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Wildlife conflicts: wolves vs. moose

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Abstract

During the last few decades, the grey wolf (*Canis lupus*) has re-colonised Scandinavia. The current population counts some 430 individuals. With the wolf re-colonisation, several conflicts have arisen. One important conflict is due to wolf predation on moose (*Alces alces*). This conflict is studied under the assumption of landowner profit maximisation as well as routinised harvesting behaviour. The analysis emphasises how compensation for the predation loss affects landowner management and harvest profitability. The solutions to the landowner problems are also compared to the overall (social planner) management situation, where traffic costs due to moose–vehicle and railway collisions are included.

Keywords: wildlife, conflicts, external costs, bioeconomic modelling

JEL code: Q24, Q28

1. Introduction

The aim of this paper is to analyse wildlife hunting under different management scenarios, and to study how predation and compensation for the predation loss may influence management decisions. The wildlife case considered is that of moose (*Alces alces*) in the Scandinavian ecological and institutional context where the landowners obtain the harvesting value and bear the cost of timber browsing damage, but do not pay for other damages by moose, such as those associated with traffic incidents. The predator is the grey wolf (*Canis lupus*). As the Scandinavian population of the grey wolf has increased significantly during the last decades, the predation problem has become a concern. Two management schemes are considered. Firstly, we study what happens to hunting and hunting profitability when a single landowner, or a

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landowner association assumed to operate as a single agent, behaves in a long-term, profit-maximising manner. Secondly, we study the outcome when the group of landowners behaves in a kind of routinised behaviour, exemplified by a harvesting scheme with a fixed fraction of the stock hunted every year. This type of management rule is common in moose management in Norway. In the next step, we compare the landowner problem to the outcome when the wolf–moose interaction is analysed from an overall (social planner) point of view, where costs of traffic incidents, due to moose–vehicle and moose–railway collisions, are included. Across these management problems, we assume that wildlife authorities are in full control and thus the wolf population is determined outside the model. However, we also study briefly an extended version of the model where the size of the wolf population is included in the social planner's problem.

The present study is a follow-up of Skonhoft (2006). Important differences include the focus on compensation payment, which was not a topic in Skonhoft (2006). Important other differences are the more explicit comparison of landowner management versus the social planner's problem and the inclusion of the optimisation of the wolf population in the social planner problem.

The moose is the most important game species in Scandinavia, with tens of thousands of animals (with a mean body weight of about 190 kg for adult females and 240 kg for adult males) shot every year (more details below). The hunt takes place in September/October and is an important, if not the most important, social and cultural event taking place during the year in many rural communities in Norway and Sweden. However, the moose is also by far the most important prey for wolves (Sand *et al.*, 2008; Zimmerman *et al.*, 2015). After the last wolves had been killed, the species became protected in Sweden in 1966 and in Norway in 1973. The wolf returned with the first confirmed reproduction in 14 years recorded in northern Sweden in the late 1970s. Since this first reproduction, the wolf population has grown steadily, with all new reproductions taking place in the southern-central parts of the Scandinavian Peninsula (Wabakken *et al.*, 2001; Stortingsmelding 2015). As in other regions around the world, the reappearance of wolves has generated several conflicts. In addition to killing sheep and moose (Milner *et al.*, 2005; Nilsen *et al.*, 2005), the presence of wolves in the various "wolf areas" is often seen as a reduction of local people's quality of life. More generally, the protection of wolves and other carnivores has stirred up controversy between "local rural people" and "urban well-educated conservation people" (Skogen *et al.*, 2012)[1].

1 In addition to the grey wolf, large carnivore species in Scandinavia include the brown bear (*Ursus arctos*), the lynx (*Lynx lynx*) and the wolverine (*Gulo gulo*). All these species were under threat in the 1960s, and the grey wolf was indeed regarded as functionally extinct. However, due to changing attitudes, an institutional change occurred, and the brown bear and the wolverine, together with the grey wolf, were all protected in the last part of the 1960s and the beginning of the 1970s. The protection of the large carnivore species was also institutionalized through several international conventions and legal provisions—for instance, the Bern convention—which required countries to commit to maintaining viable populations of wolves and other big carnivores (Ekspertutvalget 2011; Stortingsmelding 2015).

Today population control is in place to eliminate certain "problem" animals in areas with particularly large reported livestock losses (sheep and/or semi domestic reindeer). Additionally, some hunting is permissible to keep stock sizes in line with politically determined conservation measures. Generally, the wolf population in Scandinavia can be considered as strictly controlled.

To mitigate the conflict and to address the cost the wolf imposes on local farmers, the Norwegian and the Swedish governments fully compensate for domestic livestock killed by wolves (and other large predators), primarily sheep grazing in outlying fields. The payment to the livestock owners follows an *ex post* compensation scheme. The compensation is for reported and verified killings; see Skonhoft (2017) for a discussion and assessment. In contrast, there is no such compensation scheme for moose killings. However, the Norwegian Forestry Owners Association (Norges Skogeierlag), together with other interest groups such as the Norwegian Hunting and Fishing Association (Norges Jeger og Fiskeforbund), strongly promote such compensation payments to be introduced in Norway.

The economic and ecological consequences of different types of wildlife damage compensation payment schemes have been studied in various ecological and institutional settings. Performance payments, or *ex ante* payments, are conditioned upon the abundance of wildlife, and may be considered as a payment for environmental services (Engel *et al.*, 2008; Zabel *et al.*, 2011). However, *ex post* compensation for actual wildlife damages is the most common scheme around the world, both in developed and developing countries. Such programmes either imply that farmers affected by wildlife damages are compensated for killed livestock (Maclennan *et al.*, 2009; Zabel *et al.*, 2011; Skonhoft 2017) or for damages to crops (Rollins and Briggs 1996; Bulte and Rondeau 2007; Rondeau and Bulte 2007; Gren *et al.*, 2020). For both these cases, the literature has identified moral hazard as a problem attached to *ex post* compensation schemes. Typically, compensation payments may give peasants incentives to cut back on efforts to protect crops and livestock from wildlife damage (Rollins and Briggs 1996; Bulte and Rondeau 2005; Nyhus *et al.*, 2005; Maclennan *et al.*, 2009; Zabel *et al.*, 2011). Moreover, as the compensation payments for damaged crops make farming relatively more profitable than defensive activities, the effort used to protect crops is reallocated towards farming. In this way, compensation payments may act as an agricultural subsidy, and may thus imply an expansion of agriculture that is detrimental to wildlife (Nyhus *et al.*, 2005; Bulte and Rondeau 2007).

Because of the resemblance to the livestock problem, we analyse how an *ex post* compensation scheme may influence hunting and landowners' profits. Compared to the existing literature, we analyse the effects of predation combined with compensation in more detail. First of all, we analyse the compensation of wolves killing moose under two different management scenarios regarding moose—a profit-maximising landowner versus a landowner behaving in a routinised manner. We also add to the existing literature by considering further factors that may affect the difference in social surplus achieved with the landowner solutions and the social planner solution, such as the cost from traffic incidents that involve moose. Furthermore, we also study an extended version of the model in which the social planner determines both the optimal wolf population and the optimal moose population. Here, we attach an existence value to the wolf population, and introduce wolf harvesting and a feedback effect from the moose population to the wolf population (numerical response) in order to make the model more complete.

The pricing and organising of the hunt are different in Norway and Sweden. The landowners have the property right to the moose in both countries; they are in control of the annual harvest and the size of the moose population. Whereas hunters typically pay the landowner for the right to hunt in a certain area in Sweden (see, e.g. Sandstrøm *et al.*, 2013), moose hunting in Norway requires a licence per animal paid only if the animal is shot. Due to this difference in the licence system and hunting management system between Norway and Sweden, we limit our study to the case of Norway. We start in Section 2 by providing some ecological background for the analysis and formulate the growth equation of the moose population. As indicated, we consider a single landowner or a group of landowners acting as a single agent. The benefit and cost functions of this agent are discussed and formulated in Section 3. In Sections 4 and 5, the two harvesting regimes, profit maximisation and routinised behaviour, respectively, are analysed. Here, as in the rest of the paper, only steady state, or population equilibrium, is considered (but see the Appendix). While moose predation may be considered a negative external effect for the landowners, the moose population also causes some external costs. We add the damages caused by moose–vehicle and moose–train collisions into the social planner's problem analysed in Section 6. Section 7 provides a numerical illustration using a real-life example. In Section 8, we briefly consider the situation where the size of the wolf population is determined in the social planner's problem. Finally, Section 9 summarises our findings and discusses some policy implications.

