

A cost-benefit analysis of moose harvesting in Scandinavia
A stage structured modelling approach

Jon Olaf Olaussen* and Anders Skonhøft**

*Trondheim Business School,
Jonsvannsveien 82,
N-7050 Trondheim, Norway

**Department of Economics
Norwegian University of Science and Technology
N-7491 Dragvoll-Trondheim, Norway

.....

(**) Corresponding author. E-mail: Anders.skonhøft@svt.ntnu.no, Fax: +47
73596954.

Abstract

A cost-benefit analysis of moose (*Alces alces*) harvesting in Scandinavia is presented within the framework of an age structured model with four categories of animals (calves, yearlings, adult females and adult males). The paper aims to demonstrate the economic content of such a wildlife model and how this content may change under shifting economic and ecological conditions. Two different harvesting regimes are explored: landowner profit maximization, where the combined benefit of harvesting value and browsing damage is taken into account, and overall management, where the cost and damages of moose-vehicle collisions are taken into account as well. An empirical analysis of the Norwegian moose stock indicates that the present stock level is far too high compared with the overall management scenario, and that the composition of the harvest could be improved.

Key words: moose hunting, cost-benefit analysis, stage model

JEL: Q28

1. Introduction

The aim of this paper is twofold: first, to demonstrate the economic content of an age structured wildlife population model; and second, to show how this economic content may change under different management scenarios. The wildlife considered is the moose (*Alces alces*) which is studied in a Scandinavian ecological and institutional context where the landowners obtain the harvesting value and bear the cost of the timber browsing damage, but do not pay for possible other damages. Two basic management schemes are analysed; landowner management and overall management where the costs of moose-vehicle collisions are taken into account as well.

Analysing structured wildlife harvesting models, i.e., models where the species are grouped in different classes according to age and sex, has a long tradition within biology. Caswell (2001) gives an in-depth overview; see also Getz and Haigh (1989). However, economic analysis plays a minor role in these works. Economic reasoning is taken into account in Skonhøft et al. (2002) who analysed various management strategies for a mountain ungulate living in a protected area and a hunting area. Four stages were included: females and males within and outside the protected area. Because of the complexity of this model due to the dispersal mechanism, however, it is difficult to understand the various economic mechanisms influencing harvesting and abundance. The present paper aims to analyse such economic mechanisms more explicitly where a four-stage model (calves, yearlings, adult females and adult males) is formulated. Ericsson et al. (2000) studied the Swedish moose harvest policy with respect to selective versus random harvest of the different stages. They showed that the selective harvest policy was economically beneficial compared to a random harvest regime. In their simulations, however, they only accounted for hunting profit. Wam and Hofstad (2007) also studied a stage structured moose model in a Scandinavian context. The land owner profit was maximized and the trade-off between meat value and timber browsing damage was considered. Such trade-off will also be analysed here, but, as indicated, traffic damage costs will be taken into account as well. These costs are quite high, and recent estimates indicate that they may be even higher than that of the moose meat value (see below). Another important difference compared to the Wam and Hofstad study is that our model, at least to some extent, is solved analytically. We are thus able to show more directly the driving forces behind the various harvesting scenarios. As in Wam and Hofstad (2007) the

model is illustrated numerically where the Norwegian moose stock is used as an example.

The paper is organized as follows. In the next section, moose hunting in Scandinavia is briefly described. In section three the population model is formulated while section four demonstrates what happens when the hunting is steered by the traditional landowner goal of maximizing meat value. The landowner exploitation is analyzed both with and without taking the browsing damage cost into account. In section five we study the optimal sex and age composition as well as the economic consequences when the harvest is steered by the overall manager, and where the traffic damage cost, in addition to the meat value and browsing damage cost, are taken into account. The meat value is all the time assumed to be given by a fixed meat price, and the unit costs related to forest damage and traffic accidents are assumed to be constant as well. Section six illustrates the models by numerical simulations using Norwegian aggregate data and where the various scenarios are compared with recent harvest and stock data. Section seven summarizes our findings.

2. Moose hunting in Scandinavia

The moose is the world's largest member of the deer family and is found in the northern forests of North America, Europe and Russia. It is by far the most important game species in Scandinavia, and in Norway and Sweden about 35,000 and 100,000 animals, respectively, are shot every year. The value of this harvest is substantial, and the meat counts for more than 2 per cent of the yearly meat consumption in these countries. The moose hunting, which takes place in September and October, is also an important cultural event in a large number of local communities. Moose hunting has traditionally been a local activity, and landowners receive the hunting value. The hunters have been the local people; the landowners and their families and friends, and the traditional management goal has been to maximize the meat value, possibly corrected for forest browsing damage, for stable populations (more details are provided in Skonhoft and Olausson (2005) and the references therein).

The moose stock and moose harvest in Scandinavia have increased substantially since the 1950-60's when about 4-7000 moose were shot annually in Norway while it counted about 10-30000 in Sweden (see Figure 1). The explanation for these increases

is twofold. First, selective harvesting of different stages of the moose population has increased the biomass production considerably. The main principle is to harvest more bulls, yearlings and calves and less of the productive female stage to increase the meat biomass produced. Second, changing the forestry practice from selective logging to clear cutting has increased the forage production and availability (Saether et al. 1992). Note especially the extreme increase in Sweden during the late seventies and early eighties when harvest of calves first was introduced (Ericsson et al. 2000). The rapid increase in the moose population was strengthened by the fact that (especially in Sweden) the hunters came short of harvesting the reproduction in the late seventies. This changed during the eighties and the decrease in the stock reflects that the hunters kept harvesting more than the reproduction for some years.

Figure 1 about here

Recently, more attention has been paid to the increased costs associated with the high density of moose. The estimates of the annual forest damage cost due to lost forest production in Sweden vary from 400 to 1050 million NOK annually (Skogforsk 2009)¹. Based on the relative moose densities in Norway and Sweden, these estimates indicate that the yearly forest damage cost in Norway may be in the range of NOK 160-400 million. However, the Norwegian forest is less productive and one calculation indicates significant lower damage cost (Solbraa 1998) while a more recent estimate indicates the yearly damage to be about 70 million NOK (Larsen 2007, see also Storaas et al. 2001). In addition, traffic accidents due to collisions with cars and trains are costly. On average, during the period 2002-2007, 1350 and 750 moose have been killed annually by car and train, respectively, in Norway. Based on Solstad (2007), the yearly total cost of moose collisions in Norway is about 200 million NOK. The number of car-moose incidents in Sweden is between 4500-5000 annually, and the associated cost is estimated to be about 500 million NOK (Ingemarson et al. 2007).

