as $pX[s(1-\psi W)-1]$ shifts down due to predation. This direct effect is to some extent mitigated by an indirect effect because our profit maximizing farmers find it beneficial to reduce the stocking number as the marginal revenue reduces.

3.4 Predation with compensation

In Norway the farmers are subject to be fully compensated from the economic loss caused by the carnivore predation (section 1 above) by granting the farmers the market value of the animals, i.e., the slaughter value. In what follows, however, we consider a more general compensation scheme. First, we have the fixed per animal *ex post* compensation loss value, $p_X \leq p$, assumed not to exceed the market value of the animals. Second, the farmers may also be given a compensation merely for the presence of carnivores and where $p_W \geq 0$ is the per unit carnivore *ex ante* compensation value (section 1 above). These values are determined such that the farmer should be fully compensated by the Directorate for Natural Resource Management (*DNRM*).

The profit of the farmers is now described by:

(10) $\pi = pH - C(X) + (p_X M + p_W W) = psX(1-\psi W)h - C(X) + (p_X s\psi XW + p_W W)$.

When again inserting for the harvesting rate, the new profit maximizing problem reads $\max_X \pi = pX[s(1-\psi W)-1] - C(X) + (p_X s\psi XW + p_W W)$. Because we abstract from the possibility that the farmers may illegally kill, or hunt, carnivores, which indeed is a realistic assumption in our Scandinavian institutional setting (section 2 above), the *ex ante* compensation works just as a lump sum transfer and hence does not influence the stocking decision of the farmers. We therefore find the optimal stock size, related to p_X, but not to p_W, as:

(11) $X^* = (p/c)[s(1-\psi W) - 1 + (p_X / p)s\psi W]$

(superscript '*' indicates the solution with predation and compensation). The number of animals slaughtered may after some rearrangements be written as $H^* = X^*[s(1-\psi W)-1] = (p/c)[s(1-\psi W)-1][s(1-\psi W)-1+(p_X/p)s\psi W]$. The stock size, but also the number of animals slaughtered, increase with the *ex post* compensation value p_X. Not surprisingly, we also find that the optimal stock is larger than without compensation as the marginal revenue with compensation shifts up, $(X^* - X^{II}) = (p_X / c)s\psi W \geq 0$. On the other hand, the stock reduces compared to the situation without predation, $(X^* - X^I) = (p/c)[s(1-\psi W)-1+(p_X/p)s\psi W] - (p/c)(s-1) = -(p/c)(1-p_X/p)s\psi W \leq 0$. With full *ex post* compensation and $p_X = p$, following the logic of the optimization, the farmers will find it beneficial to keep the same number of animals as without predation, and the profit will be similar, $\pi^* = pX^*[s(1-\psi W)-1] - C(X^*) + ps\psi X^* W = pX^*(s-1) - C(X^*) = \pi^I$. Therefore, with full compensation the number of animals slaughtered and sold, $H^* = (p/c)[s(1-\psi W)-1](s-1)$, plus the animals consumed by the carnivores, $M^* = (p/c)s(s-1)\psi W$, will just equalize the number of animals slaughtered without predation; that is, $H^* + M^* = H^I = (p/c)(s-1)^2$. Differentiating

$\pi^* = pX^*[s(1-\psi W)-1] - C(X^*) + (p_X s\psi X^* W + p_W W)$ yields

$\partial\pi^* / \partial W = -(p - p_X)s\psi X^* + p_W$ when using the envelope theorem. Therefore, with *ex ante* compensation, it may be economically beneficial for the farmers with a higher density of carnivores. With full *ex post* compensation, $p_X = p$, and $p_W > 0$, more carnivores will be beneficial for sure.

4. The Directorate for Natural Resource Management (*DNRM*)

So far we have analyzed how the presence of carnivores and predation affect the stocking decision of the profit maximizing sheep farmers, with and without compensation. As demonstrated, the *ex ante* compensation mechanism works just as a lump-sum transfer while the *ex post* compensation motivates the farmers to increase the sheep number. For that reason, *ceteris paribus*, the predation loss will also increase with a higher per animal *ex post* compensation value. The compensation scheme and the carnivore stock are managed and controlled by The Directorate for Natural Resource Management (*DNRM*) (section 1 above). We now analyze how this agency may compose the compensation scheme; that is, how the *ex post* value p_X and *ex ante* value p_W actually may be determined. Additionally, *DNRM* controls the size of carnivore population W.