2. Ecological background and the moose growth equation

As mentioned, after re-colonisation, the Scandinavian wolf population has grown steadily. In the winter of 2016–2017, the population had reached 430 individuals; see also Figure 1 and Wabakken *et al.* (2016). The wolf lives in small family groups as packs or pairs, in the western-central part of Sweden and along the border area between Norway and Sweden. As of December 2018, at least 25 individuals were cross-boundary wolves, while 70–75 individuals inhabited Norway only.

While the re-colonised Scandinavian wolf population is small in number and patchily distributed, the density of the Scandinavian moose population is generally high, and significantly higher than in the beginning of the 1950s. The main reasons have been a highly selective harvesting scheme focusing on young males and calves, and good growth conditions associated with changing forestry practices (Saether *et al.*, 1992; Skonhoft, 2006). See Figure 2. The

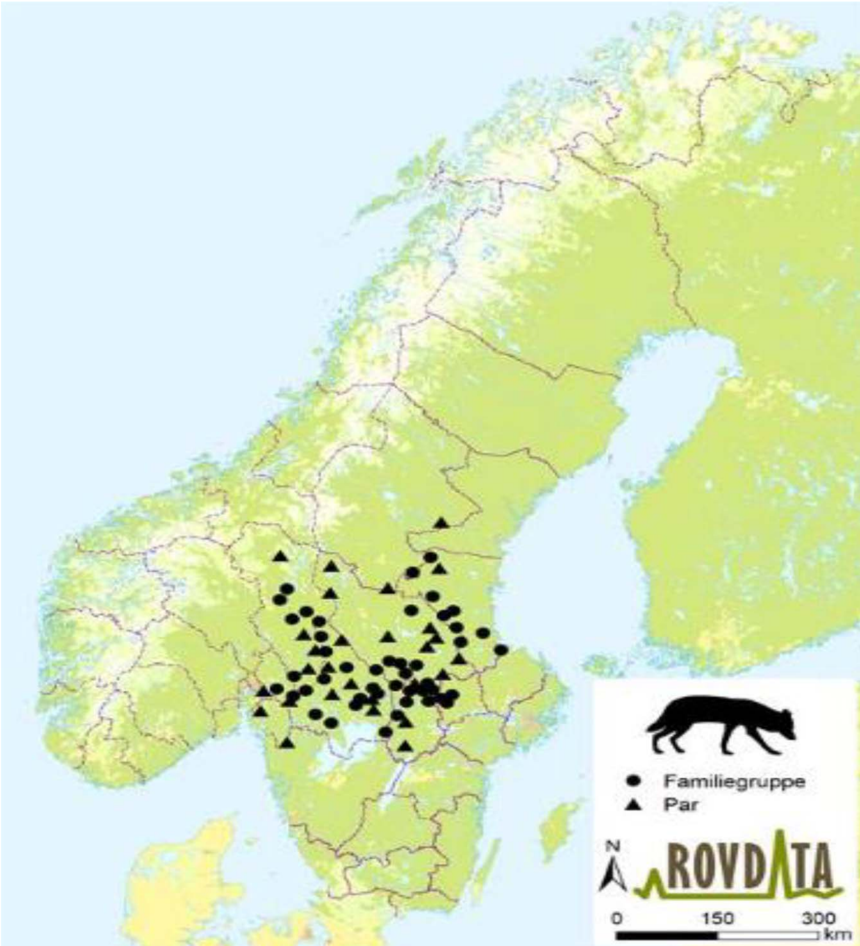

Fig. 1. Distribution of the Scandinavian (Sweden and Norway) wolf population pairs (par) and packs (familiegruppe), winter 2016–2017. *Source*: http://www.rovdata.no/.

stock became large compared to the fodder conditions and this explains the sharp decline in the hunt during the last decades in Sweden.

A study of the prey selection of wolves during summer in a wolf-ungulate system in southern-central Scandinavia found that moose constituted about 95 per cent of the total biomass killed (Sand *et al.*, 2008; Zimmerman *et al.*, 2015). Wolf predation focuses on moose calves, yearlings and older females, with calves as the main food source. While predation tends to increase with the size and number of the wolf packs, there is controversy over how it relates to the size of the moose stock. Whereas it is generally accepted that predation increases in the moose stock at low densities, it is unclear what happens at medium and high moose densities (Nilsen *et al.*, 2005). The moose population may also influence the wolf population growth (see, e.g. Boman *et al.*, 2003; Nilsen *et al.*, 2005).

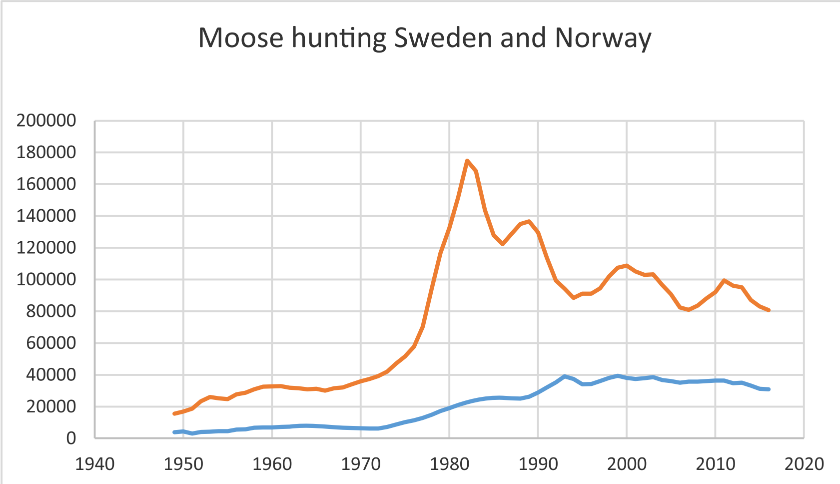

Fig. 2. Number of moose shot, Scandinavia 1949–2016. Red (upper) graph: Sweden. Blue (lower) graph: Norway. *Sources*: Statistics Norway and www.älgdata.se.

Our main analysis excludes this feedback effect (numerical response) because the Scandinavian wolf has a variety of other food sources and its population is strictly controlled by the wildlife authorities (Stortingsmelding, 2015; Widman and Elofsson, 2018). However, in Section 8, we briefly analyse the case where the feedback effect is included.

In our biomass framework, equation (1) yields the growth of the moose population for a given size of the wolf population. Included here is also the mortality loss of the moose due to traffic incidents. In Norway, for example, more than 1500 moose are killed in vehicle and railway collisions every year (see e.g. Solberg *et al.*, 2009). The moose growth equation therefore translates into four terms: natural growth in the absence of wolves minus mortality through predation, hunting and traffic incidents:

$$dX/dt = F(X) - G(W, X) - h - Q(X) \tag{1}$$

where X is the population size in year t (the time subscript is omitted), measured in number of animals, and $F(X)$ is the density-dependent natural growth function in the absence of wolf predation. Natural growth is assumed to be of the standard logistic type, with $F(0) = F(K) = 0$, where K is the carrying capacity, and $F'' < 0$ (additional details provided below). $G(W, X)$ is the predation term, where W is the (exogeneous) given size of the wolf population (but see Section 8). Predation is increasing in both the wolf population, $G_W > 0$, and the moose population, $G_X > 0$. In addition, we have $G_{WX} > 0$ and $G(0, X) = G(W, 0) = 0$. h is the harvest, while $Q(X)$ represents the mortality loss due to traffic incidents. This loss is assumed to increase in the stock size, with $Q(0) = 0$ and $Q' > 0$. The traffic mortality may be influenced by effort, for example, through winter foddering in certain locations (Solberg *et al.*, 2009), but this possibility is neglected here (see also Section 7 below).