As mentioned, the traditional exploitations scheme has been steered by the aim of maximising the meat production. This is hereafter denoted the landowner regime LO

¹ 500 to 1300 million SEK = 410 to 1066 million NOK (exchange rate 0.82 May 09).

because the landowners receive the hunting value of the meat. Depending on the migration pattern, the landowners may or may not be concerned with the browsing damage which varies in different regions (see Skonhøft and Olausen 2005 for details). We therefore distinguish between two stylized situations; the first regime LO where landowners neglect any potential browsing damage, and the other regime LOF where landowners take forest damage into account, and analyse these two as separate cases. In addition, we compare these regimes with an overall management scheme OM, where both forest damages and traffic accident costs, in addition to the meat value benefit, are taken into account. Note that this last scenario represents an overall management in a restricted sense as other benefits and costs, like the moose existence value, are not taken into account.

3. Population model

The *Alces alces* is a large ungulate with mean slaughter body weight (about 55% of live weight) for adult moose in Scandinavia of about 170 kg for males and 150 kg for females. The non-harvest mortality rates are generally low due to lack of predators, and there is no evidence of density-dependent mortality. On the other hand, fecundity has proven to be affected by the female density while the number of males seems to be of negligible importance within the range of moose densities in Scandinavia. However, it may play a role if the sex composition is very skew (see, e.g., Nilsen et al. 2005 and the references therein for more details).

Just as in Lande et al. (2003) the population at time (year) t is structured in four stages; calves $X_{c,t}$ ($yr < 1$), yearlings $X_{y,t}$ ($1 \leq yr < 2$), adult females ($yr \geq 2$) $X_{f,t}$ and adult males ($yr \geq 2$) $X_{m,t}$ so that the total moose population is

$$X_t = X_{c,t} + X_{y,t} + X_{f,t} + X_{m,t}.$$

The population is measured in spring before calving.

All stages are generally harvested, and the hunting, as already indicated, occurs in September–October (see Figure 2). Natural mortality is assumed to take place during the winter, after the hunting season, as the natural mortality throughout summer and fall is small and negligible. The same natural mortality rate is imposed for males and females, and, as mentioned, the same sex ratio is assumed for the yearlings when they enter the adult stages.

Figure 2 about here

Neglecting any stochastic variations in biology and environment, and any dispersal in and out of the considered area, the number of calves (recruitment) is first governed by $X_{c,t} = r_t X_{f,t}$ with $r_t = r(X_{f,t}, X_{m,t})$ as the fertility rate (number of calves per female). The fertility rate generally depends on both female density (number of females) and male density. It decreases in the female density $\partial r / \partial X_{f,t} = r'_f < 0$, and may also be reduced when the number of males become low, $r'_m \geq 0$. In addition, we have $r(0, X_{m,t}) > 0$ when $X_{m,t} > 0$ and $r(X_{f,t}, 0) = 0$. Therefore, the recruitment function yields:

$$(1) \quad X_{c,t} = r(X_{f,t}, X_{m,t}) X_{f,t}.$$

The recruitment function may be a one-peaked value function in the female density, but intuitively $\partial X_{c,t} / \partial X_{f,t} = (r + r'_f X_{f,t}) > 0$ should hold in an optimal harvesting programme, at least when females represent meat hunting value only. If not, less female hunting coincides with less recruitment which barely can represent an efficient harvest strategy (see also section four and six below).

The number of yearlings follows next as:

$$(2) \quad X_{y,t+1} = s_c (1 - h_{c,t}) X_{c,t}$$

where s_c is the fixed calf natural survival rate (fraction) and $0 \leq h_{c,t} < 1$ is the calf harvesting rate. Finally, the abundance of (adult) females and (adult) males become:

$$(3) \quad X_{f,t+1} = 0.5s_y (1 - h_{y,t}) X_{y,t} + s(1 - h_{f,t}) X_{f,t}$$

and

$$(4) \quad X_{m,t+1} = 0.5s_y (1 - h_{y,t}) X_{y,t} + s(1 - h_{m,t}) X_{m,t},$$

respectively, and where the same sex ratio is assumed for the yearlings when they enter the adult stages. s is the fixed natural survival rate, identical for females and males while s_y is the yearling survival rate. $0 \leq h_{y,t} < 1$, $h_{f,t}$ and $h_{m,t}$ are the harvesting rates of yearlings, females and males, respectively. While the calf and yearling harvesting rates must be less than one to omit stock depletion, the harvest rates of the adult females and males can in principle equalize one. However, if $h_{m,t} = 1$ and $h_{f,t} = 1$ we find that the adults in the long term will be individuals of age

two only. This may lead to evolutionary drift (Solberg et al. 2009 and references therein). For this reason, we restrict the adult harvest rates to be below one, i.e., $0 \leq h_{m,t} < 1$ and $0 \leq h_{f,t} < 1$.

The population model (1) – (4) has a recursive structure, and when combining (1) and (2) we find:

$$(5) \quad X_{y,t+1} = s_c(1 - h_{c,t})r(X_{f,t}, X_{m,t})X_{f,t}.$$

Therefore, equations (3) – (5) is a reduced form model in three stages and where all equations are first order difference equations. This form is used when studying the different exploitation schemes below. The system may, however, be reduced further when omitting the yearling population. When combining equations (5) and (3), the female population growth hence reads

$$X_{f,t+1} = 0.5s_y(1 - h_{y,t})s_c(1 - h_{c,t-1})r(X_{f,t-1}, X_{m,t-1})X_{f,t-1} + s(1 - h_{f,t})X_{f,t} \text{ while}$$

combining equations (5) and (4) yields the male population growth as

$$X_{m,t+1} = 0.5s_y(1 - h_{y,t})s_c(1 - h_{c,t-1})r(X_{f,t-1}, X_{m,t-1})X_{f,t-1} + s(1 - h_{m,t})X_{m,t}.$$

These two equations represent a system of two interconnected second order non-linear difference equations, and numerical analyses demonstrate that the equilibrium is unique and stable for fixed harvesting rates (see e.g., Gandolfo 2001 for a theoretical exposition).