While predation is related to the number of carnivores together with the size of the sheep population, feedback effects may also be present as the size of the sheep population can influence carnivore growth. However, in areas colonizing carnivore populations, or carnivore populations strongly controlled, as in Scandinavia, this relationship will appear less interactive indicating that the carnivores are not able to respond numerically to variations in the sheep population (Nilsen at al. 2005). Any numerical response is hence neglected, and the carnivore natural growth is independent of the size of the sheep population. Therefore, the carnivore natural growth function is given by $G(W_t)$, assumed to be density dependent of the logistic type (see below). With y_t as the number of carnivores controlled/hunted at time t, the carnivore growth equation reads:

(12) $$W_{t+1} = W_t + G(W_t) - y_t .$$

The equilibrium carnivore population is then simply given by:

(13) $$y = G(W) .$$

The current equilibrium net benefit function of *DNRM* is composed of the conservation value of the carnivores and the compensation cost paid to the farmers and is defined as:

(14) $$U = B(W) + qG(W) - (p_X s\psi XW + p_W W) ,$$

such that $B(W)$ is the conservation value, with $B' > 0$, $B'' \leq 0$ and $B(0) = 0$, while the compensation payment is represented by the last bracket term. In addition, we have also included a hunting value with $q \geq 0$ as the per unit net hunting value assumed to be fixed and independent of the number of carnivores hunted. A non-negative control value is included as the hunt is supposed to be managed through a license hunting scheme and where the hunters are paying a fixed price per license. There are certainly some costs of organizing the hunt, and q is thus the net price.

We solve the strategic interaction between *DNRM* and the farmers as a Stackelberg game with *DNRM* as the leader and the farmers as the follower (section 1 above). Thus, in the first stage, *DNRM* maximizes the net benefit by controlling the carnivore population and fixing the *ex post* and *ex ante* compensation values. In the second stage, the farmers maximize profit subject to the imposed compensation policy and predation pressure. The game is solved by backward induction, and where Eq. (11) with $\partial X^* / \partial p_X = X_p^* > 0$, and $\partial X^* / \partial W = X_W^* \leq 0$, is the reaction function of the farmers. Therefore, in the first stage, *DNRM* maximizes the net benefit Eq. (14) subject to X^* by controlling the carnivore population and fixing *the ex post* and *ex ante* compensation values. The first order necessary conditions when having a positive carnivore stock are:

(15) $\partial U / \partial W = B'(W) + qG'(W) - p_X s\psi[X^* + X_W^* W] - p_W = 0$; $W > 0$,

and

(16) $\partial U / \partial p_X = -s\psi W(X^* + p_X X_p^*) \leq 0$; $p_X \geq 0$.

Because higher *ex post* compensation means that it is profitably for the farmers to increase the sheep stock, i.e., $X_p^* > 0$, condition (16) yields $\partial U / \partial p_X < 0$ with $p_X^* = 0$. Therefore, it does not pay for *DNRM* to introduce *ex post* compensation because more animals increase the predation and compensation payment. With no *ex post* payment Eq. (15) simplifies to $B'(W) + qG'(W) = p_W$. This condition indicates that the marginal stock benefit, composed of the marginal conservation value plus the marginal net benefit of controlling the wildlife, should equalize the marginal cost, fixed by the *ex ante* compensation value. The sufficiency condition of the *DNRM* optimization problem is $B''(W) + qG''(W) < 0$ which with $q > 0$ is satisfied when the natural growth function is strictly concave and the conservation value function is concave.