3. The moose benefit and cost to the landowners

Recent estimates value the meat of moose harvested in Norway at more than NOK 370 million annually (Olaussen and Skonhoft, 2011). With a yearly hunt of 35,000–40,000 animals, this equals to about NOK 10,000 per animal hunted[2]. According to the Norwegian Wildlife Act, landowners are entitled to the hunting value of moose, which they realise by selling licences to hunt on their land [3]. The yearly net hunting income is given by the first term in equation (2), where p is the hunting licence price net of hunting costs, which is assumed to be fixed and independent of the harvest and stock size. This assumption is justified by the fact that there is competition among many landowners supplying hunting licences[4]. As already indicated, following the practice in Norway, a licence allows the buyer to kill one animal, with the licence paid for only if the animal is killed. Each hunter also pays a (small) fixed fee regardless whether any animal is shot, this fee component is neglected in our analysis.

On the other hand, when practising forestry, landowners also bear the economic loss from browsing damage by moose, this occurs mostly during the winter when young pine trees are the main food source for the moose. The damage varies with the quality of the timber stand, the productivity of the forest and the density of moose. Quite frequently, there will also be a time lag between the occurrence of browsing and the associated economic loss. The yearly money value of the browsing damage for the individual landowner is therefore difficult to assess. Skonhoft and Olaussen (2005) refer to several studies indicating that the browsing damage for the whole of Norway is somewhere in the range of NOK 20–400 million. The most recent estimate is NOK 70 million. A simple, but realistic, way to account for the browsing cost is to relate it to the size of the moose population, $D = D(X)$, with $D(0) = 0$ and $D' > 0$. We also assume $D'' \geq 0$, see Skonhoft and Olaussen (2005) for more details.

2 Exchange rate: 1 euro ≈ 9.90 NOK (December 2018).

3 From a legal point of view, the landowners do not own, but have the hunting rights to wildlife residing on their land. From an economic point of view, however, considering property as a benefit stream, a property right is the capacity to control the current and future appropriation of the benefit stream (Bromley 1991, Demsetz 1967). To have property right to the wildlife in this sense requires to be in control of the harvesting. In Norway, moose management is based on local administration at the municipality level, where locally elected boards determine the hunting quotas (Storaas et al. 2001). Landowners will typically be represented in these boards and thus have a significant saying when it comes to determining the hunting quotas. In the model, we cultivate the landowners as decision makers and make them able to control the harvesting and the moose population both in the case of profit-maximization and routinised behaviour.

4 Including a downward sloping demand curve such that the landowner faces a trade-off between price and the size of the hunt, together with a negative stock value (see main text below), may give rise to a much more complicated model than the present one, including, among others, the possibility of multiple equilibria (Chen and Skonhoft 2013).

The wildlife authorities in Norway have declared that wolf management must take place in a multi-use landscape. As forest and mountain areas are important grazing resources for both wild game and domestic livestock, there will be conflicting interests as wolves prey on both moose and sheep. Thus, besides securing a "sustainable" wolf population, an important dimension of wolf management in Scandinavia is to reduce the conflicts associated with it (see, e.g. Stortingmelding, 2015). One way to reduce the conflicts is to establish a compensation payment scheme for moose preyed on by wolves, just as for the sheep killings by large carnivores. The present sheep compensation scheme in Norway (and Sweden) is as indicated of the *ex post* type, and it is this scheme we will analyse for moose loss. To receive compensation, the landowners will have to register and document the number of moose killed by wolves, an activity representing costs for the landowner. We assume that all moose killed by wolves are registered and documented and that the cost of this activity is proportional to the number of killed moose. The proposed compensation payment net of registration and documentation cost is restricted to the full meat, or hunting, value of the moose. Therefore, with $0 < z \leq p$ as the *ex post* net compensation value (NOK/animal), the current (yearly) landowner net benefit reads:

$$\pi = ph - D(X) + zG\left(W, X\right). \tag{2}$$

4. The profit-maximising landowner

We analyse the economics of the wolf–moose interaction under the assumption that the landowner, or our cooperative group of landowners acting as a single agent, maximises profit. As noted above, the landowner has the property right to the moose through the control of the annual harvest and the size of the moose population. However, the annual harvest and the hunting income of the landowner also depend on the number of wolves and the predation pressure. Hence, the presence of wolves infringes on the landowner's property right to the moose, as it lowers his capacity to appropriate the benefit stream from the moose. With equation (2) describing the current net benefit of the landowner, and assuming present-value profit maximising, the harvesting strategy of the landowners is to maximise $\int_{t=0}^{\infty}[ph - D(X) + zG(W,X)]e^{-\delta t}dt$ subject to the ecological growth equation (1) with a fixed wolf population. Additionally, the initial size of the moose population has to be taken into account. $\delta \geq 0$ is the (annual) discount rate, assumed to be constant over time.

In the Appendix, it is shown that the landowner golden-rule condition becomes:

$$F'(X) - \frac{(p-z)\,G_X\left(W,X\right)}{p} - Q'(X) - \frac{D'(X)}{p} = \delta. \tag{3}$$

This equation determines stock size X^* (the superscript "$*$" indicates the profit maximisation solution), and indicates that the net internal rate of return of the moose population should equalise the external rate of return δ. Multiplying by p and rearranging, this golden-rule condition also states that the net marginal value of the moose population "in the forest", $pF' - (p - z)G_X - pQ' - D'$, equalises the marginal harvesting value "in the bank", $p\delta$. This steady state will be unique when the sufficiency condition is satisfied (see Appendix).

According to equation (3), the stock size will always be below the maximum sustainable yield (msy) level; $F'(X^*) > 0$, or $X^* < X_{\text{msy}}$.

We can find an explicit expression for the stock size under the assumption of the standard logistic natural growth of the moose population, $F(X) = rX(1 - X/K)$, and the Lotka–Volterra model with the predation effect (functional response) as $G(W, X) = \psi WX$. Here, r is the intrinsic growth rate and K is the carrying capacity, while $\psi > 0$ indicates the strength of the predation pressure. If we additionally assume a linear traffic mortality function $Q(X) = qX$ and linear browsing damage function $D(X) = dX$, the stock size becomes $X^* = (K/2r)[r - d/p - (p - z)\psi W/p - q - \delta]$. Steady-state harvest follows as $h^* = F(X^*) - Q(X^*) - G(W, X^*)$, which with the above stated functional forms reads $h^* = X^*[r(1 - X^*/K) - q - \psi W]$. A higher harvesting price may either increase or reduce the optimal steady state stock as well as the harvest depending on the degree of compensation. However, with full compensation, a higher price will always increase the stock. On the other hand, higher marginal damage cost and higher marginal traffic mortality work in the direction of a smaller stock size and a smaller harvest.

With $z < p$, the stock effect of increased predation pressure is $dX^*/dW = (p - z)G_{XW}/(pF'' - D'' - (p - z)G_{XX} - pQ'') < 0$, or $dX^*/dW = -\psi K(p - z)/2rp < 0$ with the above specified functional forms. The predation effect increases with a higher harvesting price while it reduces with the amount of compensation. The profitability effect of increased predation pressure follows as $d\pi^*/dW = [p(F' - Q' - G_X) - D' + zG_X](dX^*/dW) + zG_W$. By using the optimality condition equation (3), this may be simplified to $d\pi^*/dW = p\delta(dX^*/dW) - (p - z)G_W < 0$, or $d\pi^*/dW = -\psi(p - z)(\delta K/2r + X^*) < 0$. The marginal profitability loss of predation is therefore proportional to the optimised size of the moose stock.