Omitting the time subscript, the female equilibrium (when $X_f > 0$ and $X_m > 0$) reads:

$$(6) \quad 1 = 0.5s_y(1 - h_y)s_c(1 - h_c)r(X_f, X_m) + s(1 - h_f)$$

while

$$(7) \quad X_m = 0.5s_y(1 - h_y)s_c(1 - h_c)r(X_f, X_m)X_f + s(1 - h_m)X_m$$

represents the male population equilibrium. The female equilibrium condition (6) slopes upward in the $X_m - X_f$ plane, but becomes flat when of X_m is ‘large’ as the number of males then has a negligible fertility effect. Higher harvesting rates h_c , h_y and h_f shift it down. The male equilibrium equation (7) slopes upward as well, but will bend backwards for ‘large’ values of X_f when $(r + r' X_f)$ becomes negative

(see also above)². As indicated, it will be a unique biological equilibrium for fixed harvesting rates (see Figure 3). Higher harvesting rates h_c , h_y and h_m shift the male equilibrium condition inwards. Therefore, not surprisingly, more aggressive harvesting of all stages reduces the female as well as the male density. On the other hand, the yearlings abundance $X_y = s_c(1-h_c)r(X_f, X_m)X_f$ increases under higher harvesting pressure if the harvesting activity initially is modest and the intersection of the male and female equilibrium conditions takes place on the backward bending part of the male equilibrium schedule. The same will be so for the equilibrium calf population, $X_c = r(X_f, X_m)X_f$. On the contrary, if the intersection between the male and female equilibrium schedules takes place on the upward sloping part of the male schedule, increased harvesting activity reduces all stages of the population.

Figure 3 about here

When combining the above equilibrium equations (6) and (7), the male–female proportion may be written as $X_m / X_f = [1 - s(1 - h_f)] / [1 - s(1 - h_m)]$. Therefore, the yearling harvest (as well as the calf harvest) does not influence the equilibrium adult population proportion because the natural mortality of males and females is equal, and the same fraction of yearlings enters the female and male populations. It is also seen that sex-skewed adult harvesting rates translate directly into sex-skewed adult abundance. In an unexploited system, we have $X_m / X_f = 1$ together with equation (6) as $r(X_f, X_m) = (1 - s) / 0.5s_y s_c$.

4. Landowner exploitation

We first study the situation where the landowner, or the group of landowners acting as a single agent through a landowner association, maximises the meat value while taking the timber browsing damage cost into account. This is the LOF regime (section two above). Because natural mortality basically occurs during the winter, after the hunting season (see above), the number of animals removed in the different categories

² The slope of the female population equilibrium (6) is given by $dX_f / dX_m = -r'_m / r'_f$ while $dX_f / dX_m = [1 - s(1 - h_m) - 0.5s_y(1 - h_y)s_c(1 - h_c)X_f r'_m] / [0.5s_y(1 - h_y)s_c(1 - h_c)(r + r'_f X_f)]$ is for the male population equilibrium (7).

in year t are $H_{c,t} = h_{c,t}X_{c,t}$, $H_{y,t} = h_{y,t}X_{y,t}$, $H_{f,t} = h_{f,t}X_{f,t}$ and $H_{m,t} = h_{m,t}X_{m,t}$. In this regime, as well as in the LO regime where the browsing damage costs are neglected and the overall management regime OM, the current hunting value is accordingly:

$$(8) \quad Q_t = p(w_c h_{c,t} X_{c,t} + w_y h_{y,t} X_{y,t} + w_f h_{f,t} X_{f,t} + w_m h_{m,t} X_{m,t}).$$

$w_c < w_y < w_f < w_m$ are the (average) body slaughter weights (kilogram per animal) of the four stages and p (NOK per kilogram) the hunting price, assumed to be similar for all stages. The hunting price is supposed to be independent of the amount harvested and the stock sizes, and is fixed over time. When further assuming that the cost of the landowners of organizing this hunting is stock independent, the harvest price p is a 'net' price.

As already indicated, the forest browsing damage on pine trees occur during the winter when other food sources are restricted. The population sizes during the winter hence determine the browsing damage, and this is approximated by the population sizes after the hunting, but before natural mortality³. The damage costs are approximated by linear functions. The current browsing damage cost is hence given by:

$$(9) \quad D_t = d_c(1 - h_{c,t})X_{c,t} + d_y(1 - h_{y,t})X_{y,t} + d_f(1 - h_{f,t})X_{f,t} + d_m(1 - h_{m,t})X_{m,t}$$

and where $d_c < d_y < d_f = d_m$ are the per animal (NOK per animal) cost which differ among the stages as in Wam and Hofstad (2007). As no more cost and benefit components are included for the landowner, the current landowner profit is $(Q_t - D_t)$ in the LOF regime and simply Q_t in the LO regime. Henceforth, only the LOF maximization problem is analyzed as the LO is completely analogous with $D_t = 0$.

The present-value landowner profit is to be maximised subject to the above biological constraints. In addition to these constraints, a female - calf harvest restriction is included because the common hunting code of conduct is to never shoot an adult

³ The average stock sizes over the winter possibly describes the actual browsing damage better, but comes at the cost of considerable notational clutter without altering the qualitative aspect of the model. How to decide on this and, and similar questions, is an inherent problem of time discrete models.

female without also harvesting her calf (Wam and Hofstad 2007).⁴ This restriction is included simply as:

$$(10) \quad h_{f,t}X_{f,t} \leq h_{c,t}X_{c,t},$$

indicating that the harvest of the adult females never can exceed the calf harvesting.

