Environ Resource Econ (2017) 67:905–923
DOI 10.1007/s10640-016-0011-9

The Silence of the Lambs: Payment for Carnivore Conservation and Livestock Farming Under Strategic Behavior

Anders Skonhoft[1]

Accepted: 16 February 2016 / Published online: 21 March 2016

Abstract During the last few decades, the number of large carnivores (wolf, bear, lynx and wolverines) has increased significantly in Scandinavia. As a result of more predation of livestock, conflicts with livestock farmers have deepened. We model this conflict using sheep farming as an example, and in instances in which 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*). *Ex-post* compensation payment is practiced in many countries where farmers are affected by killed and injured livestock, but also damages to crops. *Ex-ante* payment implies payment for environmental services and is also widely practiced. In the first part of the paper, the stocking decision of a group of farmers 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 is not beneficial for *DNRM* to use *ex-post*, but only *ex-ante* compensation. The solution to the game is compared to the social planner solution, and numerical illustrations indicate that the efficiency loss of the *ex-ante* compensation scheme to be small.

Keywords Carnivore conservation · Sheep farming · Compensation · Stackelberg game

JEL Classification Q20 · Q18

1 Introduction

In many instances, humans derive benefits from wild animals. However we also find that, often, wild animals create economic costs. Large herbivores, for example, provide value

✉ Anders Skonhoft
Anders.skonhoft@svt.ntnu.no

1 Department of Economics, Norwegian University of Science and Technology, Dragvoll, 7491 Trondheim, Norway

through hunting and trapping (e.g., Zivin et al. 2000) while simultaneously causing grazing or browsing damage. Nuisance may also occur through ecological interaction when, for example, large carnivores prey upon livestock or large herbivores or through grazing competition between wildlife and livestock. The outcomes are often property and grazing right conflicts (see, e.g., Skonhoft 2006; Zabel et al. 2011). A conflict of this type in which wild carnivores prey 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 suffer predation and loss of animals. In areas where big carnivores are prevalent, conflicts between sheep farming and the policy goal of sustaining large carnivore populations are often prevalent. In total, there are approximately 2.3 million summer grazing livestock (cattle, goats, horses and sheep) in Norway, of which approximately 2.1 million are sheep. Yearly, about 40,000–50,000 of these animals including ewes, but mostly lambs, are killed during the summer grazing due to predation (Ekspertutvalget 2011). In economic terms this loss is modest; however certain farmers and areas are severely exposed. These losses are subject to being fully compensated by the State through the slaughter value, and farmers may also be compensated for the effort spent to recover and verify cadavers. Nevertheless, there is no compensation for the 'emotional costs' of losing livestock (Ekspertutvalget 2011).

This paper presents research regarding this conflict and analyzes how farmers' stock decisions are influenced by the presence of carnivores, and the availability of compensation. Two compensation schemes are considered. First, we examine the existing scheme under which farmers are paid according to the number of verified sheep lost to carnivores during the summer grazing season. This is the *ex-post* compensation scheme. Alternatively, farmers could be compensated merely according to the presence of large carnivores in the area before the grazing season starts. This is the *ex-ante* compensation scheme, which is practiced in the Saami reindeer herding in Sweden (see, e.g., Direktoratet 2011; Zabel et al. 2014). Such a scheme is currently considered for the Saami reindeer herding in Norway (Direktoratet 2011).

A recent paper studying tiger conservation in India by Zabel et al. (2011) analyzes the efficiency of these two conservation schemes. They find that livestock holders have no incentive to protect livestock from carnivores under the *ex-post* scheme, while the opposite occurs when the ex-*ante* scheme is utilized. Our model has some similarities with Zabel et al. (2011), yet one important difference is that while Zabel et al. hold livestock and harvest fixed, our model allows the stock decision of the farmers to be influenced by the degree of predation and compensation. In a Scandinavian setting, this mechanism strengthens the predictive value of the analysis. Additionally, as illegal hunting is relatively limited and hence negligible in a Scandinavian setting, our model does not consider the farmers' effort to harvest or poach large carnivores (Ekspertutvalget 2011). As in Zabel et al. we study the stocking problem and predation in ecological equilibrium; hence, any dynamic considerations are outside the scope of the present analysis.

The economic and ecological consequences of wildlife damage compensation have been studied in many different ecological and institutional settings. Generally, payments are either made explicitly for wildlife damages, or as remuneration for the presence of wildlife in certain locations (Ferraro and Kiss 2002). Performance payments, or *ex-ante* payments, are conditioned upon the abundance of wildlife, and may be considered as a payment for environmental services (PES). For their mechanism of translating external, non-market environmental services values into economic incentives that provide environmental services these PES schemes have attracted increasing interest during the last years (see, e.g., the overview in Engel et al. 2008). However, *ex-post* compensation for actual wildlife damages is the most common compensation payment scheme and it is practiced around the world, both in developed and developing countries. Such programs generally imply that farmers affected by wildlife damages are compensated for killed and injured livestock, but also damages to crops (see, e.g., Rondeau and Bulte 2007).

In our analysis of *ex-post* and *ex-ante* compensation schemes, we include 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, which controls the carnivore population and manages the compensation scheme. The sheep farmers are assumed to maximize profit while the *DNRM* aims to maximize conservation benefits less compensation payments. The agents interact strategically through a Stackelberg game with *DNRM* as the leader and the group of farmers as the follower. With the inclusion of a government agency, the Stackelberg game seems to be the most realistic formulation [see, e.g., the classical (Schelling 1960)]. We assume complete and symmetric information. Our paper adds to a growing literature on strategic behavior in natural resource management, including Stackelberg games (see, e.g., Sandal and Steinshamn 2004).