It is evident that compensation works as if the predation nuisance effect diminishes, and the landowner will find it beneficial to keep a larger moose stock, i.e. $dX^*/dz > 0$, or $dX^*/dz = \psi WK/2rp$ with the specific functional forms. With equilibrium harvest defined as $h^* = F(X^*) - G(W, X^*) - Q(X^*)$, we find the effect of compensation on the harvest as $dh^*/dz = (F' - G_X - Q')(dX^*/dz)$. Therefore, the effect of compensation on the harvest will be positive and in the same direction as the effect on the stock as long as $F' > (Q' + G_X)$, but is generally ambiguous. Moreover, a certain value of the compensation may lead to a peak value for the harvest. On the other hand, compensation unambiguously increases profit, and by using the optimality condition, we find the marginal effect as $d\pi^*/dz = p\delta(dX^*/dz) + G(W, X^*)$.

With full compensation and $z = p$, the golden rule equation (3) simplifies to $F'(X^*) - Q'(X^*) - \frac{D'(X^*)}{p} = \delta$. The steady state stock size, and also the equilibrium harvest, will then be identical to the hypothetical situation without predation. Accordingly, with full compensation and following the logic of profit maximisation, the landowner will be indifferent whether the moose is either hunted or consumed by the wolves. The steady state profit will be identical as well, $\pi^* = p[h^* + G(W, X^*)] - D(X^*)$. These observations are stated as:

Result 1: *With profit maximisation, ex post compensation motivates the landowner to increase the size of the moose stock and the predation loss increases. The equilibrium harvest effect is ambiguous. With full ex post compensation, the size of the moose stock and profit will be as without predation.*

This effect of full compensation has been noted before. The sheep-predation analysis in Skonhoft (2017) similarly finds for full compensation that the landowner is indifferent to whether the prey is harvested or consumed by the carnivores.

5. Routinised behaviour

Moose harvesting schemes, as well as other natural resource management schemes, often follow standard routines. The meat value and sale of hunting licences are always of importance in Scandinavian moose management. Browsing damage may be taken into account, but often in an *ad hoc* manner (Saether *et al.*, 1992). Additionally, due to various uncertainties, lack of information, and so forth, we find that landowner management often reduces to simple goals concerning the equilibrium population size and/or the yearly size of the harvest. Such simple goals are implemented through various types of routinised harvesting rules, which may include threshold harvesting, fixed quota harvesting and fixed proportional harvesting. For more on these harvesting rules, see e.g. Lande *et al.* (2003, Ch. 6)[5].

The institutional setting of the routinised behaviour model is similar to that of profit-maximisation. The landowner has a restrained property right to the moose, restrained due to the presence of wolves and the predation pressure. With routinised behaviour, exemplified by the popular fixed proportional harvest strategy (Saether *et al.*, 1992), harvest is simply given as:

$$h = \gamma X, \tag{4}$$

such that $\gamma > 0$ yields the fixed harvesting proportion. Accordingly, the moose stock dynamics equation now reads:

$$dX/dt = F(X) - G(W, X) - \gamma X - Q(X). \tag{5}$$

5 These types of harvesting rules have clear similarities with so-called harvest control rules in fisheries. For a review, see e.g. Deroba and Bence (2008).

This is a separable differential equation, which is stable when the total animal loss function $G(W,X) + \gamma X + Q(X)$ intersects with the natural growth function $F(X)$ from below; that is, $(\gamma + G_x + Q') > F'$ at the equilibrium. This is assumed to hold, and the associated equilibrium $F(X) = G(W,X) + \gamma X + Q(X)$, determining X^{**}(superscript "$**$" indicates equilibrium under routinised management), will be unique with our strictly concave logistic natural growth function and $G(W,X) + \gamma X + Q(X)$ as a convex function. The harvest then becomes $h^{**} = \gamma X^{**}$.

A higher wolf population yields $dX^{**}/dW = -G_W/(\gamma - F' + G_x + Q') < 0$. Therefore, the equilibrium harvest also decreases, $dh^{**}/dW = \gamma(dX^{**}/dW) < 0$. With the linear traffic mortality function, the Lotka–Volterra predation function and the logistic natural moose growth function, the stock equilibrium reads $X^{**} = K[1 - (\psi W + \gamma + q)/r]$, with $dX^{**}/dW = -\psi K/r$ and $dh^{**}/dW = -\gamma K\psi/r$. Recall that we found $dX^{*}/dW = -\psi K(p - z)/2rp$ under profit maximisation. It therefore follows that the marginal predation stock loss always will be higher under routinised landowner behaviour. The reason for this outcome is that the profit maximizing landowner accounts for the predation pressure when determining the stock size.

Compensation works as a lump sum transfer under routinised behaviour and hence has no effect on the harvest activity of the landowner. Accordingly, the steady state profit reads $\pi^{**} = p\gamma X^{**} - D(X^{**}) + zG(W,X^{**})$. Therefore, for a given size of the wolf population, the profit increases proportionally with the amount of compensation, $d\pi^{**}/dz = G(W,X^{**})$. Inserting for the above stock effect of predation, $d\pi^{**}/dW = \frac{G_W[D' - (p-z)\gamma + z(Q' - F')]}{(\gamma - F' + Q' + G_x)}$ now describes the profitability impact of a higher wolf population. This profitability effect can be either positive or negative. With full compensation and $z = p$, it simplifies to $d\pi^{**}/dW = \frac{G_W[D' + p(Q' - F')]}{(\gamma - F' + Q' + G_x)}$. Therefore, under full compensation, more wolves may in fact increase the landowner profit if $D'(X^{**})/p > [F'(X^{**}) - Q'(X^{**})]$ holds. With linear browsing damage and traffic mortality functions, together with logistic growth and the Lotka–Volterra predation function, and when also inserting for X^{**} this inequality reads $d/p > (2\gamma + 2\psi W + q - r)$[6]. This is stated as:

Result 2: *Under routinised harvesting and compensation, a higher wolf population and more predation may improve the economic conditions for the landowner. Given full compensation, this happens when the marginal cost associated with the forest damage is relatively high, the marginal income of moose harvesting is relatively low, and the predation pressure is relatively moderate.*

6 We should also check the profitability conditions for the landowner, and the condition for an interior stable solution. While positive profit in the absence of compensation demands $\gamma > d/p$ with the linear damage function, the condition for an interior solution is $(\gamma + G_x + Q') > F'$, or $(\gamma + \psi W + q) > r - 2rX^{**}/K$. When inserting for X^{**}, it yields $r > \gamma + \psi W + q$.

6. The social planner solution

So far, the landowner has determined the harvest and moose population for a given size of the wolf population. When not being fully compensated through the *ex post* compensation scheme, this may be seen as an institutional outcome where the landowner has the hunting rights and control over the moose population but is a victim of the predation caused by the wolf. However, the moose is responsible for generating some externalities as well. The most important is damage costs related to moose–vehicle and moose–railway collisions, largely experienced by people who do not own hunting land or engage in moose hunting. The yearly costs in Norway may be in the range NOK 200–300 millions (Solberg *et al.*, 2009; Olaussen and Skonhoft, 2011), and can even be higher than the meat value of the moose in many areas (see also http://www.hjortevilt.no/elgkrasj-koster-samfunnet-hundrevis-av-millioner/)[7]. In the social planner model, this cost component is therefore included.

As discussed in Solberg *et al.* (2009), many factors affect traffic damages and the associated costs in Scandinavia. The most important factors seem to be snow conditions during winter and the amount of traffic together with the animal density. A simple, yet realistic, way to account for the moose–vehicle damage cost in our considered area, just as for the browsing damage cost, is to relate it to the moose density and assume, *ceteris paribus,* that higher density means more damages and higher costs. Therefore, when neglecting possible effort to reduce these damages, we introduce the traffic damage cost function as $A = A(X)$ with $A(0) = 0$ and $A' > 0$. Notice the similarity with the moose traffic mortality function.