This restriction must always hold in any harvest scheme. The problem is hence to

$$\max_{h_{c,t}, h_{y,t}, h_{f,t}, h_{m,t}} \sum_{t=0}^{t=\infty} \rho^t (Q_t - D_t) \text{ subject to the growth equations (3) – (5), and (10).}$$

$\rho = 1/(1 + \delta)$ is the discount factor with $\delta \geq 0$ as the (yearly) discount rate. The

Lagrangian of this problem may be written as

$$\begin{aligned} L = \sum_{t=0}^{\infty} \rho^t \left\{ \right. & p \left(w_c h_{c,t} r(X_{f,t}, X_{m,t}) X_{f,t} + w_y h_{y,t} X_{y,t} + w_f h_{f,t} X_{f,t} + w_m h_{m,t} X_{m,t} \right) \\ & - [d_c (1 - h_{c,t}) r(X_{f,t}, X_{m,t}) X_{f,t} + d_y (1 - h_{y,t}) X_{y,t} + d_f (1 - h_{f,t}) X_{f,t} + d_m (1 - h_{m,t}) X_{m,t}] \\ & - \rho \eta_{t+1} [X_{y,t+1} - s_c (1 - h_{c,t}) r(X_{f,t}, X_{m,t}) X_{f,t}] \\ & - \rho \lambda_{t+1} [X_{f,t+1} - 0.5 s_y (1 - h_{y,t}) X_{y,t} - s (1 - h_{f,t}) X_{f,t}] \\ & \left. - \rho \mu_{t+1} [X_{m,t+1} - 0.5 s_y (1 - h_{y,t}) X_{y,t} - s (1 - h_{m,t}) X_{m,t}] - \rho \omega_{t+1} [h_{f,t} X_{f,t} - h_{c,t} r(X_{f,t}, X_{m,t}) X_{f,t}] \right\} \end{aligned}$$

and where $\eta_t > 0$, $\lambda_t > 0$, $\mu_t > 0$ and $\omega \geq 0$ are the shadow prices of the yearling,

female and male populations, and the female – calf harvesting restriction,

respectively. Notice that the population equation shadow prices, in contrast to the

female – calf constraint shadow price, always will be strictly positive.

All the first-order control conditions of this maximizing problem are stated with the actual complementary slackness conditions and where the possibility for keeping each of the stages unexploited is considered while harvesting whole sub populations are not possible (section three above). These control conditions then read⁵:

$$(11) \quad \frac{\partial L}{\partial h_{c,t}} = r X_{f,t} (p w_c + d_c - \rho \eta_{t+1} s_c + \rho \omega_{t+1}) \leq 0 ; 0 \leq h_{c,t} < 1,$$

⁴ As mentioned, calving takes place early spring (May) while harvest takes place in the autumn (September - October). (See Figure 2). Since the calves are dependent on their mother the first winter, this female – calf harvest restriction is also implemented in several local harvest regulation plans (Solberg 2009, see also e.g. Glomfjord-Spildra Storvald 2009). Surprisingly, this important feature of the management practice is neglected in both Nilsen et. al. (2005) and Lande et al. (2001).

⁵ As the recruitment function may not be concave in the female abundance when the number of females becomes ‘large’, we have a potential non-convexity problem in our optimization. However, as already indicated (section three), such large female population can not represent an optimal harvesting policy. See also numerical section below.

$$(12) \quad \frac{\partial L}{\partial h_{y,t}} = X_{y,t}(pw_y + d_y - \rho\lambda_{t+1}0.5s_y - \rho\mu_{t+1}0.5s_y) \leq 0 ; 0 \leq h_{y,t} < 1,$$

$$(13) \quad \frac{\partial L}{\partial h_{f,t}} = X_{f,t}(pw_f + d_f - \rho\lambda_{t+1}s - \rho\omega_{t+1}) \leq 0 ; 0 \leq h_{f,t} < 1$$

and

$$(14) \quad \frac{\partial L}{\partial h_{m,t}} = X_{m,t}(pw_m + d_m - \rho\mu_{t+1}s) \leq 0 ; 0 \leq h_{m,t} < 1.$$

The state, or portfolio conditions, with $X_{y,t} > 0$, $X_{f,t} > 0$ and $X_{m,t} > 0$, are:

$$(15) \quad \frac{\partial L}{\partial X_{y,t}} = pw_y h_{y,t} - d_y(1-h_{y,t}) - \eta_t + \rho\lambda_{t+1}0.5s_y(1-h_{y,t}) + \rho\mu_{t+1}0.5s_y(1-h_{y,t}) = 0,$$

$$(16) \quad \frac{\partial L}{\partial X_{f,t}} = pw_c h_{c,t}(r + r'_f X_{f,t}) + pw_f h_{f,t} - d_f(1-h_{f,t}) + \rho\eta_{t+1}s_c(1-h_{c,t})(r + r'_f X_{f,t}) - \lambda_t \\ + \rho\lambda_{t+1}s(1-h_{f,t}) - \rho\omega_{t+1}[h_{f,t} - h_{c,t}(r + r'_f X_{f,t})] = 0$$

and

$$(17) \quad \frac{\partial L}{\partial X_{m,t}} = pw_c h_{c,t}r'_m X_{f,t} + pw_m h_{m,t} - d_m(1-h_{m,t}) + \rho\eta_{t+1}s_c(1-h_{c,t})r'_m X_{f,t} \\ - \mu_t + \rho\mu_{t+1}s(1-h_{m,t}) + \rho\omega_{t+1}h_{c,t}r'_m X_{f,t} = 0$$

Condition (11) says that calf harvest should take up to the point where marginal harvest income plus the benefit of reduced browsing damage is equal to, or below, the cost in term of reduced yearling growth evaluated at its shadow price while also taking the discount rent into account. The female - calf harvesting restriction shadow price is also included in this condition. When this condition holds as an inequality, the marginal benefit is below its marginal cost and harvesting of this stage is thus not profitable, $h_{c,t} = 0$. In a similar manner, condition (12) indicates that harvesting of the yearlings should take place up to the point where the marginal benefit is equal to, or below, the cost in terms of reduced population of males and females. The female condition (13) is simpler as reduced stock growth works only through its own stage. The shadow cost of the female - calf harvesting constraint is also included here, indicating this as an additional shadow cost. The male condition (14) is analogous to

the female harvesting condition. As mentioned (section three), it is assumed that $h_{m,t}$ is less than one as well. The portfolio conditions (15) – (17) steer the shadow price values. These conditions essentially state that the number of the different categories of animals should be maintained so that natural growth is equal the shadow price growth, adjusted for the discount factor.