In Sect. 2, we provide a brief background of the Nordic carnivore—sheep conflict. The stocking problem of sheep farmers is studied under various assumptions concerning predation and compensation in Sect. 3. As already indicated, poaching is neglected, and here we also neglect any protective effort exerted by the attempting to reduce the loss of sheep from predation. In Sect. 4, we consider the problem of the *DNRM*, which is composed of deciding the compensation scheme and managing the carnivore stock, and the Stackelberg game is solved. In Sect. 5, the social planner solution is analyzed and compared to the game solution while Sect. 6 presents a numerical illustration. Section 7 discusses some extensions of the baseline model. First, we include protective effort of the farmers to reduce the predation loss. Moreover, in Sects. 3–6 we have consistently assumed that the carnivore growth is independent of the sheep stock, and hence in Sect. 7 we also consider the situation where this feed-back effect is included. Section 8 concludes the paper.

2 Ecological and Economic Background

Large carnivore species in Scandinavia include the grey wolf (*canis lupus*), the brown bear (*ursus arctos*), the lynx (*lynx lynx*) and the wolverine (*gulo gulo*). By the mid-1960s, the grey wolf was regarded as functionally extinct; in the latter part of the 1970s, the first confirmed reproduction in 15 years was recorded in northern Sweden. Since that time, all reproductions have been located in the southern-central parts of the Scandinavian Peninsula (Wabakken et al. 2001). The wolf population in Scandinavia now equals 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 last year's population change.

Bear, lynx and wolverine populations were also small and threatened in the 1960s. However, due to changing attitudes, an institutional change occurred, and the wolf, as well as other big carnivores, became protected by the Norwegian state in 1972. The existence value of these species was also institutionalized through several international conventions and legal provisions; Norway became a signatory to the Bern-convention in 1986, which required countries to commit to maintaining viable populations of wolves and the other big carnivores (Ekspertutvalget 2011). The hunting season on lynx has been limited: hunting is immediately stopped when the hunting quota is reached. Wolf, wolverine and bear populations are controlled to eliminate certain ‘problem’ animals in areas with particularly large reported

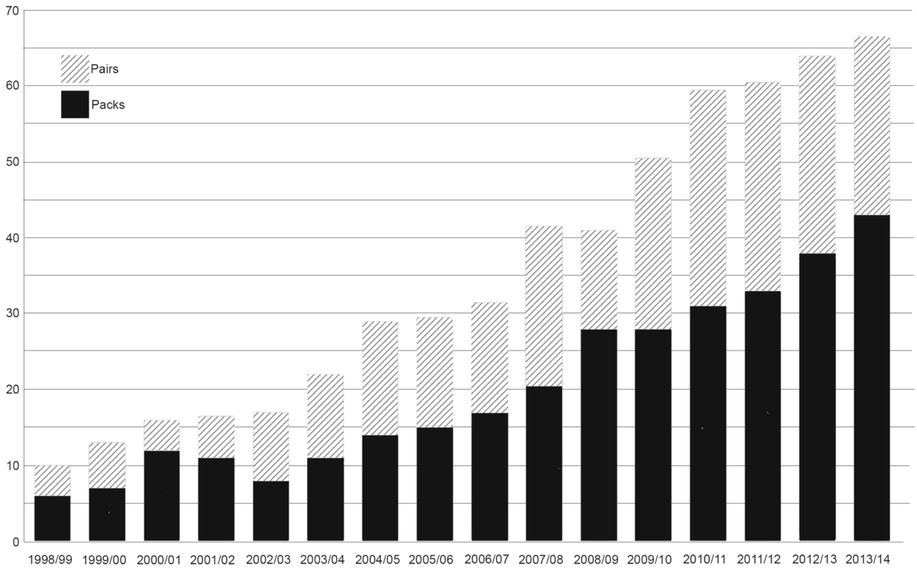

Fig. 1 Estimated wolf population in Sweden and Norway 1988–2014. *Source*: http://www.rovdata.no/

sheep and/or reindeer losses. Additionally, some hunting is permitted to keep stock sizes in line with politically-determined conservation measures (Ekspertutvalget 2011). There are reported instances of illegal hunting, particularly in the more northerly parts of Scandinavia. However, where sheep farming is prevalent, illegal hunting is considered to be small.

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

While, in total, sheep farming is a small economic activity, it is an important source of income in many rural communities. There are 13,000 sheep farms in Norway which graze approximately 2.1 million animals during the outdoors grazing season (Ekspertutvalget 2011). This number has been quite stable since the middle of the 1980s. Norwegian farms are located close to mountainous and other sparsely populated areas, or along the coast. The main product is meat, accounting for about 80 % of the average farmer's income. The remaining income comes from wool, as 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. Farmers control the spring lambing scheme by using the In Vitro Fertilization protocol to time 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 sheep is harvested during summer. When weather conditions permit, sheep are released into rough grazing areas in the valleys and mountains. Natural mortality, including accidents and various types of diseases, generally takes place during the summer grazing season. The length of the outdoor grazing season is relatively fixed and ends between late