The moose population certainly also has an intrinsic value, which values species conservation valued in its own right. However, due to the large number of moose in Norway and Scandinavia (see Section 2), this value will, at the margin, generally be rather small in our considered area. The analysis that follows refrains from including an intrinsic moose value. We also neglect the intrinsic value of the wolves because the wildlife authorities strictly control the wolf population (but see Section 8). Accordingly, after also neglecting other possible cost and benefit components, including the recreational surplus accruing to the hunters buying hunting licences, and the costs, or benefits, of controlling the wolf population (Section 8), the current (yearly) social surplus of our moose population is defined as:

$$S = ph - D(X) - A(X). \tag{6}$$

7 Traffic damage costs pertain to deer species in general at the international level. In USA, for instance, it was reported that the white-tailed deer was involved in 1.5 million yearly car collisions some years ago and where the damages have been estimated at more than $2 billion (Rondeau and Conrad 2003).

With the same discount rate as in the landowner problem, the social planner present-value maximizing $\int_0^\infty [ph - D(X) - A(X)]e^{-\delta t}dt$ now yields the golden-rule condition:

$$F'(X) - G_X(W, X) - Q'(X) - \frac{D'(X) + A'(X)}{p} = \delta. \tag{7}$$

This equation determines X^S (superscript "*s*" indicates the steady state social planner solution). Comparing equation (7) to the landowner maximisation golden-rule condition equation (3), we easily find the result $X^S < X^*$ for all $z \le p$. The stock now reads $X^S = (K/2r)(r - (d + a)/p - \psi W - q - \delta)$ when applying the linear traffic damage cost function $A(X) = aX$ together with the other functional forms specified above. The difference compared to the profit-maximizing solution is then $X^S - X^* = -(K/2rp)(a + z\psi W) < 0$, affected by the predation pressure and the amount of compensation, together with the traffic damages costs. Comparing the social planner solution to the routinised landowner solution with $X^{**} = K[1 - (\psi W + \gamma + q)/r]$, we find that the stock difference for obvious reasons is indeterminate.

The steady state surplus in the profit maximizing solution denoted as S^*, is defined through $S^* = \pi^* - zG(W, X^*) - A(X^*)$. With large traffic damage costs, S^* can be negative, thus implying that private management and private property rights to the moose is highly inefficient from a social perspective (see also numerical Section 7). The effect of a higher predation pressure is $dS^*/dW = d\pi^*/dW - z[G_W + G_X(dX^*/dW)] - A'(dX^*/dW)$. Inserted for the profitability effect (Section 4), this expression may also be stated as $dS^*/dW = [p\delta - zG_X - A'](dX^*/dW) - pG_W$. The sign is indeterminate, indicating that a higher wolf population may either increase or reduce the social surplus under private management guided by profit maximisation. When inserting for the predation effects, G_X and G_w together with dX^*/dW and also utilising the functional forms specified above, we find after some rearrangements: $dS^*/dW = (\psi K/2r)\{(1/p)[(p^2 - z^2)\psi W + a(p - z)] - p(r - d/p - q) + \delta z\}$. Therefore, $dS^*/dW > 0$ holds if $a/p > [p/(p - z)](r - d/p - q - \delta z/p) - [(p + z)/p]\psi W$. The marginal traffic damage must therefore be of a certain minimum to fulfil this condition. Without compensation and $z = 0$, this condition simplifies to $a/p > (r - d/p - \psi W - q)$. With full compensation, we find $dS^*/dW = -(\psi Kp/2r)(r - d/p - q - \delta) = -\psi pX^*$, which shows that in this situation a larger wolf population will always reduce the social surplus under profit maximisation.

Under routinised behaviour, the expression for the social surplus is $S^{**} = \pi^{**} - A(X^{**}) - zG(W, X^{**}) = p\gamma X^{**} - D(X^{**}) - A(X^{**})$, with the predation effect as $dS^{**}/dW = (p\gamma - D' - A')(dX^{**}/dW)$. Inserting for dX^{**}/dW then yields $dS^{**}/dW = G_W(D' - p\gamma + A')/(\gamma - F' + G_x + Q')$. Notice that the amount of compensation plays no role here. When again applying the linear damage functions, a higher wolf population and more predation thus improve the social benefit if $a/p > (\gamma - d/p)$, or $a > (p\gamma - d)$. Therefore, if the marginal traffic damage exceeds the marginal landowner profit in absence of compensation, more wolves will increase the social surplus when landowner management is steered by routinised harvesting behaviour. These observations are stated as:

Result 3: *For a sufficiently high marginal traffic damage cost, more wolves and more predation may increase the social surplus when landowner moose management is steered by profit maximisation as well as routinised behaviour. With full compensation and profit maximisation, more wolves reduce the social surplus for sure.*

We also assess the effect of compensation. With more compensation, z shifts up, the moose population increases with optimised behaviour and profit maximisation, but not with routinised behaviour as the compensation then represents a lump sum transfer. Therefore, we may state:

Result 4: *Under profit maximisation, more compensation induces a larger discrepancy between landowner management and the social planner solution, while the discrepancy is unaffected under routinised behaviour.*

Per definition, the present-value social surplus in the social planner solution will be higher than the present-value social surplus in the landowner profit maximizing solution. Nothing can, however, generally be inferred about the steady state (golden rule) surplus difference. On the other hand, in steady state with zero discounting, where the steady state of dynamic optimisation problems coincides with equilibrium (static) optimisation problems (see, e.g. Clark, 1990), the steady state surplus of the social planner solution will exceed the steady state social surplus in the profit maximizing problem. Therefore, when $\delta = 0$ and when S^s denotes the optimised steady state surplus in the social planner solution, $S^* < S^s$ also holds per definition. With $S^* = \pi^* - zG(W, X^*) - A(X^*)$, we find $dS^*/dz = d\pi^*/dz - G(W, X^*) - zG_X(W, X^*)(dX^*/dz) - A'(X^*)(dX^*/dz)$. Inserting for $d\pi^*/dz$ with $\delta = 0$ (Section 4 above) yields then $dS^*/dz = -[A'(X^*)(dX^*/dz) + zG_x(W, X^*)(dX^*/dz)] < 0$. Thus, the difference compared to the steady state surplus in the social planner solution widens through two effects. The first term $A'(X^*)(dX^*/dz)$ reflects that higher moose density following more compensation is accompanied by higher external costs through higher traffic damage costs. The other term $zG_x(W, X^*)(dX^*/dz)$ yields the increased (financial) social loss due to more predation following more compensation. With our functional forms, we find $dS^*/dz = -(a/p + z\psi W/p)$ and state:

Result 5: *When management is steered by private property rights guided by profit maximisation, more compensation reduces the steady state social surplus both through higher traffic damage costs and higher predation loss.*

7. Numerical illustration

7.1. Data and specific functional forms

The various harvesting schemes will now be studied numerically with an illustrative example from the north-eastern part of Hedmark County, some 200 km north of Oslo, Norway (see Figure 1). The size of the area is about

1000 square km, with a moose population of about 1300 individuals. A wolf pack of 5–12 individuals has been present here for the last 15–20 years. The yearly predation, mainly calves and yearlings, has been difficult to assess, but earlier estimates indicate it is in the range of 0–18 moose/wolf/100 days (Gundersen, 2003). Also, the wolf population is strictly controlled in this area (Stortingsmelding, 2015).