With zero *ex post* compensation and the farm profit as $\pi^* = pX^*[s(1-\psi W)-1] - (c/2)(X^*)^2 + p_W W$, or $\pi^* = (p^2/2c)[s(1-\psi W)-1]^2 + p_W W$ when inserting for X^* (section 3.4 above), the whole predation compensation is channeled through the *ex* *ante* mechanism. When the farmers are subject to be fully compensated it should satisfy $(\pi^I - \pi^*) = (p^2/2c)(s-1)^2 - \{(p^2/2c)[s(1-\psi W)-1]^2 + p_W W\} = 0$. After some small rearrangements is may also be written as:

(17) $p_W = p^2\psi s(s-1)/c - ((p\psi s)^2/2c)W$.

Therefore, when the farmers are only compensated trough the *ex ante* scheme, a higher number of carnivores is accompanied by a smaller per carnivore compensation value. The total compensation value is now $p_W W = [p^2\psi s(s-1)/c]W - ((p\psi s)^2/2c)W^2$. This is a strictly concave function reaching a peak value when $W = (s-1)/\psi s$ and hence $X^* = 0$ and the whole sheep population is consumed by the carnivores (section 3.3).

When assuming logistic natural growth for the carnivore population, $G(W) = fW(1-W/K)$, with $f > 0$ as the intrinsic growth rate and $K > 0$ as the carrying capacity and, for simplicity, a linear conservation value function $B(W) = bW$ with $b > 0$, Eq.(15) with $p_X^* = 0$ reads:

(18) $p_W = (b+qf) - (2fq/K)W$.

With our specific functional forms, Eq. (18) together with Eq. (17) therefore jointly determines the optimal carnivore stock W^* and the compensation value p_W^* . Solving for the carnivore stock we find:

(19) $$W^* = \frac{(b+qf) - p^2\psi s(s-1)/c}{(2fq/K) - (p\psi s)^2/2c} ,$$

which represents a meaningful solution if $(b+qf) - p^2\psi s(s-1)/c > 0$ together with $(2fq/K) - (p\psi s)^2/2c > 0$ hold. This indicates that the predation cannot be too aggressive. Additionally, we must have $q > 0$. These conditions hold for a wide range of chosen parameter values (numerical section 6 below). When inserting Eq. (19) into Eq. (18) (or Eq. 17) we can next find p_W^* , while inserting for W^* into Eq. (11) with $p_X^* = 0$ yields X^*.

We find by differentiation of Eq. (19) that more aggressive predation means that *DNRM* will benefit from keeping a smaller carnivore population, $\partial W^*/\partial\psi < 0$, and therefore also a higher per animal compensation value. For our baseline parameter values (section 6), we also find $\partial X^*/\partial\psi > 0$. As the sheep population with $p_X^* = 0$ is given by $X^* = (p/c)[s(1-\psi W^*)-1]$ and differentiation yields $\partial X^*/\partial\psi = -(ps/c)[W^* + \psi(\partial W^*/\partial\psi)]$, this indicates $[W^* + \psi(\partial W^*/\partial\psi)] < 0$. Therefore, the direct negative effect of more aggressive predation $-(ps/c)W^{*} < 0$ is dominated by the indirect positive effect $-(ps/c)\psi(\partial W^{*}/\partial\psi) > 0$ feeding back from *DNRM*. Not surprisingly, a higher intrinsic value of the carnivores means that *DNRM* will find it rewarding to keep a higher carnivore population, $\partial W^{*}/\partial b > 0$, and therefore a lower per animal *ex ante* compensation value, $\partial p_W^{*}/\partial b < 0$. The total compensation value to the farmers increases, $\partial(p_W^{*}W^{*})/\partial b > 0$. In this case it is seen directly from $X^{*} = (p/c)[s(1-\psi W^{*})-1]$ that it is profitable for the farmers to reduce the size of the sheep population, $\partial X^{*}/\partial b < 0$. More valuable farms products through a higher sheep slaughter value will motivate the farmers to increase the sheep stock. As the farm loss due to predation becomes higher, this will feed back to *DNRM* who finds it beneficial to reduce the number of carnivores to lower the predation pressure and the compensation payment to the farmers. Thus, we have $\partial X^{*}/\partial p > 0$ together with $\partial W^{*}/\partial p < 0$. More sensitivity results are demonstrated in the numerical section.