These first order conditions together with the biological constraints comprise a complex dynamic system with eleven unknowns and eleven equations. It is therefore difficult, if not impossible, to assess the dynamics analytically. However, quite surprisingly, it is possible to draw some important conclusions about the harvesting composition. To do this, we assume as a starting point that the female - calf harvesting constraint is not binding, $\omega_l = 0$. Given this assumption, it is first supposed that yearling, female as well as male harvest take place; that is, $h_{y,t} > 0, h_{f,t} > 0$ and $h_{m,t} > 0$. All the control conditions (12) – (14) then holds as equations. Combining these equations (with positive stock sizes) yields

$pw_y + d_y = 0.5(s_y / s)(pw_f + d_f + pw_m + d_m)$ when the shadow prices are substituted away. As only parameters are included, this equation will then hold only by accident. Therefore, harvesting of all these three categories of animals can not represent an optimal solution when the female - calf harvesting constraint is not binding.

Suppose next that we still have adult male and yearling harvest while adult female harvest does not take place; that is, $h_{m,t} > 0, h_{y,t} > 0$ and $h_{f,t} = 0$. Combination of conditions (12) – (14) then yields $pw_y + d_y > 0.5(s_y / s)(pw_f + d_f + pw_m + d_m)$. Because adult and yearling survival rates s and s_y are more or less identical (Table 1, numerical section), the yearling weight is below that of the females, which again is below that of the males, $w_y < w_f < w_m$ and the marginal browsing damage of adults typically is above that of the yearlings, $d_y < d_f = d_m$ (Table 1), we find that the above inequality represents a contradiction.⁶ Note that the hunting price and the size of the

⁶ Note that the reasoning is strictly dependent on the structure of the parameter values. For example, for species where $s_y \ll s$ holds, harvest of males and yearlings without female harvest may be an optimal option.

browsing damage work in the same direction in this reasoning. Note also that there are the cost/price ratios that matter for the outcome, not the price nor the absolute (marginal) costs.

In a similar manner, still with $\omega_t = 0$, we find that zero male and positive female harvest together with positive yearling harvest contradict the optimality conditions for the given structure of the parameter values. The assumption of zero male and zero female harvest together with positive yearling harvest contradict the optimality conditions as well. We may therefore conclude that yearling harvest together with zero harvest of one, or both, of the adult categories are not possible options following the logic of the optimization under the assumption of constant harvest price and constant browsing damages for all categories of animals. On the other hand, we find that zero yearling harvest together with positive harvest of one, or both, of the adult categories do not contradict the optimality conditions.

Still under the assumption of an unbinding adult female - calf constraint (10), it is also possible to show that zero calf harvest will be optimal suggested that there is no yearling harvest. With zero yearling harvest $h_{y,t} = 0$, the yearling state condition (15) writes $\eta_t + d_y = \rho\lambda_{t+1}0.5s_y + \rho\mu_{t+1}0.5s_y$ while the yearling control condition (12) reads $pw_y + d_y < \rho\lambda_{t+1}0.5s_y + \rho\mu_{t+1}0.5s_y$. Combination of these two conditions yield $\eta_t > pw_y$. When using the calf control condition (11) with $\omega_t = 0$ under the assumption of positive calf harvest together with the above inequality, we find $(1/\rho s_c)(pw_c + d_c) > pw_y$. This inequality, however, implies a contradiction because of the substantial higher weight and hence more valuable harvest of the yearling than the calf category (again, see Table 1 numerical section). Suggested that there is no harvest of the yearling stage, it can not be beneficial to harvest the calf population either. Therefore, adult harvest only is optimal when the landowner aims to maximise meat value benefit while correcting for the timber browsing damage when the female - calf harvest constraint is not binding.

From this discussion we can conclude that the adult female - calf harvesting constraint must bind, and hence the same number of calf and female harvest, either zero or

positive, must be included in the optimal solution. This will be so during the transitional phase before steady state is reached as well as in the steady state. This constraint will certainly also influence the above reasoning about the various possibilities of yearling harvest together with adult female adult and male harvesting, and we may hence find that yearling and male harvest only can occur in the optimal solution. The intuition is straightforward as the harvest of females implies an extra cost in terms of reducing all other stages when the calf female restriction is binding as more calves are harvested than in the unrestricted case. This extra cost may turn the optimal harvest scheme in favour of male and yearling harvest. We may also find that male harvest together with calf and hence adult female harvest, without yearling harvest, can represent the optimal strategy.

It can also be shown that zero yearling harvest together with positive calf harvest no longer represents a contradiction. To see this, we again combine the yearling state condition (15) and the yearling control condition (12) and the calf control condition (11), now under the assumption of a binding female – calf harvest constraint. The result is now $(1/\rho s_c)(pw_c + d_c + \rho\omega_{t+1}) > pw_y$ which may hold due to the positive shadow price of the female – calf constraint. Therefore, suggested that we have male harvest which has the highest meat value as well as the highest browsing damage cost, we can have calf and female harvest together with zero yearling harvest. Depending on the cost and benefit differences among the different categories of animals, yearling harvest alone together with male harvest may also represent an optimal option. However, as the numerical results indicate, male harvest together with both yearling and calf (and female) harvest will not be included in the optimal harvest strategy. We have not been able to show that this is a general result, but sensitivity analyses indicate that it holds in the range of realistic parameter values.

In the LO regime where the browsing damage is neglected, we find the same optimality conditions as the above conditions (11) - (17), except that the marginal damage term is missing. Therefore, if the female – calf harvesting constraint is neglected, we will reach the same type of harvesting conclusions in this regime as in the LOF regime because, as already noted, the damage cost structure is of the same type as the marginal harvest benefit structure; that is, $d_c < d_y < d_f \leq d_m$ and

$w_c < w_y < w_f < w_m$. However, with the female-calf constraint binding, we may reach opposite conclusions than in the LOF regime due to, among others, that the value of the female – calf constraint shadow price changes when the damage cost components are not included. Indeed, this also happens (again, see numerical section).