As indicated, the natural growth function of the moose population in the absence of predation is, as in Saether *et al.* (1992) and Skonhoft and Olaussen (2005), assumed to be of the standard logistic type while the functional response of the wolf population is specified as in the Lotka–Volterra model. As also indicated, we use linear traffic mortality, browsing damage and traffic damage cost functions. Table 1 presents the baseline parameter values. The carrying capacity, scaling the size of the moose population, is $K = 4600$ (# of moose), which implies about 4.6 moose/km^2. The predation pressure rate is assumed to be $\alpha W = 0.05$. The high predation pressure of $\alpha W = 0.10$ and no predation at all contrast to this baseline value. The harvesting fraction under routinised behaviour is assumed to be 30 per cent, $\gamma = 0.3$, which represents an often used harvest rate. Based on an estimate of NOK 70 million for browsing damage costs and 250 million for traffic damage costs for the whole of Norway, the baseline marginal browsing and traffic damage costs are assumed to be 500 (NOK/moose) and 1800 (NOK/moose), respectively. As indicated, these costs may vary considerably among different areas. The baseline traffic damage cost is quite moderate given the very low human population density and low traffic volume in the considered area. However, we will also run model simulations with alternative values for this cost. Anecdotical evidence from Norway seems to indicate that while the landowners consider wildlife as a reproductive capital in a biological sense, they do not consider it as capital in a financial sense. Accordingly, the baseline discount rate is assumed to be zero, $\delta = 0$, under profit maximizing behaviour to reflect that the typical landowner ignores the adjustment of the harvest for the opportunity cost of this financial capital. A meaningful comparison of the steady state's surplus in the social planner and the landowner profit maximisation solutions can then also be carried out (Section 6 above).

7.2. Results

Table 2 reports the steady state results under profit maximisation and under routinised behaviour, both under full compensation. This full compensation situation is contrasted with one of no compensation at all (in brackets). Under profit maximisation, the number of animals is higher with full compensation. Table 2 also shows that profit and stock size are the same as without predation. The sum of hunting and killing by wolves then just equals what the harvest would be in the absence of predation. The harvest is slightly higher with full compensation than no compensation, but this outcome is generally ambiguous (Result 1). Under routinised behaviour and the linear damage cost assumption, we find that higher predation pressure reduces profit with full compensation as

Table 1. Baseline economic and ecological parameter values

Description	Parameter	Value	Unit	Source/Reference
Moose intrinsic growth rate	r	0.47		Olaussen and Skonhoft (2011)
Moose carrying capacity	K	4,600	# of moose	Given (scaling the system)
Traffic damage mortality rate	q	0.02		Solberg *et al.* (2009)
Predation rate	ψW	0.05		Assumed
Hunting price	p	9,800	NOK/moose	Olaussen and Skonhoft (2011)
Unit browsing damage cost	d	500	NOK/moose	Skonhoft and Olaussen (2005)
Unit traffic damage cost	a	1,800	NOK/moose	www.Hjorteviltportalen
Discount rent	δ	0.00		Assumed
Harvesting fraction routinised behaviour	γ	0.3		Saether *et al.* (1992)

2010 price level. Exchange rate: 1 euro ≈ 9.90 NOK (December 2018).

well as without compensation (cf. Result 2). We also find that the profitability discrepancy between optimised and routinised management increases when compensation is included, because compensation influences the behaviour of the landowner under the optimised scheme, but not under routinised behaviour.

Table 3 demonstrates the social planner solution where the traffic damage cost is included. The table also includes the social surplus obtained under both landowner management schemes with full compensation and without compensation (in brackets). We find that the social surplus following the social planner solution is significantly lower than the landowner profit under profit maximisation as well as under routinised behaviour (Table 2). Furthermore, we see that a situation of more wolves and more predation yields a lower social surplus when the harvest is steered by profit maximisation both with full compensation and without compensation (cf. Result 3). As explained in Section 7, the reason for this outcome without compensation is that the baseline traffic damage cost is assumed to be quite modest. The social surplus becomes lower under routinised behaviour as well with more wolves. It is also evident that the compensation induces a larger discrepancy between the preferred stock of the landowner under profit maximisation and the social planner solution but is unaffected under routinised behaviour (Result 4). At the same time, the steady state social surplus reduces when compensation is included under profit maximisation. This illustrates the double social loss through higher traffic damage costs together with higher compensation costs (Result 5). A similar picture emerges under the other two predation scenarios with

Table 2. Profit maximisation and routinised behaviour with and without compensation (steady state)

Predation pressure	Profit maximisation with full compensation. Without compensation in brackets				Routinised behaviour with full compensation. Without compensation in brackets			
	Moose stock size X^* (# of moose)	Moose harvest h^* (# of moose)	Predation loss (# of moose)	Profit π^* (1,000 NOK)	Moose stock size X^{**} (# of moose)	Moose harvest h^{**} (# of moose)	Predation loss (# of moose)	Profit π^{**} (1,000 NOK)
Baseline predation, $\psi W = 0.05$	1,952 (1,708)	391 (385)	98 (85)	3,817 (2,920)	979 (979)	294 (294)	49 (49)	2,868 (2,388)
Zero predation, $\psi W = 0$	1,952	489	0	3,817	1,468	440	0	3,582
High predation, $\psi W = 0.10$	1,952 (1,463)	294 (293)	195 (146)	3,817 (2,143)	489 (489)	147 (147)	49 (49)	1,673 (1,194)

Baseline parameter values, and high and zero predation pressure.

Table 3. Social planner solution, and social surplus landowner solutions (steady state)

	Social planner solution				Social surplus landowner management (1,000 NOK)	
Predation pressure	Moose stock size X^s (# of moose)	Moose harvest h^s (# of moose)	Predation (# of moose)	Social surplus S^s (1,000 NOK)	Profit maximisation with full compensation S^*. Without compensation in brackets	Landowner routinised behaviour with full compensation S^{**}. Without compensation in brackets
Baseline predation, $\psi W = 0.05$	859	268	43	739	−458 (17)	724 (724)
Zero predation, $\psi W = 0$	1,103	372	0	1,219	498 (498)	1,086 (1,086)
High predation, $\psi W = 0.10$	614	176	61	378	−1,416 (−344)	362 (362)

Baseline parameter values, and high and low predation pressure.

profit maximisation, while the steady state social loss is unaffected by compensation when moose management is under private control with routinised behaviour.

Table 4 reports some sensitivity results under full compensation, where row two indicates the profitability effects of a substantially higher traffic damage cost, and where 4500 (NOK/moose) replaces the baseline value of 1800. As discussed above, this is not an unrealistic assumption for damage cost in certain areas. The social surplus becomes significantly negative when the management is directed by landowner profit maximisation and even more so with higher predation pressure (cf. Result 3). In this case, the social planner solution indicates depletion of the moose stock. Next, we find that the landowner profit becomes significantly lower under both profit maximisation and routinised behaviour when the browsing damage cost shifts up. The social surplus is reduced as well. However, the profit shifts upwards under routinised behaviour when the predation pressure increases (Result 2), and the social surplus becomes less negative. Finally, we examined the profitability effects of a higher discount rent. The most interesting outcome here is that the steady state social surplus increases compared to the baseline situation when management is steered by landowner profit maximisation. The reason is that the traffic damage cost is reduced; the higher discount rent motivates the landowner to keep a smaller steady state moose stock.

8. An extended social planner model

As mentioned in Section 2, the wolf population as well as the other big carnivores are strictly controlled by the wildlife authorities in Norway in order to keep the various public conflicts associated with the population at an acceptable level. The costs and benefits of controlling the wolf population have therefore not been included in the above social planner model. However, it may be interesting to study a more complete model where wolf harvest and the feedback effect from the moose population to the wolf population (numerical response) are included. The intrinsic value of the wolves should then also be included. The present practice of the government controlling the wolf population in Norway is quite costly (see, e.g. Stortingsmelding, 2015). For illustration purposes, we consider a situation where the wolf offtake has a positive value through a potential market for hunting licences. For simplicity, it is assumed that the price per licence is fixed.