5. Social planner solution

To assess the efficiency loss of the above Stackelberg game, this solution is now compared to the social planner solution. Included in the social planner objective function is the (unweighted) sum of the sheep farmer profit and the *DNRM* benefit of the carnivores, comprising the conservation value and the net license hunting value:

(20) $$S = [pH - C(X)] + [B(W) + qy] = [pX[s(1-\psi W)-1] - C(X)] + [B(W) + qG(W)].$$

The first order necessary conditions of the social planner maximization problem are:

(21) $$\partial S/\partial X = p[s(1-\psi W)-1] - C'(X) = 0;\ X > 0\ ,$$

and

(22) $$\partial S/\partial W = -pXs\psi + B'(W) + qG'(W) = 0;\ W > 0\ .$$

These two equations therefore jointly determine the social optimal stock sizes X^{P} and W^{P} (superscript 'P' indicates social planner solution).The sufficiency conditions are $\partial^2 S/\partial X^2 = -C''(X) < 0$, $\partial^2 S/\partial W^2 = B''(W) + qG''(W) < 0$, and $(\partial^2 S/\partial W^2)(\partial^2 S/\partial X^2) - (\partial^2 S/\partial X\partial W)^2 = -C''(X)[B''(W) + qG''(W)] - (ps\psi)^2 > 0$. Inserted for our specific functional forms, the last condition reads $2cfq/K - (ps\psi)^2 > 0$. Therefore, just as in the Stackelberg solution, there must be a restriction on the predation loss to obtain a meaningful interior solution.

As there is no externalitity running from sheep farming to carnivore conservation as no numerical response is included in our ecological model (section 4 above), Eq. (21) will be similar to the optimization problem of the farmers with predation, but with no *ex post* compensation, as given by Eq. (9). However, the carnivore optimality condition Eq. (22) is different from Eq. (15) with $p_X^* = 0$ in the Stackelberg solution. As the social cost of predation is given by the term $pX^P s\psi$, we find that $pX^P s\psi < p_W^*$ yields $W^P > W^*$, and *vice versa*. With our specific functional forms, combination of Eqs. (21) and (22) gives:

(23) $$W^P = \frac{(b + qf) - p^2\psi s(s-1)/c}{(2fq/K) - (p\psi s)^2/c}.$$

Eq. (23) is slightly different from Eq. (19), and indicates that $W^P > W^*$ holds for all feasible $\psi > 0$. Therefore, the social cost of predation is less than the *ex ante* compensation value, and the carnivore population will be too small while the sheep population will be too large in the Stackelberg solution from the social planner's point of view. As we have an externality running from carnivore conservation to sheep farming, this result is indeed surprising. This result is therefore explained by the compensation mechanism, and the fact that the farmers should be fully compensated. However, the difference between the Stackelberg and the social planner solutions are quite modest as the magnitude of the term $(p\psi s)^2/c$ in Eq. (23) (and the term $(p\psi s)^2/2c$ in Eq. 19) is small compared to the magnitude of the term $(2fq/K)$ in Eq. (23) (and Eq. 19) within the whole range of realistic parameter values. See numerical section 6 below. The efficiency loss of the above Stackelberg game seems therefore to be quite modest.

6. Numerical illustration

6.1 Data

To shed some further light of the above analysis, we proceed with a numerical illustration. We do not attempt to accurately describe the economic situation of the considered group of Scandinavian sheep farmers, but aim to demonstrate our solutions with reasonable realistic parameter values. All functional forms are specified above, and the numerical illustration is performed by using baseline parameter values found in Table 1. The sheep data is from Gauteplass and Skonhoft (2015), with the value of the cost parameter c scaled such that the number of sheep without predation (and compensation), $X^I = (p/c)(s-1) = (2,000/1.3)0.7 = 1,077$, may represent an area with a small group of farmers (6 – 8) with medium sized farms. Therefore, with the baseline value of the predation coefficient $\psi = 0.003$, we find that, say, 10 carnivores (e.g., lynx) represents a predation rate of $M/sX = \psi W = 0.003 \cdot 10 = 0.03$, or 3 %, which may be quite realistic (cf. Figure 2). The carnivore intrinsic baseline value $b = 10$ (1000 NOK/animal) and the hunting value $q = 100$ (1000 NOK/animal) are determined such that the carnivore population just equalizes its carrying capacity of $K = 25$ with a maximum specific growth rate of $f = 0.1$ when *DNRM* optimizes the carnivore population without predation and hence pay no compensation (Eq. 15). $f = 0.1$ is within the range of realistic values for our large carnivore species.