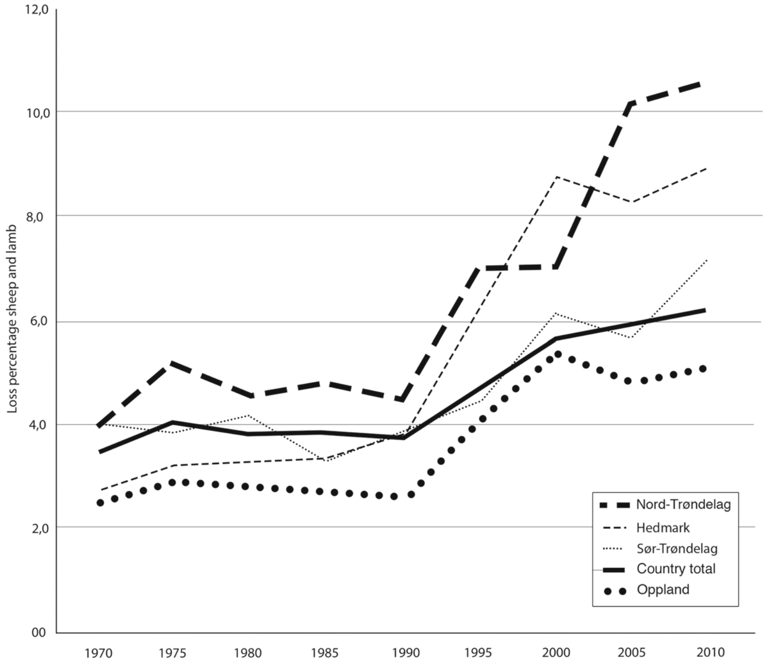

Fig. 2 Sheep loss in Norwegian counties with high carnivore prevalence 1990–2010. In % of summer grazing population. *Source*: Ekspertutvalget (2011)

August and the middle of September. After the grazing season, the animals are mustered and the wool is shorn. Slaughtering takes place either immediately or after a period of grazing on farmland (more details are provided in Austrheim et al. 2008).

In the last few years, about 125,000 animals have been reported lost during the summer grazing season. It is estimated that about one-third of this total loss, or approximately 40,000–50,000 animals, is due to predation caused by the four large carnivores. The rest is loss related to accidents and diseases (so called 'normal loss', Ekspertutvalget 2011). While predation takes place during the entire rough grazing period, there are certain different patterns among the four carnivores. Most notable is killing by wolverines, which almost always takes place in late summer or early fall and just before slaughtering. The geographical predation pattern is also distinct: predation by wolverines is most prevalent in the northern part of Norway whereas lynx predation is concentrated in the south-eastern part the country. The predation loss in the south-western part of Norway is small and negligible, simply due to the essential absence of carnivores, while it is evident in certain regions in the southern-central and northern-central parts of the country.

Figure 2 demonstrates predation losses as a percentage of total summer grazing animals in the four counties with the most extensive predation pressure. Additionally, the national county average is depicted. 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 area. All these counties, except Oppland, border Sweden. Figure 2 clearly demonstrates a growing predation problem emerging during the last two decades. Until about 1990, with no predation, normal loss was more or less constant and in the range of 3–4.5 % per year. From the beginning of the 1990s, total loss increased dramatically in these counties, especially in

Hedmark, where it has exceeded 10 % during the last few years. Annual predation loss in this county is thus estimated at approximately 5–6 % of the summer grazing population. Annual predation loss in Sør-Trøndelag county is estimated at a lesser but still significant 3 %.

3 Livestock Holdings of the Farmers

3.1 Livestock Growth and Equilibrium Harvesting

We start by looking at the stocking problem of our group of sheep farmers, with and without predation. The sheep growth model is formulated in discrete time, and assumes additions to the stock occur once per year, in the spring, and that all natural mortality takes place during the outdoor grazing season. As mentioned, slaughtering also takes place once a year, in September–October, after the end of the summer grazing season. We use a biomass model and do not distinguish between different age classes of the sheep. The natural growth rate is assumed constant, which is a reasonable assumption with a domestic animal stock managed with controlled breeding and maintenance. The growth of the farmers' sheep flock in the absence of predation is thus governed by:

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

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; Sect. 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:

$$h = (1 - 1/s). \tag{2}$$

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

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

where predation is assumed to be purely additive to natural mortality, also a realistic assumption for a domestic animal stock. Predation occurs generally during the entire grazing season, but possibly at a higher rate in late summer/early fall than in the beginning of the grazing season (Sect. 2). In what follows, we assume that all predation takes place after natural growth, but before slaughtering. Predation loss in number of animals is then defined as $M_t = sX_t m_t$, while the number of animals slaughtered in the 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:

$$h = 1 - 1/s(1 - m). \tag{4}$$

Therefore, the higher the predation rate, the fewer animals are left for slaughtering in order 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 first consider the stocking problem without predation. 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. Farm capacity is assumed to be fixed (but see Gauteplass and Skonhoft 2015), and costs thus comprise 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:

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

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

$$X^I = (p/c)(s - 1) \tag{6}$$

(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 can also be seen that slaughtering increases unambiguously with a higher price to cost ratio.

3.3 Stocking With Predation, but Without Compensation

We then proceed to solve the stocking problem of the farmers experiencing predation. We assume the predation loss to increase linearly with sheep density, assuming constant predation rates, consistent with the moose–wolf interaction analysis in Nilsen et al. (2005). 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 predation pressure, depending on type and composition of predators in the considered area, alternative food sources for area carnivores, measures taken by the farmers to protect their livestock, how farmers organize the rough grazing period during which the sheep stock is exposed to 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 carnivore density, we have:

$$m = \psi W \tag{7}$$

for a fixed number of carnivores.

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

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

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:

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

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 the 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 can also be seen that predation has a smaller profitability effect on the margin with a high rather 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 declines.

3.4 Predation with Compensation

In Norway, government is obligated to fully compensate farmers at the market value of the animals, i.e., the slaughter value, for losses caused by carnivore predation (Sect. 1). In what follows, however, we consider a more general compensation scheme. First, we set the fixed per animal *ex-post* compensation loss value, $p_X \leq p$, not to exceed the market value of the animals. Second, we assume the farmers may also receive compensation merely for the presence of carnivores, where $p_W \geq 0$ is the per unit carnivore *ex-ante* compensation value. These values are determined such that the farmer should be fully compensated by the *DNRM* (Sect. 4).