5. Overall optimality

So far the harvest decision has been determined by the landowner, or the landowner association acting as a single agent, with and without taking browsing damage into account. However, to assess the social value of the moose harvest, more cost and benefit components should be included. As already mentioned, the single most important of these is the damage related to moose-vehicle and moose-railway collisions. These costs can be considerable (section two) and are not experienced by the landowners. A simple, yet realistic way to account for these damage costs is, just as for the browsing damage, to relate it to the population density, and where, *ceteris paribus*, a higher density means more damage. As most of the traffic incidents happen during the winter (see above), this cost component is also approximated by the population size after harvesting (but before natural mortality). Again, we assume the cost function to be linear; that is:

$$(18) \quad T_t = t_c(1 - h_{c,t})X_{c,t} + t_y(1 - h_{y,t})X_{y,t} + t_f(1 - h_{f,t})X_{f,t} + t_m(1 - h_{m,t})X_{m,t}$$

so that t_i is the per animal (NOK per animal) cost which, just as for the browsing damage cost, varies among the different stages. The current overall surplus hence reads $(Q_t - D_t - T_t)$.

The overall management problem (OM regime) is then to

$$\max_{h_{c,t}, h_{y,t}, h_{f,t}, h_{m,t}} \sum_{t=0}^{t=\infty} \rho^t (Q_t - D_t - T_t) , \text{ again subject to the above biological growth equations}$$

(3) – (5), together with the female – calf harvest constraint (10). It is easily recognized that the first order conditions of this problem will be just as above except that the additional traffic damage terms are included. The control conditions hence read:

$$(19) \quad \frac{\partial L}{\partial h_{c,t}} = rX_{f,t}(pw_c + d_c + t_c - \rho\eta_{t+1}s_c + \rho\omega_{t+1}) \leq 0 ; 0 \leq h_{c,t} < 1,$$

$$(20) \quad \frac{\partial L}{\partial h_{y,t}} = X_{y,t}(pw_y + d_y + t_y - \rho\lambda_{t+1}0.5s_y - \rho\mu_{t+1}0.5s_y) \leq 0 ; 0 \leq h_{y,t} < 1,$$

$$(21) \quad \frac{\partial L}{\partial h_{f,t}} = X_{f,t}(pw_f + d_f + t_f - \rho\lambda_{t+1}s - \rho\omega_{t+1}) \leq 0 ; 0 \leq h_{f,t} < 1$$

and

$$(22) \quad \frac{\partial L}{\partial h_{m,t}} = X_{m,t}(pw_m + d_m + t_m - \rho\mu_{t+1}s) \leq 0 ; 0 \leq h_{m,t} < 1.$$

As harvest reduces the traffic damage cost, just as it reduces the browsing damage cost, and because the marginal damage generally increases with the size of the animals so that $t_c < t_y < t_f \leq t_m$ (again, see numerical section), we find that the structure of the solution of this problem will be as above and hence the female – calf harvest restriction will still bind so that the same number of hunted calf and adult females, either positive or zero, will be included in the optimal solution. However, we may suspect that the harvest of the different stages and the harvest composition may change due to a shift in the female- calf harvest constraint shadow price. Moreover, we may also suspect that the harvest will be more aggressive now and the number of animals will be lower. This will be so because higher damage costs work exactly as a higher harvest price.

6. Numerical illustration

6.1 Data and specific functional forms

The exploitation will now be illustrated numerically. The fertility rate, decreasing in the number of females, is specified as a sigmoidal function with an increasing degree of density dependence at high densities (Nilsen et al. 2005). The function reads:

$$(23) \quad r_t = r(X_{f,t}, X_{m,t}) = \frac{\tilde{r}}{1 + (X_{f,t} / K)^b} (1 - e^{-aX_{m,t}})$$

with $\tilde{r} > 0$ as the intrinsic growth rate (maximum number of calves per female). The fertility rate shifts down with a smaller male – female population ratio and where $a > 0$ yields this composition ratio effect. $K > 0$ is the female stock level for which density-dependent fertility is equal to density-independent fertility. Thus, for a stock level above K , density-dependent factors dominate. This parameter scales the population sizes, and its value is contingent upon factors like the size of the area, the

biological productivity of the grazing and browsing resources, and so forth. The compensation parameter $b > 0$ indicates to what extent density-independent effects compensate for changes in the stock size.

Equation (23) implies a recruitment function

$X_{c,t} = r(X_{f,t}, X_{m,t})X_{f,t} = \tilde{r}(1 - e^{-aX_{m,t}})X_{f,t} / [1 + (X_{f,t} / K)^b]$ and is of the so-called Shepherd type. With $b > 1$, which is assumed, we have the Ricker version meaning that $\partial X_{c,t} / \partial X_{f,t} < 0$ for a high female density. However, as already indicated, $\partial X_{c,t} / \partial X_{f,t} > 0$ will hold in the optimal harvest programme and the recruitment function is then concave in the number of females⁷. Table 1 gives the baseline parameter values for this function as well as the economic parameter values. In the present exposition we want to mimic the management of the whole Norwegian moose population. The baseline value of the parameter K is scaled in this way and is assumed to be 80,000 animals. Notice also that it is assumed a zero discount rate. It is well known that the steady state of the dynamic optimization problem then coincides with the problem of maximizing the current animal benefit in biological equilibrium. Hence, the steady state results are similar with the results of the equilibrium harvest problem.

Table 1 about here

6.2 Results

We first present the basic dynamic harvesting results⁸. As already mentioned (section four) it is difficult, if not impossible, to say something analytically about the dynamics. However, due to the strong degree of linearity in the model together with density dependent regulating through the recruitment function, we may suspect the model to approach a stable equilibrium. This is confirmed by the numerical results

⁷ Differentiation yields $\partial X_{c,t} / \partial X_{f,t} = [K^b + (1-b)X_{f,t}^b](1 - e^{-aX_{m,t}}) / (K^b + X_{f,t}^b)^2$.