Table 1 about here

6.2 Results

Under the hypothetical scenario with no predation and $\psi = 0$, we first find that750 out of the optimal stock size of 1,077 animals will be slaughtered. The yearly farm profit becomes 754 (1,000 NOK). In the Stackelberg solution with the baseline parameter values, the optimal flock size reduces with about 100 individuals and the number of sheep consumed by the carnivore stock of 12 animals adds up to 59 (column one, Table 2). The per carnivore *ex ante* compensation value becomes11 (1,000 NOK) and the sheep farmers are then just as well off as without predation. As indicated above, the social planner solution (column two) yields small differences compared to the Stackelberg solution. The total surplus is therefore also only slightly higher in the planner solution. However, under the hypothetical scenario that the farm profit and the *DNRM* benefit are distributed according to where the cost and benefit accrue, we find the sheep farmers will be substantial worse off while *DNRM* will be substantial better off in the social planner solution.

Table 2 about here

In Table 2 we have also included some sensitivity analysis of the Stackelberg solution. When shifting up the predation coefficient to $\psi = 0.005$ (column four), which may be interpreted as, say, reduced alternative food conditions for the carnivores, *DNRM* finds it beneficially to reduce the number of carnivores quite dramatically. As a consequence, the sheep loss reduces and the sheep stock increases significantly. See also the above section 4. The *DNRM* net benefit reduces and becomes only slightly positive. The 25 % slaughter price increase to $p = 2,500$ (NOK/animal) strongly affects the profit of the farmers which increases 50 % compared to the baseline case (column three). The per animal predation loss cost will thus increase and *DNRM* will reduce the number of carnivores and the predation pressure, while the *ex ante* compensation value shifts up. Finally, the effects of a higher intrinsic carnivore value are demonstrated (column five). As expected, *DNRM* finds in profitable to hold a larger carnivore stock which spills over to a lower sheep stock. Because of more carnivores, the *ex ante* per animal compensation value reduces to keep the amount of compensation unchanged.

7. Concluding remarks

In this paper have, from a theoretical point of view analyzed the conflict between carnivore conservation and livestock holding exemplified by sheep farming within an ecological and institutional context found in Scandinavia. Included in our model are a group of sheep farmers and the government agency *DNRM* (Directorate for Natural Resource Management). These agents interact strategically through a Stackelberg game with *DNRM* as the leader, and where the predation loss of the farmers is fully compensated. The compensation may take place *ex post* or *ex ante*, and where the *ex post* scheme is paid according the actual loss at the end of the grazing season while the *ex ante* scheme is related to the size of the carnivore population in the beginning of the grazing season.

Our main finding may be summarized as follows: 1) It does not pay for DNRM to use *ex post* compensation as this scheme motivates the farmers to keep more animals and thus increase the scope for compensation payment. Therefore, the whole compensation payment is channeled through the *ex ante* scheme. 2) The *ex ante* compensation value is inversely related to the size of the carnivore population. Our numerical illustrations indicate that 3) More aggressive predation through, say, reduced alternative food sources for the carnivores, leads to a smaller carnivore population while the farmers find it beneficially to increase the sheep stock. More valuable farm products through higher slaughter value of the sheep works in the same direction, while higher conservation value of the carnivores has opposite effects. We also find that 4) The social cost of predation is less than the *ex ante* compensation value, and the carnivore population will be too small while the sheep population will be too large compared to the social planner solution. However, we find the efficiency loss of the Stackelberg game to be small.