The wolf growth equation is first written as:

$$dW/dt = H(W) + R\,(X, W) - f, \tag{8}$$

with $H(W)$ as the natural growth function in the absence of moose, also assumed to be of the logistic type. $R(W, X) > 0$ is the numerical response growth term, assumed to increase in both populations, $R_X > 0$ and $R_W > 0$, and f is the control, or offtake, of the wolf population. When including the same moose cost and benefit components as above (Section 6), and in addition

Table 4. Sensitivity analysis full compensation (steady state). Baseline predation $\psi W = 0.05$. High predation $\psi W = 0.10$ in brackets

Partial parameter changes	Landowner profit maximisation		Landowner routinised behaviour		Social planner solution
	Landowner profit π^* (1,000 NOK)	Social surplus S^* (1,000 NOK)	Landowner profit π^{**} (1,000 NOK)	Social surplus S^{**} (1,000 NOK)	Social surplus S^s (1,000 NOK)
Baseline parameter values	3,817 (3,817)	−458 (−1,416)	2,868 (1,674)	724 (362)	739 (377)
Increased traffic damage cost, $a = 4500$(NOK/moose)	3,817 (3,817)	−5,925 (−6,882)	2,868 (1,674)	−2,016 (−1,008)	0[a] (0)[a]
Increased browsing damage cost, $d = 3000$ (NOK/moose)	496 (496)	−1,045 (−1,391)	421 (450)	−1,772 (−861)	0 (0)
Increased discount rent, $\delta = 0.05$ (5%)	3,757 (3,757)	17 (−819)	2,868 (1,674)	724 (362)	679 (318)

[a]Indicates depletion of the moose stock.

the wolf intrinsic value $U(W)$, with $U' > 0$ and $U'' \leq 0$, and a positive hunting value, where hunting licences are sold at the fixed market price $m > 0$, the current net social benefit of the combined moose—wolf population is defined by:

$$S = ph - D(X) - A(X) + mf + U(W). \tag{9}$$

With the social planner problem now stated as maximizing the present value net benefit $\int_0^\infty [ph - D(X) - A(X) + mf + U(W)]e^{-\delta t} dt$ s.t. the biological growth equations (1) and (8), we find the golden-rule (steady state) conditions as (see Appendix for details):

$$F'(X) - G_X(W,X) + \frac{m}{p} R_X(W,X) - Q'(X) - \frac{D'(X) + A'(X)}{p} = \delta \tag{10}$$

and

$$H'(W) + R_W(W,X) - \frac{pG_W(W,X)}{m} + \frac{U'(W)}{m} = \delta. \tag{11}$$

These two equations jointly determine X^S and W^S. The only difference between the new moose optimality condition in equation (10) and the previous one in equation (7), is the term $(m/p)R_X(W,X)$ included in the extended model. This term works partially in the direction of a larger moose population. Equation (11) is the optimality condition for the wolf population, and states, just as the moose population equation, that the internal rate of return should equalise the external rate of return δ. The optimised size of the wolf population may be either below or above that of W_{msy}. The steady state will be unique when the sufficiency conditions are satisfied (see Appendix).

As indicated, a logistic function is assumed to describe the natural growth of the wolf population in the absence of moose, $H(X) = sW(1 - W/L)$, and where s is the intrinsic growth rate and L denotes the carrying capacity. The Lotka–Volterra numerical response function reads $R(X,W) = \theta XW$, where θ indicates the strength of the feed-back term. In addition, the wolf intrinsic value function is (somewhat unrealistic) assumed to be linear, $U(W) = uW$. With these additional specifications, equations (10) and (11) read $(r - 2rX/K) - \psi W + \frac{m}{p}\theta W - q - \frac{d+a}{p} = \delta$ and $(s - \frac{2sW}{L}) + \theta X - \frac{p}{m}\psi X + \frac{u}{m} = \delta$, respectively, which also may be written as:

$$X = (K/2r)\left[\left(\frac{m\theta}{p} - \psi\right)W + \left(r - q - \frac{(d+a)}{p} - \delta\right)\right] \tag{10'}$$

and

$$W = (L/2s)\left[\left(\theta - \frac{p\psi}{m}\right)X + \left(s + \frac{u}{m} - \delta\right)\right] \tag{11'}$$

These equations may slope either upwards or downwards in the $X - W$ space. They slope upwards when $(m\theta/p - \psi) > 0$, or $m/p > \psi/\theta$

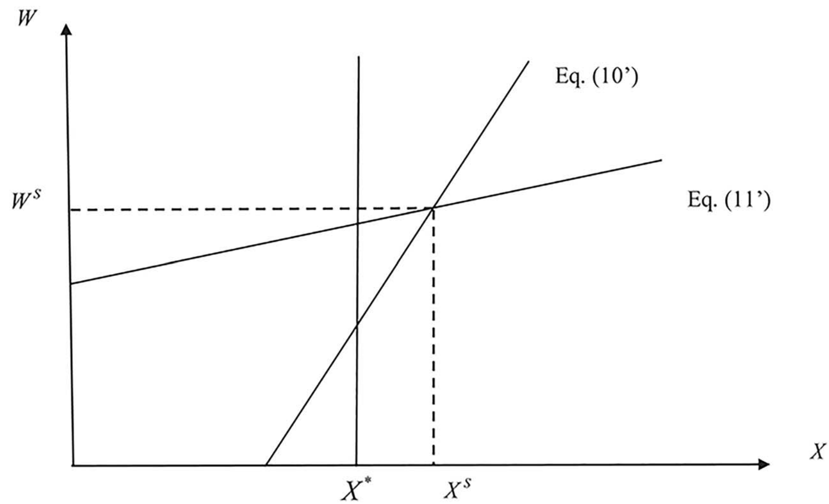

Fig. 3. Steady state extended social planner model. Profit maximisation solution equation (3) with full compensation.

holds. This condition thus indicates that the wolf–moose harvesting price ratio exceeds the prey–predator intensity ratio. This condition can also be stated as $m\theta WX > p\psi WX$, indicating that the wolf predation value gain exceeds the moose predation value loss (see also Hannesson, 1983 studying a predator–prey fishery model). Furthermore, in this case, equation (10') will be more positively sloped than equation (11) due to the sufficiency conditions (see Appendix). In the opposite situation with $(m\theta/p - \psi) < 0$, both equations slope downwards. The solution is illustrated with upward sloping equations in Figure 3. It is observed that equation (10') intersects with the X-axis for $X = (K/2r)(r - q - (d + a)/p - \delta)$.

We can now compare the solution of this extended model to that of the previous landowner problems. Because nothing definite can be said with regard to the routinised behaviour solution, we only compare with the optimised problem. With full compensation, the optimised steady state stock defined by equation (3) reads as $X^* = (K/2r)[r - d/p - q - \delta]$ with the specific functional forms. Accordingly, X^* will be located to the right-hand side of the intersection point of equation (10') with the X-axis, and where the difference is determined by the size of the traffic damage cost component. We may therefore find that $X^S > X^*$ if the traffic damage cost is "small". This case is illustrated in Figure 3. We can now state this as:

Result 6: *In a situation where the wolf predation value gain exceeds the moose predation value loss combined with low traffic damage costs, it may be beneficial to keep a higher moose stock from a social point of view than from the landowner perspective.*

If $X^S > X^*$ holds with full compensation it will also hold for partial compensation and no compensation at all as $\partial X^*/\partial z > 0$. Notice that Result

6 is for the above considered case of $(m\theta/p - \psi) < 0$, and not for when the moose predation value loss exceeds the wolf predation value gain. Notice also that this result holds when the hunting represents a value, and not a cost.

9. Concluding observations

We have analysed a reduced form moose–wolf ecological model, where the size of the wolf population affects the moose population growth, but not *vice versa*. In the Norwegian institutional setting where the value of hunting moose belongs to landowners and a system is in place of a hunting licence per animal shot, we use this model to analyse moose management under two assumptions: landowner profit maximisation versus routinised harvesting behaviour. The hunting value minus the browsing damage costs comprises the landowner profit. When the landowner is compensated for the predation loss through an *ex post* compensation scheme for moose killed by wolves (which has been proposed in Norway), the profit-maximizing landowner is motivated to hold a higher moose stock than without compensation. Accordingly, the forest browsing damage cost increases, as does the number of moose killed by wolves, thus raising the compensation costs further. When the landowner is fully compensated, the landowner is motivated to keep the same moose stock as in the situation without predation. We find that full compensation of the landowner under routinised behaviour leads to an economic outcome of more aggressive predation that is ambiguous. Additionally, we consider the social planner solution, where the damage costs due to moose–vehicle and moose–train collisions are included. Because of the traffic nuisance, which is external to the landowner, it is always beneficial for the social planner to keep a smaller moose stock compared to the situation where the profit-maximizing landowner directs management. This is the case irrespective of the amount of predation. We also find that the social costs may increase significantly with increasing *ex post* compensation. The extended social planner model where the feed-back effect from the moose to the wolf (numerical response) is included, demonstrates that under certain conditions it may be beneficial to keep a higher moose stock from a social point of view than from the landowner perspective.