Moreover, we find $\partial^2 X_{c,t} / \partial X_{f,t}^2 = -v[(b+1)K^b + (1-b)X_{f,t}^b]$ where the coefficient v collects terms and is positive. It is easily recognized that $\partial X_{c,t} / \partial X_{f,t} \geq 0$ implies $\partial^2 X_{c,t} / \partial X_{f,t}^2 \leq 0$. For the given parameter values of b and K (Table 1), we find $\partial X_{c,t} / \partial X_{f,t} \geq 0$ when $X_{f,t} \leq 80,000$.

⁸ The dynamic optimization was performed with the Premium Solver, an extended version of the Solver tool bundled with Microsoft Excel.

where the dynamics have similarities with the Most Rapid Approach Path (MRAP), but with some degree of undershooting and overshooting depending on the initial situation, parameter values and management regime. Figure 4 shows the harvest rate dynamics with the baseline parameter values under the overall management scenario (OM). Under this management scheme and for these parameter values and initial values, assumed to be 30,000 for all categories of animals, there is no harvest of yearlings, but harvest of calves and females, together with males. As seen, the harvest rates seem to reach the equilibrium, or steady state, values quite fast.

Figure 4 about here

Tables 2 and 3 report the detailed steady state results under the baseline parameter value scenario for all management regimes. In addition, we have included recent harvest and stock data in Norway where the present total stock is about 160,000 and total harvest is about 36,000 individuals, indicated by the harvesting scheme denoted as Current (see also Figure 1). In the LO regime with meat value maximization only, the calf, yearling, female and male harvest rates become zero, 0.81, zero and 0.14, respectively. The low male harvest rate may seem surprising as this is the far most valuable animal category (cf. Table 1). The high yearling harvest is also surprising as it was demonstrated (section four) that it was not beneficial to harvest this category with an unbinding female- calf harvest constraint. However, with this constraint binding, it was seen that yearling harvest together with male harvest could possibly also represent the optimal strategy. Therefore, in this LO regime the yearling control condition (12) (without damage cost) holds as an equation, meaning that the yearling marginal harvest value equalizes the average survival adjusted shadow value of the adult female and male animals. The male control condition holds as an equation as well. On the other hand, the calf control condition (11) indicates that the calf harvest value is below that of the survival adjusted yearling shadow value minus the shadow value of the female – calf harvest constraint. Note that these results confirm that $\partial X_{c,t} / \partial X_{f,t} = (r + r'_f X_{f,t}) > 0$ holds, and hence the female population size is below the peak value of the recruitment function, i.e., 80,000 animals for the given parameter values (footnote 7). At the same time, this means that this steady state solution is located at the upward bending part of the male population equilibrium condition in the

above Figure 3. This will also hold in all regimes (see below). The harvest pattern in the LO regime means that the adult female population becomes far higher than the male population, and the adult population proportion X_m / X_f yields 0.28 (20,860/74,520). As shown above (section three), only the adult harvest influences this proportion. The annual meat value (Q) is about NOK 372 million (Table 3). Adjusted for browsing and traffic damage costs, the annual overall surplus (Q - D - T) reduces to about NOK 58 million in this LO scheme.

Tables 2 and 3 about here

In the LOF regime, the harvest, as suspected, becomes generally higher than under the LO scheme. Male harvest is now accompanied by female and calf harvest while the yearling population is unexploited. The calf, female and male harvest rate increases from zero to 0.26, from zero to 0.17 and from 0.14 to 0.80, respectively, while the yearling harvest rate decreases from 0.81 to zero. Hence, a substantial change in the harvest pattern takes place when the browsing damage cost is included. The adult population proportion X_m / X_f reduces moderately to 0.27 as a higher male harvest rate is accompanied by a higher female rate as well (again, see section three). Overall, the total stock decreases from 182,000 animals to 157,500, where the bulk of the reduction comes from the reduction in the yearling and female stock. The reduction in the yearling stock, even though there is no harvest of this category of animals, is due to the direct effect of increased calf harvest and the indirect effect of increased female harvest. The relatively small reduction of the total stock (13.5%) leads to an even smaller reduction in the harvest income; from about 372 to about 362 million (<3%). This may be explained by the fact that as more calves are harvested, the weight loss of harvesting calves instead of yearlings is more than compensated by the increase in male and female harvest. At the same time, as the composition of the stock is altered towards less males and females, the forests as well as the traffic damage cost are reduced. In the end, the overall surplus (Q - D - T) increases by about 85% (from about 58 to 107 million) when the browsing damage 'externality' is taken into account (cf. section two above). It is also interesting to note that by taking the forest browsing damage into account, the landowners, as a by-product, reduce the traffic

damage cost and thereby moves the solution substantially closer to the overall management solution.

Under the overall management scenario OM, the harvest rate of females (0.24), males (0.94) and calves (0.27) are higher than under any of the other regimes while the harvest rate of the yearling category still is zero. The yearling population is hence again dramatically reduced; now from about 41,000 individuals under the LO scheme to somewhat below 26,000 under OM. This reduction is again due to increased harvest of calves and females as explained above. Note that almost all adult males are harvested under the OM regime, and hence only those needed to secure recruitment are spared. However, note also that the male yearling entering the adult stage takes part in reproduction from the male side. This male harvest rate may seem extreme, but hinges crucially on the magnitude of the traffic damage costs. The other age classes are also reduced significantly, leaving the total stock at 126,400 animals. The hunting income is reduced to about NOK 322 million while the overall surplus is 130% higher than under the LO regime, and about 23% higher than in the LOF regime. Compared to the current management regime discussed below, the overall management would increase the overall surplus by about 30%; from about 101 million to 132 million NOK.