The profit of the farmers is now described by:

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

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 hunt, or kill, carnivores, a realistic assumption in our Scandinavian institutional setting (Sect. 2 above), we find the optimal stock size, related to p_X, but not to p_W, as:

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

(superscript '*' indicates the solution with predation and compensation). This is stated as:

Result 1 *The ex-ante compensation works solely as a lump sum transfer and does not influence the stocking decision of the farmers.*

Next, we find that the number of animals slaughtered after some rearrangements may 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 optimal stock size, but also the number of animals slaughtered, increase with the *ex-post* compensation value p_X. This is stated as:

Result 2 *A higher ex-post compensation value motives the farmers to increase the number of animals as well the number of animals slaughtered.*

Not surprisingly, we also find that the optimal stock is larger than without compensation as the marginal revenue with compensation shifts upward, $(X^* - X^{II}) = (p_X/c)s\psi W \geq 0$. 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 can 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 definitively be beneficial, $\partial\pi^*/\partial W > 0$.

4 The Management Problem of 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 predation and with and without compensation. As demonstrated, the *ex-ante* compensation mechanism works solely as a lump-sum transfer while the *ex-post* compensation motivates the farmers to increase the number of sheep. For that reason, *ceteris paribus*, 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 *DNRM* (Sect. 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, we assume *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 where carnivore populations are strongly controlled, as in Scandinavia, this relationship will appear less interactive, indicating that carnivores cannot respond numerically to variations in the sheep population (see Nilsen et al. 2005 and the references therein). The carnivores also have several alternative food sources. For example, in Scandinavia, the main prey of the wolves is moose (*Alces alces*) (Nilsen et al. 2005; Boman et al. 2003). Any numerical response is hence neglected and carnivore natural growth is independent of the size of the sheep population (but see Sect. 7) and given by $G(W_t)$, assumed to be density dependent of the logistic type. With y_t as the number of carnivores controlled/hunted at time t, the carnivore growth equation reads:

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

The equilibrium carnivore population is then simply given by:

$$y = G(W). \tag{13}$$

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:

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

such that $B(W)$ is the conservation value (intrinsic value), with $B' > 0$, $B'' \leq 0$ and $B(0) = 0$, while the compensation payment is represented by the last bracketed term. In addition, we have 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 may be managed through a license hunting scheme and where the hunters pay a fixed price per license This hunting price may also be given a wider interpretation by including a value to reduce to carnivore population in terms of better hunting upon prey ungulates like moose and roe deer (*Capreolus capreolus*) (Boman et al. 2003).

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 (Sect. 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) $X^* = (p/c)[s(1 - \psi W) - 1 + (p_X/p)s\psi W]$, or $X^* = X^*(W, p_X)$, with $\partial X^*/\partial W = X^*_W \leq 0$ and $\partial X^*/\partial p_X = X^*_p > 0$, 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:

$$\partial U/\partial W = B'(W) + qG'(W) - p_X s\psi \left(X^* + X^*_W W\right) - p_W = 0; \quad W > 0, \tag{15}$$

and

$$\partial U/\partial p_X = -s\psi W \left(X^* + p_X X^*_p\right) \leq 0; \quad p_X \geq 0. \tag{16}$$

Because higher *ex-post* compensation means that it is profitable for the farmers to increase the sheep stock, i.e., $X^*_p > 0$, condition (16) yields $\partial U/\partial p_X < 0$ with $p^*_X = 0$. This is stated as:

Result 3 *It is not beneficial for DNRM to introduce ex-post compensation because more livestock increase both predation and compensation payments. The whole compensation payment should be channeled through the ex-ante mechanism.*

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, 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^* (Sect. 3.4 above), the whole of the predation compensation is channeled through the *ex-ante* mechanism. When the farmers are subject to being 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 it may also be written as:

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

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 (Sect. 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 constant marginal conservation value $B'(W) = b > 0$, Eq. (15) with $p_X^* = 0$ reads:

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

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:

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

which represents a meaningful solution with $[(b+qf) - p^2\psi s(s-1)/c] > 0$ and $[(2fq/K) - (p\psi s)^2/2c] > 0$. This indicates that the predation cannot be too aggressive. This condition holds for a wide range of chosen parameter values (numerical Sect. 6 below). Additionally, we must have $q > 0$. When inserting Eqs. (19) into (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, $\partial p_W^*/\partial\psi > 0$. For our baseline parameter values (Sect. 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 carnivore intrinsic value means that *DNRM* will find it rewarding to maintain a higher carnivore population, $\partial W^*/\partial b > 0$, while the effect on the *ex-ante* compensation value is ambiguous, $\partial p_W^*/\partial b < 0$ (Eqs. 17, 18). 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, $\partial X^*/\partial b < 0$. Greater value for farm products, achieved 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,* which finds it beneficial to reduce the number of carnivores to lower predation pressure and compensation payments 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 farmers' profit and the *DNRM* benefit of the carnivores, comprising the conservation value and the net license hunting value:

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

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

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

and

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

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 predation loss to obtain a meaningful interior solution.