The main policy implication of our analysis is that the present Norwegian *ex post* compensation system should be replaced by an *ex ante* scheme. However, there are certain challenges posing this scheme that has not been considered here. Most important is that the group of sheep farmers has been considered as a single agent in our reasoning. Therefore, possible distribution problems among the farmers related to the *ex ante* compensation system has not been an issue. Such problems may come up as the farmers included in our group may be hit in various degree by the carnivores; that is, while some farmers may experience small sheep losses, other may experience large losses. Distribution problem of this type is taken up in Direktoratet (2011) and Zabel et al. (2014). Effort use by the farmers to protect the sheep stock from predation has neither been included in our model. Protection measures can take place in several ways. For example, the farmers can guard the sheep through the summer grazing season, and guarding dogs may be used (Ekspertutvalget 2011). Another option may be to shorten the rough grazing period. This can particularly be an efficient measure to reduce the wolverine predation as wolverine predation basically takes place late in the grazing season (Ekspertutvalget 2011).

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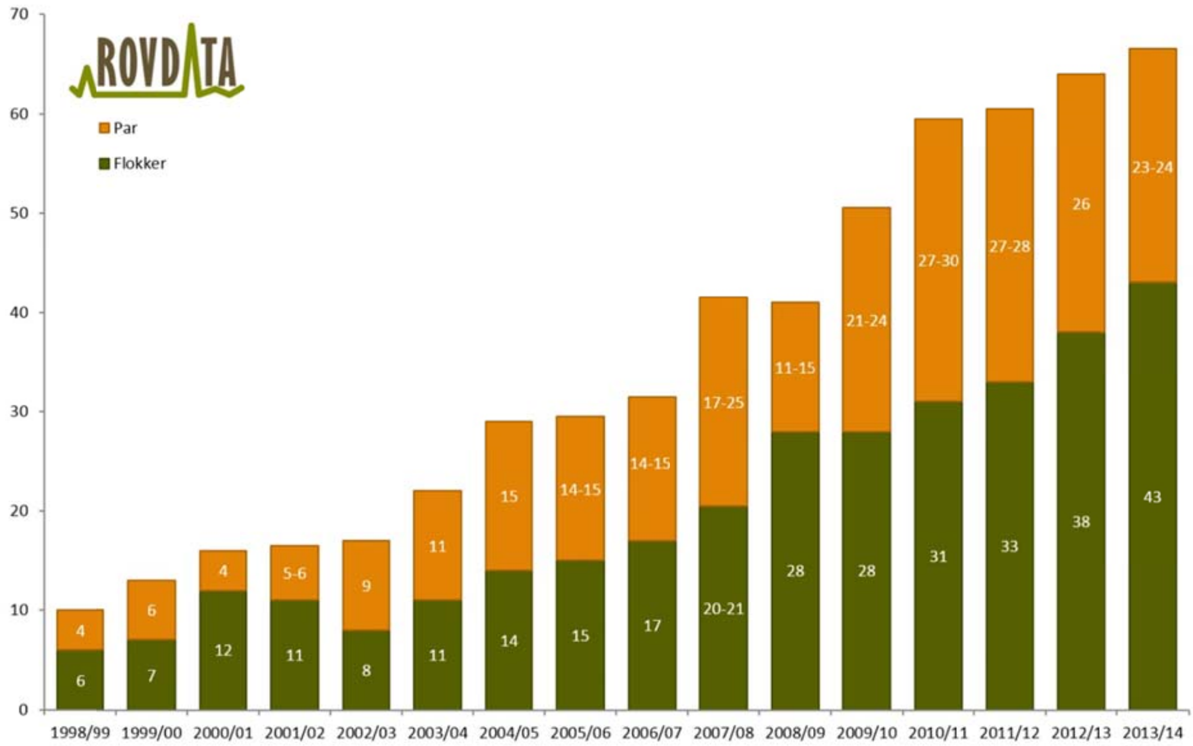
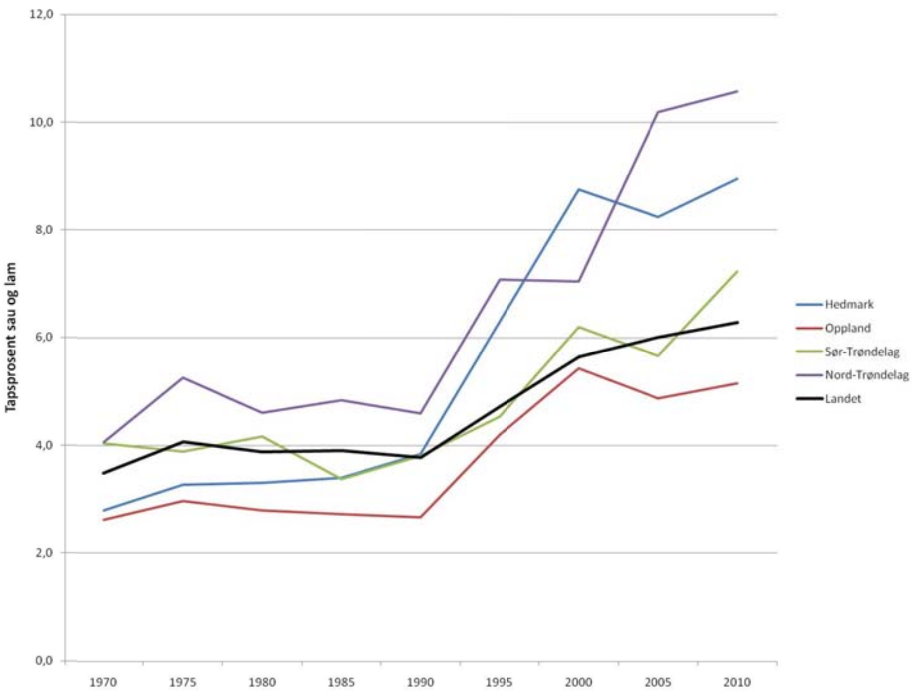
Figure 1. Estimated wolf population in Sweden and Norway 1988 – 2014. In black; number of individuals living in flocks. In shaded; number of couples