Our results are based on a deterministic biomass approach, and only steady state analysis is considered. As wolf predation on moose basically concerns calves and yearlings, more realistic would be a more detailed biological model that distinguishes the different stage categories of the moose population. Irrespective of these caveats, our analysis points unambiguously in the direction of some important policy implications. The first important policy implication is that the proposed scheme to compensate the landowner *ex post* for predation only would incur an additional social loss and hence should be rejected, i.e. $z = 0$. Therefore, if the wildlife authorities want to introduce compensation for moose killed by wolves to address distributional concerns, we recommend this to be of the *ex ante* type which has no effect on the harvesting behaviour of the landowner. The second important policy implication of our analysis is that the external traffic damage cost should be included in Norwegian moose management, for example through taxation correcting the hunting price. Under the assumption of profit maximisation, it will motivate the landowner to keep a smaller stock size. With a fixed tax τ per hunted moose, the current landowner profit reads $\pi = ph - D(X) - \tau h$ when omitting the compensation payment. The new landowner golden-rule condition $F'(X) - G_X(W, X) - Q'(X) - D'(X)/(p - \tau) = \delta$ then replaces equation (3) (with $z = 0$). When comparing with the social planner solution equation (7), it is straightforward to demonstrate that $\tau^S = pA'(X^S)/[D'(X^S) + A'(X^S)]$ will implement the steady state planner solution (the Pigou tax). When again using the linear cost functions, it reads $\tau^S = pa/(d + a)$. Hence, the optimal tax rate is increasing in both the hunting licence price and the traffic damage cost, and decreasing in the browsing damage cost parameter.

However, taxation correcting the hunting price for traffic damage has no effect following the logic of routinised behaviour. Hence, harvest control directly regulating the offtake through regional hunting quotas could potentially be a more realistic and effective regulation instrument for the wildlife authorities. In fact, Sweden has already introduced such quantity regulation primarily by establishing a management system through the identification of specific management areas at the local and regional level with a wide representation of stakeholders in order to balance the hunting income with the browsing and traffic costs (Sandström *et al.*, 2013).

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Appendix

The profit-maximizing landowner problem

The current-value Hamiltonian of the present-value landowner profit-maximizing problem stated in Section x is $H = ph - D(X) + zG(W,X) + \lambda[F(X) - G(W,X) - Q(X) - h]$ where $\lambda > 0$ is the moose shadow price ("the value of the moose in the forest"). The first-order conditions for the maximum are first the control condition $\partial H/\partial h = p - \lambda \gtreqless 0$ with:

$$h = \begin{cases} 0 & \\ h^* & \text{if} \\ h^{\max} & \end{cases} \begin{matrix} p < \lambda \\ p = \lambda \\ p > \lambda \end{matrix} . \tag{A1}$$

Therefore, we have bang–bang control, either through no harvesting at all, or harvesting at the maximum level, or singular control h^*, as is expected with an objective function that is linear in the control variable, and where the instantaneous hunting cannot exceed the maximum $h^{\max}$.

The adjoint equation, when $X > 0$, is given as:

$$d\lambda/dt = \delta\lambda - \partial H/\partial X = \delta\lambda + D' - zG_X - \lambda\left(F' - G_X - Q'\right), \tag{A2}$$

and indicates that the sum of the moose capital gain $d\lambda/dt$ and the net stock effect $\lambda(F' - G_X - Q') - D' + zG_X$ resulting from maintaining one unit of moose must be equal to the marginal benefit of harvesting and putting the proceeds in the "bank", $\delta\lambda$. As the Hamiltonian is linear in the control variable, the sufficient condition for this problem boils down to that the Hamiltonian should be concave in the stock variable X, i.e. the weak arrow sufficiency condition is satisfied. This requires $H_{XX} = -D'' + zG_{XX} + \lambda(F'' - G_{XX} - Q'') \leq 0$. With singular control $\lambda = p$, it also reads $pF'' \leq pQ'' + D'' + (p - z)G_{XX}$ and implies that, at the optimum, the marginal harvest benefit should decline more than that of the combined value of the marginal damage cost and the marginal reduced harvest loss due to predation and traffic loss when also taking the compensation into account.

In this paper, we are only concerned with studying the equilibrium, or steady state. Steady state is defined by $dX/dt = d\lambda/dt = 0$. Therefore, when assuming singular control and inserting this into equation (A2), we find the optimal steady state, or golden-rule condition, as stated in equation (3) in the main text.

An extended social planner model

The current-value Hamiltonian of the extended social planner problem formulated in Section 8 with a positive wolf harvesting value writes.

$H = ph - D(X) - A(X) + mf + U(W) + \lambda[F(X) - G(W,X) - Q(X) - h] + \mu[H(W) + R(W,X) - f]$, and where μ is the wolf shadow price. The first-order conditions for maximum include now the control conditions $\partial H/\partial h = p - \lambda \gtreqless 0$ and $\partial H/\partial f = p + \mu \gtreqless 0$ with:

$$h = \begin{cases} 0 & \text{if} \quad p < \lambda \\ h^S & \quad\quad p = \lambda \\ h^{\max} & \quad\quad p > \lambda \end{cases} \tag{A3}$$

and

$$f = \begin{cases} 0 & \text{if} \quad m < \mu \\ f^S & \quad\quad m = \mu \\ f^{\max} & \quad\quad m > \mu \end{cases}, \tag{A4}$$

respectively. The adjoint equations, when $X > 0$ and $W > 0$, are next given as:

$$d\lambda/dt = \delta\lambda - \partial H/\partial X = \delta\lambda + D' + A' - \lambda\left(F' - G_X - Q'\right) - \mu R_X \tag{A5}$$

and

$$d\mu/dt = \delta\mu - \partial H/\partial W = \delta\mu - U' + \lambda G_W - \mu\left(H' + R_W\right). \tag{A6}$$

It is well-known that the dynamics of the above system representing a “double singular” control, is complicated (see, e.g. Clark, 1990, Ch. 10 and Mesterton-Gibbons, 1996). However, to find the steady state, or golden rule, conditions are straightforward. With $d\lambda/dt = d\mu/dt = 0$, and assuming singular controls, $p = \lambda$ and $m = \mu$, equations (10) and (11) in the main text give the result.

As the Hamiltonian here is linear in both the control variable, the sufficient conditions for this problem are concavity of the Hamiltonian in both stock variables X and W (again, the weak Arrow sufficiency condition). This requires $H_{XX} = -D'' - A'' + \lambda(F'' - G_{XX} - Q'') + \mu R_{XX} \leq 0$ and $H_{WW} = U'' - \lambda G_{WW} + \mu(H'' + R_{WW}) \leq 0$. Additionally, it requires $(H_{XX}H_{WW} - {H_{XW}}^2) \geq 0$, where $H_{XW} = -\lambda G_{XW} + \mu R_{XW}$. With our specified functional forms and inserting for the shadow prices, these conditions boil down to $H_{XX} = -2rXp/K \leq 0$ and $H_{WW} = -2sWm/L \leq 0$. With $H_{XW} = (-p\psi + m\theta)$, it additionally demands $(H_{XX}H_{WW} - {H_{XW}}^2) = (2rXp/K)(2sWm/L) - (m\theta - p\psi)^2 > 0$. This last condition indicates that equation (10’) has a more positive or less negative slope than equation (11’).