As there is no externality running from sheep farming to carnivore conservation, and as no numerical response is included in our ecological model (Sect. 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 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, combining Eqs. (21) and (22) gives:

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

The social planner solution is slightly different from the Stackelberg solution, and where the only difference is that the term $(p\psi s)^2/c$ in the nominator in Eq. (23) replaces the term $(p\psi s)^2/2c$ in the nominator in Eq. (19). We therefore find that $W^P > W^*$ holds for all feasible $\psi > 0$, and the social cost of predation is less than the per unit carnivore *ex-ante* compensation value. Accordingly, $X^P < X^*$ also holds. This is stated as:

Result 4 *From the social planner's point of view, the carnivore population will be too small while the sheep population will be too large in the Stackelberg solution.*

As we have an externality running from carnivore conservation to sheep farming, this outcome is indeed surprising. This result is therefore explained by the compensation mechanism, and the fact that the farmers should be fully compensated.

By combining Eqs. (23) and (19) the discrepancy between the planner and the Stackelberg solutions can be expressed as $\frac{W^P}{W^*} = \frac{(2fq/K)-(p\psi s)^2/2c}{(2fq/K)-(p\psi s)^2/c}$ which hence exceeds 1 for all feasible $\psi > 0$. It can easily be demonstrated that W^P/W^* reduces with higher values of f, q and c while it widens with higher values of p, ψ, s and K. Therefore, for example, more profitable sheep farming through a higher slaughter price will increase the discrepancy between the number of carnivores in the planner solution and the Stackelberg solution. However, within the range of realistic parameter values, the difference between the W^P and W^* becomes small. See numerical Sect. 6. The efficiency loss of the above Stackelberg game seems therefore to be quite modest.

6 Numerical Illustration

6.1 Data

To shed further light on the above analysis, we proceed with a numerical illustration. We do not attempt to accurately describe the economic situation of the group of Scandinavian sheep farmers considered here, but aim to demonstrate our solutions with reasonable realistic parameter values. All functional forms are specified above, and the numerical illustration is performed applying the baseline parameter values found in Table 1. We use the sheep data from Gauteplass and Skonhoft (2015), and scale the cost parameter c so that the number of sheep in the absence of predation, (and compensation), $X^I = (p/c)(s-1) = (2000/1.3)(1.7-1) = 1077$, may represent an area with a small group of farmers (6–8) with medium-sized farms. The baseline predation coefficient is assumed to be $\psi = 0.002$ and we find that that, e.g., 10 carnivores represent a predation rate of $M/sX = \psi W = 0.002 \cdot 10 = 0.02$, or 2 %. Following Fig. 2 and the related discussion this is a quite realistic number. As indicated in Sect. 5, the carnivore hunting value typically includes a pure hunting value plus the opportunity value of reduced moose and roe deer predation. Based on the hunting value of moose in Norway (Olaussen and Skonhoft 2011) and the addition of a pure hunting value, we use $q = 20$ (1000 NOK/animal) as our baseline value. As there are no studies attempting to value carnivore conservation in Norway we have little information concerning this. However Boman et al. (2003) refer to a valuation study in Sweden where is was found no marginal effect; that is, a fixed existence value that did not increase with a higher (hypothetical) wolf population. Accordingly, we include a fixed positive existence value (which has no effects on the results), but we also add a modest constant marginal effect, $b = 5.2$ (1000 NOK/animal). As a consequence, when *DNRM* optimizes the carnivore population in the absence of predation and hence no compensation payment (Eq. 15), the carnivore population is equal to its carrying capacity of $K = 25$ with a maximum specific growth rate of $f = 0.26$. $f = 0.26$ is within the range of realistic values for our large carnivore species (see, e.g., Boman et al. 2003; Caughley and Sinclair 1994, Chap. 4).

6.2 Results

Under the hypothetical scenario with no predation and $\psi = 0$, we find that 750 of the 1077 animals corresponding to the optimal stock size, will be slaughtered. The yearly farm profit

Table 1 Baseline parameter values

Parameter	Description	Value
$r = (s-1)$	Sheep animal growth rate	0.7
f	Carnivore intrinsic growth rate	0.26
K	Carnivore carrying capacity	25 (# of animals)
ψ	Predation coefficient	0.002 (1/animal)
p	Sheep slaughter meat price	2000 (NOK/animal)
c	Sheep operating cost	1.3 (NOK/animal^2)
b	Carnivore intrinsic value	5.2 (1000 NOK/animal)
q	Carnivore hunting value	20 (1000 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 15 % ($p = 2300$)	Predation coefficient reduced 50 % ($\psi = 0.001$)	Carnivore intrinsic value up 100 % ($b = 10, 4$)
Sheep stock X (# of animals)	1036	1034	1227	1034	968
Sheep slaughtering H (# of animals)	698	695	852	695	609
Sheep predation M (# of animals)	27	28	7	29	68
Carnivore stock W (# of animals)	8	9	2	16	21
Carnivore harvest y (# of animals)	1	1	0	1	1
Ex ante compensation value p_W (in 1000 NOK/animal)	7	–	10	4	6
Sheep farm profit π (in 1000 NOK)	754	696[a]	997	754	754
DNRM net benefit U (in 1000 NOK)[b]	12	71[a]	1	56	90
Total surplus S (in 1000 NOK)	766	767	998	810	844

[a] 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

[b] Positive constant carnivore existence value not included

is 754 (1000 NOK). In the Stackelberg solution with the baseline parameter values (column one, Table 2), the optimal flock size decreases by approximately 50 individuals, and 27 sheep are consumed by a carnivore stock of 8 animals. The per carnivore *ex-ante* compensation value is 7 (1000 NOK) and the sheep farmers are just as well off as without predation. As indicated in Sect. 5, the differences between the social planner solution (column two) and the Stackelberg solution are small. The social planner solution yields a slightly higher carnivore stock and a smaller stock of sheep. With our parameter values, 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 accordingly small compared to the magnitude of the term $(2fq(K)$ in Eq. (23) (and Eq. 19). Total surplus is moderately higher in the planner solution. However, in the hypothetical scenario where the farm profit and the *DNRM* benefit are distributed according to where the costs and benefits accrue, we find the sheep farmers will be substantially worse off while *DNRM* will be substantially better off in the social planner solution.