Source: http://www.rovdata.no/

Figure 2. Sheep loss in Norwegian counties with high carnivore prevalence 1990 – 2010. In % of summer grazing population



Source: Ekspertutvalget (2011)

Table 1. Baseline parameter values

Parameter	Description	Value
$r = (s - 1)$	Sheep animal growth rate	0.7
f	Carnivore intrinsic growth rate	0.1
K	Carnivore carrying capacity	25 (# of animals)
ψ	Predation coefficient	0.003 (1/animal)
p	Sheep slaughter meat price	2,000 (NOK/animal)
c	Sheep operating cost	1.3 (NOK/animal^2)
b	Carnivore intrinsic value	10 (1,000 NOK/animal)
q	Carnivore hunting value	100 (1,000 NOK/ animal)

Sources and assumptions; see main text

Table 2. Optimal solutions and sensitivity results

Baseline parameter values			Sensitivity analysis Stackelberg solution		
	Stackelberg solution	Social planner solution	Slaughter price up 25% ($p = 2,500$)	Predation coefficient up 67% ($\psi = 0.005$)	Carnivore intrinsic value up 50% ($b = 15$)
Sheep stock (# of animals)	984	979	1,305	1,045	932
Sheep slaughtering (# of animals)	629	623	885	710	565
Sheep predation (# of animals)	59	62	28	22	88
Carnivore stock (# of animals)	12	13	4	2	18
Carnivore harvest (# of animals)	1	1	0	0	0
Ex ante compensation value (in 1,000 NOK/animal)	11	-	17	18	10
Sheep farmer profit (in 1,000 NOK)	754	623[1)]	1,178	754	754
DNRM net benefit (in 1,000 NOK)	56	188[1)]	6	2	136
Total surplus (in 1,000 NOK)	810	811	1,184	756	890

1) Under the hypothetical situation where the profit and benefit streams are distributed to the farmers and *DNRM* according to where the cost and benefits accrue