In Table 2 we have also included some sensitivity analysis of the Stackelberg solution. When the predation coefficient shifts down and $\psi = 0.001$ (column four), through, for instance improved access to alternative food for the carnivores, *DNRM* will find it beneficial to dramatically increase the number of carnivores. Subsequently, the number of sheep lost to predation rises and sheep stock $X^* = (p/c)[s(1-\psi W^*)-1]$ is reduced. As the changes in ψ and W^* have contradictive effects the reduction in stock size is small. The *DNRM* net benefit increases significantly. A 15 % increase in the slaughter price, i.e. $p = 2300$ (NOK/animal) (column three), strongly affects the profit of the farmers as it rise by more than 30 % compared to the baseline case. Accordingly, the compensation payment should also increase by more than 30 %. The per animal predation loss cost increases and *DNRM* will reduce the number of carnivores and the predation pressure, while the *ex-ante* compensation value shifts upward. Finally, the effects of a higher existence carnivore value are demonstrated (column five), and as expected, *DNRM* finds in profitable to keep a larger carnivore stock, which spills over to a smaller sheep stock. The *ex-ante* per animal compensation value reduces, but modestly.

7 Extensions

In the following we briefly look at two extensions of the above model. The first obvious extension we examine is just as in Zabel et al. (2011), to include the farmers' effort to protect sheep from predation. See also Bulte and Rondeau (2007) who discuss the affected farmers' incentives for protection for in a developing country context. In our Nordic setting there are various protection measures that can take place. For instance, the farmers may guard the sheep through the summer grazing season, often with the help of guard dogs. Another option is to shorten the rough grazing period and bring the animals back earlier in the fall (Ekspertutvalget 2011). The latter may be a particularly efficient measure to reduce wolverine predation as the wolverine predation basically takes place early fall (above Sect. 2).

Both of these as well as other possible measures to protect the sheep from predation is included in the effort variable e. Effort use is modelled by introducing the function $\tilde{W} = \tilde{W}(W, e)$, where $\tilde{W}$ is the 'effective' number of carnivores preying upon the sheep when protective effort is exerted with $\partial\tilde{W}/\partial e = \tilde{W}_e < 0$, $\tilde{W}_W > 0$ and $\tilde{W} = \tilde{W}(W, 0) = W$. We assume a decreasing marginal effect, i.e., $\tilde{W}_{ee} \geq 0$. The functional form $\tilde{W} = W\exp(-\rho e)$, where $\rho > 0$ is a parameter, satisfies these properties. With $\tilde{C}(e)$ as the effort cost function where $\tilde{C}' > 0$, $\tilde{C}'' \geq 0$ and $\tilde{C}(0) = 0$, the profit maximizing problem of our group of farmers is now described by $\max_{X,e} \pi = pX[s(1-\psi\tilde{W}(W, e)) - 1] - C(X) - \tilde{C}(e) + (p_X s\psi X\tilde{W}(W, e) + p_W W)$ (see Sect. 3.4). The first order necessary conditions for maximum are $\partial\pi/\partial X = 0$, with $X > 0$, which implies:

$$X = (p/c)\left[s(1-\psi\tilde{W}(W, e)) - 1 + (p_X/p)s\psi\tilde{W}(W, e)\right] \tag{11'}$$

when inserting $C(X) = (c/2)X^2$, and

$$\partial\pi/\partial e = -(p - p_X)Xs\psi\tilde{W}_e(W, e) - \tilde{C}'(e) \leq 0; \quad e \geq 0. \tag{24}$$

The first of these conditions is similar to the above (Sect. 3.4), except that now predation mortality is influenced by the protective effort use. From condition (24) it is seen that when the per animal *ex post* compensation value is less than market value of the sheep, $p > p_X$, and $-(p - p_X)Xs\psi\tilde{W}_e(W, 0) > \tilde{C}'(0)$ holds, protective effort is a profitable option. We then have $-(p - p_X)Xs\psi\tilde{W}_e(W, e) = \tilde{C}'(e)$, and where the LHS indicates the marginal gain of supplying protective effort.

Notice that the *ex-ante* compensation value still is excluded from the farmers' optimality conditions, and hence it remains to act solely as a lump sum transfer. With positive effort use, the conditions (11′) and (24) consequently define the sheep stock and effort use as functions of the number of carnivores and the *ex post* compensation value; that is, $X^* = X^*(W, p_X)$ and $e^* = e^*(W, p_X)$, respectively. $X^* = X^*(W, p_X)$ is again the reaction function of the farmers that feed into the optimization problem of the *DNRM* leading to the similar conditions (15) and (16) as above, and still with $p_X^* = 0$. The effort function, on the other hand, feeds into the profit function of the farmers which now is defined by $\pi^* = pX^*[s(1 - \psi\tilde{W}(W, e^*) - 1] - (c/2)(X^*)^2 - \tilde{C}(e^*) + p_W W$, or $\pi^* = (p^2/2c)[s(1 - \psi\tilde{W}(W, e^*(W, 0)) - 1]^2 - \tilde{C}(e^*(W, 0)) + p_W W$ when inserting for $X^* = (p/c)[s(1 - \psi\tilde{W}(W, e^*)) - 1]$ and $e^* = e^*(W, 0)$. The profit will be higher than in the case without effort; otherwise it would have not been beneficial to support protective effort. Equation (15) and the condition that the farmers are fully compensated, $\pi^1 - \pi^* = 0$, or $(p^2/2c)(s - 1)^2 = (p^2/2c)[s(1 - \psi\tilde{W}(W, e^*(W, 0)) - 1]^2 - \tilde{C}(e^*(W, 0)) + p_W W$, jointly determine the number of carnivores W^* and the ex-ante compensation value p_W^*. As in Sect. 4, we next find the optimal livestock size through $X^* = X^*(W^*, 0)$, and the optimal effort use through $e^* = e^*(W^*, 0)$. We might expect that the stock of sheep will be higher than in the case without protective effort. This however, is difficult to prove. Moreover, the relationship between the sheep number and the size of the carnivore stock is no longer as unambiguous as in the previous situation without protective effort. This can be confirmed by taking the differential of $X^* = (p/c)[s(1 - \psi\tilde{W}(W^*, e^*(W^*, 0)) - 1]$.

Next, we examine an extension of the carnivore natural growth function. In the above Sects. 3–6, we have consistently assumed that the carnivore growth is independent of the sheep stock, and hence ignored any possible numerical response. Although this is a realistic assumption in areas where carnivores prey upon sheep in Norway and Scandinavia (see Sect. 4 above), it may not fit as well in areas with different carnivore species and feeding conditions. Here the actual predator–prey relationship could include numerical responses. In order to see how this might influence our reasoning, we include a brief analysis where this feedback is taken into account. In what follows, similarly to the basic model, protective effort of the farmers is disregarded.

The carnivore natural growth equation is now rewritten to $G(W, X)$ with $G_X > 0$. If we assume that the farmers are ignorant of this feedback effect, the reaction function $X^* = X^*(W, p_X)$ through Eq. (11) is left unchanged and this new carnivore natural growth assumption hence only influences the *DNRM*'s optimization problem. The current net benefit function (14) of *DNRM* changes slightly to:

$$U = B(W) + qG(W, X) - (p_X s\psi XW + p_W W). \tag{14'}$$

The first order conditions are now:

$$\begin{aligned} \partial U/\partial W = B'(W) + q\left[G_W(W, X^*) + G_X(W, X^*)X_W^*\right] \\ - p_X s\psi\left(X^* + X_W^* W\right) - p_W = 0; \quad W > 0 \end{aligned} \tag{25}$$

together with:

$$\partial U/\partial p_X = qG_X(W, X^*)X_p^* - s\psi W\left(X^* + p_X X_p^*\right) \leq 0; \quad p_X \geq 0, \tag{26}$$

and where this last condition replaces condition (16). As the first term in (26) is positive, $\partial U/\partial p_X$ is no longer negative for sure. With $p_X > 0$ we have $qG_X(W, X^*)X_p^* = s\psi W(X^* + p_X X_p^*)$, indicating that ex-post compensation will be beneficial for *DNRM* if the livestock provides significant feeding support to a valuable carnivore stock. We may specify the carnivore natural growth function as $G(W, X) = fW(1 - W/K) + \theta sXW$ where K now is the carrying capacity net of sheep and the parameter $\theta > 0$ measures the strength of the numerical response. $p_X > 0$ then implies $q\theta WX_p^* = \psi W(X^* + p_X X_p^*)$, or $p_X = (q\theta/\psi - X^*/X_p^*)$, and demands $p_X < q\theta/\psi$, or $p_X\psi sXW < q\theta sXW$. Therefore, if ex-post compensation is profitable for *DNRM*, the value of the sheep feeding support must exceed the sheep predation loss, evaluated by the ex-post compensation value.

If *ex-post* as well as *ex-ante* compensation are beneficial, the farm profit reads $\pi^* = pX^*[s(1 - \psi W - 1] - (c/2)(X^*)^2 + (p_X s\psi X^* + p_W W)$ with$X^* = X^*(W, p_X) = (p/c)[s(1 - \psi W) - 1 + (p_X/p)s\psi W]$. The condition that the farmers should be fully compensated, now represented by

$\pi^1 - \pi^* = 0$, or $(p^2/2c)(s-1)^2 = pX^*[s(1 - \psi W - 1] - (c/2)(X^*)^2 + (p_X s\psi X^* + p_W W)$ together with Eqs. (25) and (26) then determine the compensation values p_X^* and p_W^* as well as the optimal number of carnivores W^*. As seen, this is a much more complicated case to analyse than the baseline situation without the carnivore feedback effect through the natural growth function.

8 Concluding Remarks

In this paper we 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*. These agents interact strategically through a Stackelberg game with *DNRM* as the leader, and where the predation loss of the farmers is fully compensated. Full compensation implies that the farmers' profit with and without predation loss should be identical. The compensation could be either *ex-post* or *ex-ante*, where the *ex-post* scheme is paid according to 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 findings are summarized in Results 1–4. Result 4 indicates that the Stackelberg solution yields a carnivore population that is too small and a sheep population too large in comparison to the social planner solution, albeit, the numerical illustration reveals that the difference is small. Result 3 stating that *ex-post* compensation is not beneficial is in line with Zabel et al. (2011). The mechanism leading to this outcome in our present reasoning is, however quite different from that of Zabel et al. While the stocking decision of the farmers in our model is influenced by the degree of predation and compensation, the harvest is fixed in Zabel et al. Furthermore, poaching is an important mechanism in Zabel et al., yet it is not included in our Scandinavian setting where illegal hunting is small and negligible. Protective effort use and the inclusion of a feedback effect from the sheep stock to the carnivore growth have been analyzed separately in extensions of the model. Even when taking account of protective effort, we find that only *ex-ante* compensation is optimal. When numerical response is included and the carnivore natural growth depends on the size of the sheep stock, it is shown that *ex-post* compensation may be profitable when the sheep stock provides significant feeding support to a valuable carnivore stock.

The primary 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 challenging aspects of this scheme that have not been analyzed. Most important is the fact that our study has considered the group of farmers as a single agent. Therefore, possible distribution problems among the farmers related to the *ex-ante* compensation system have not been an issue. Such problems may arise if the farmers in our group face heterogeneous effects in regard to the carnivores; that is, if some farmers experience small sheep losses while others experience large losses. There are also general common pool natural resource management problems connected to the distribution of *ex-ante* benefits. Such distribution problems are reviewed in Direktoratet (2011) and Zabel et al. (2014). The only *ex-ante* compensation program for wildlife damages currently operating in Scandinavia is related to Saami reindeer herding in Sweden where lynx and wolverine populations prey upon semi domestic reindeer livestock. This compensation program has been active since 1996, and the experiences have been promising. An important reason for this success is that, due to the organization of the herding, the individual herders all face very similar predation effects related to the carnivores (Direktoratet 2011).

As mentioned (Sect. 1 above) *ex-ante* payment conditioned upon the abundance and damages caused by the wildlife is a form of payment for environmental services (PES). An important characteristic of most PES schemes, including the present case, is that they are linked to certain ecological, or environmental, outcomes. While the PES scheme in our Scandinavian study is related to wildlife conservation and where no costs should be imposed on the farmers affected by this conservation, we find that many PES schemes in developing countries have a wider scope. However, when introducing more measures and combining conservation and development, research indicate that the outcomes will become extensively more complicated than in our setting (see, e.g., Johannesen and Skonhoft 2005; Rondeau and Bulte 2007).

Acknowledgements Thanks to two reviewers and associate editor Daniel Rondeau for constructive and very helpful comments on an earlier draft of this paper. Parts of the analysis in Sect. 7 are directly based upon these comments. Thanks also to Jan Tore Solstad for comments and discussions and to participants at the EAERE conference in Helsinki June 2015 and the NRM conference in Bordeaux July 2015 for valuable comments.

References

Austrheim G, Asheim LJ, Bjarnason G, Feilberg J, Fosaa AM, Holand Ø, Høegh K, Jónsdóttir IS, Magnússon B, Mortensen LE, Mysterud A, Olsen E, Skonhoft A, Steinheim G, Thórhallsdóttir AG (2008) Sheep grazing in the North Atlantic region: a long term perspective on management, resource economy and ecology. Report Zoology Ser. 2008, 3 Vitenskapsmuseet NTNU

Boman M, Bostedt G, Persson J (2003) The bioeconomics of the spatial distribution of an endangered species: the case of the Swedish wolf population. J Bioecon 5:55–74

Bulte E, Rondeau D (2007) Compensation for wildlife damages: habitat conversion, species preservation and local welfare. J Environ Econ Manag 54:311–322

Caughley G, Sinclair A (1994) Wildlife ecology. Basic Blackwell, Cambridge

Clark C (1990) Mathematical bioeconomics, 2nd edn. John Wiley, New York

Direktoratet (2011) Utredning—erstatningsordning for tamrein. Direktoratet for Naturforvaltning, Trondheim

Ekspertutvalget (2011) Innstilling fra ekspertutvalg vedrørende endringer i erstatningsordningen for rovviltskade på husdyr. Direktoratet for Naturforvaltning, Trondheim

Engel S, Pagiola S, Wunder S (2008) Designing payments for environmental services in theory and practice: an overview of the issues. Ecol Econ 85:663–674
Ferraro PJ, Kiss A (2002) Direct payment to conserve biodiverssity. Science 298:1718–11719
Gauteplass A, Skonhoft A (2015) Optimal exploitation of a renewable resource with capital limitations: Nordic sheep farming with and without grazing externalities. Eur Rev Agric Econ 42:25–50
Johannesen AB, Skonhoft A (2005) Tourism, poaching and wildlife conservation: what can integrated conservation and development projects accomplish? Resour Energy Econ 27:208–226
Nilsen E, Pettersen T, Gundersen H, Milner J, Mysterud A, Solberg E, Andreassen H, Stensseth NC (2005) Moose harvesting in presence of wolves. J Appl Ecol 42:389–399
Olaussen JO, Skonhoft A (2011) A cost–benefit analysis of moose harvest in Scandinavia. Astage structured modelling approach. Resour Energy Econ 33:589–611
Rondeau D, Bulte E (2007) Wildlife damage and agriculture: a dynamic analysis of compensation schemes. Am J Agric Econ 89:490–507
Schelling T (1960) The strategy of conflict. Harvard University Press, Cambridge
Sandal L, Steinshamn SI (2004) Dynamic Cournot-competetive harvesting of a common pool resource. J Econ Dyn Control 28:1781–1799
Skonhoft A (2006) The costs and benefits of animal predation. Ecol Econ 28:830–841
Skogen K, Krange O, Figari H (2012) Ulvekonflikter. Akademika Forlag, Oslo
Wabakken P, Sand H, Liberg O, Bjarvall A (2001) The recovery, distribution, and population dynamics of wolves on the Scandinavian peninsula, 1978–1998. Can J Zool 79:710–725
Zabel A, Pittel K, Bostedt G, Engel S (2011) Comparing conventional and new policy approaches for carnivore conservation: theoretical results and applications to tiger preservation. Environ Resour Econ 48:287–311
Zabel A, Bostedt G, Engel S (2014) Performance payments for groups: the case of carnivore conservation in Northern Sweden. Environ Resour Econ 59:613–631
Zivin J, Hueth BM, Zilberman D (2000) Managing a multiple-use resource: the case of feral pig management in Californian rangeland. J Environ Econ Manag 39:189–204