As indicated, Current reflects the present harvest pattern in Norway, and is based on the official hunting statistics (SSB 2009) together with the Table 1 cost and price assumptions. Here, all stages are harvested and the harvest rates of calves, yearlings, females and males are 0.19, 0.28, 0.13 and 0.60, respectively. This harvest scheme indicates that both the traffic damage cost (T), the browsing damage cost (D) as well as hunting income (Q) are somewhat between the LO and LOF results. Furthermore, it seems evident that the results are closer to the LOF than the LO regime and the overall surplus is less than 5% below the outcome of the LOF regime. These results demonstrate the harvest trade offs between the different stages as the composition of harvest between stages can be quite different. For example, as seen, here yearling harvest is zero under the LOF scheme and 0.28 under the Current management practice while the overall harvest and profit change just modestly.

We have also assessed how sensitive the results are to the cost assumptions. In the following, 10% increases in the baseline browsing and traffic damage cost parameters are considered while all other parameters are kept unchanged. Table 4 indicates that these changes have quite modest harvest as well as stock effects. For example, the 10% cost increase reduces the overall stock size under the OM scheme by less than 4% (from 126,400 to 122,200). However, the economic consequences are more severe as the overall surplus (Q-D-T) is reduced by about 14% (Table 5). This indicates that the profit function is substantially nonlinear. Obviously, the overall surplus difference between the LO and the OM regimes increases when the cost increases since the LO regime is based on maximizing hunting value only. The overall surplus difference between the OM and the LOF regime increases as well because the stock is adjusted only with respect to the browsing damage under the LOF scheme. On the other hand, as the economic performances of the management regimes are increasing in increasing costs, they are also decreasing with decreasing costs. In the extreme case, that is when both traffic and browsing costs are zero, the overall surplus will of course be identical under all schemes.

Tables 4 and 5 about here

7. Concluding remarks

The paper has analysed the cost and benefit of the Scandinavian moose population within a four stage model with density-dependent fertility and density independent mortality. Two basic exploitation schemes, landowner exploitation (LO and LOF) and overall management (OM), have been studied and it is demonstrated how changing harvest mortality of the different stages is accompanied by significant profitability changes while leaving total harvest more or less unchanged. The different ways to compose the harvest, e.g. in yearlings or females, and how the various management regimes induce different composition of the harvest are highlighted. We find that the female-calf harvest restriction, typically neglected in the existing literature on moose harvesting, will be binding. Therefore, the same number of calves as females should always be harvested in the optimal solution, irrespective of harvesting regime.

The numerical section illustrates the predictions from the theoretical model. In the hunting value only management scheme (LO-scenario), we find that zero calf and

female harvest and high yearling harvest are accompanied by a modest male harvest. We also find that under the overall management scenario (OM), no yearlings harvest is optimal while calves and females should be harvested. Moreover, the male stage is more aggressively harvested than the other stages in the LOF and OM regime, but not the LO regime since its influence on recruitment is small, even for small and modest stock levels.

Comparing the Current management regime of moose in Norway with the overall management (OM) regime studied here shows that the moose stock in Norway generally is far too high. The calculated yearly overall loss is about NOK 30 million. The most significant difference between the two solutions is that the OM management regime suggests that no yearlings should be harvested, while the harvest of yearlings in the Current management is substantial.

Therefore, from an overall perspective, this analysis indicates that the moose stock in Norway is too high causing too much browsing damage and traffic damage compared to the hunting value income obtained. The massive increase in the moose stock in Scandinavia since the seventies must be seen as a large scale ecological project to maximize the meat production from moose. From an economic point of view, maximizing meat production without taking forest and traffic damage costs into account seems strange. Thus, a harvest pattern of the different age classes that maximizes meat production is not in accordance with the economic optimal harvest pattern. As mentioned, our study is a restricted cost-benefit analysis in the sense that some values, such as non-use values and existence values are neglected. However, still we have added insight into the picture presented by Ericsson et al (2000) who showed that selective harvesting pays off compared to a random harvesting pattern. Both the stage-structured harvest pattern and the overall stock size should be balanced by the costs they bring along.

Literature

Caswell, H., 2001. *Matrix Population Models: Construction, analysis and interpretation* (2th. Ed.). Sinauer, Boston.

Ericsson, G., Bomann, M., and Mattsson, L., 2000. Selective versus Random Moose Harvesting: Does it pay to be a prudent predator? *Journal of Bioeconomics* 2, 117—132.

Gandolfo, G., 1996. *Economic Dynamics*. Springer, Berlin.

Getz, A., Haigh, R. G., 1989. *Population Harvesting*. Princeton University Press, Princeton.

Glomsfjord-Spildra Storvald, 2009. Bestandsplan for Glomsfjord-Spildra Storvald 2009-2011, ([http://www.meloy.kommune.no/nordland/meloy/k2post.nsf/viewAttachmentsMail/C1256D11002BF5F9C12575A7002B0657/\\$FILE/09009107.PDF](http://www.meloy.kommune.no/nordland/meloy/k2post.nsf/viewAttachmentsMail/C1256D11002BF5F9C12575A7002B0657/$FILE/09009107.PDF)).

Ingemarson, F., Claesson, S., and Thuresson, T., 2007. Älg- och rådjurstammarnas kostnader och värden. Skogstyrelsen Rapport 3 2007, Skogstyrelsens Forlag.

Lande, R., Engen S., and Sæther, B-E., 2003. *Stochastic Population Dynamics in Ecology and Conservation*. Oxford University Press.

Larsen, S. M., 2007. Forvaltning av elg; hosting, beiteskader og predasjon. Master thesis, Norwegian University of Science and technology.

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

Saether, B-E., Solbraa, K., Sødal, D. P., and Hjeljord, O., 1992. Sluttrapport Elg-Skog-Samfunn. Forskningsrapport nr. 28 NINA, Trondheim.

Skogforsk, 2009. Älgskadorna kostar en miljard per år, Press Release, (http://www.skogforsk.se/templates/sf_NewsPage.aspx?id=10501)

- Skonhoft, A., Yoccoz, N., and Stenseth, N.C. 2002. Management of chamois (*Rupicapra rupicapra*) moving between a protected core area and a hunting area. *Ecological Applications* 12, 1199--1211.
- Skonhoft, A., Olaussen, J.O., 2005. Managing a migratory species that is both a value and pest. *Land Economics* 81, 34--50.
- Solberg, E.J., Røed, K.H., Flagstad, Ø., Sæther, B.-E., Heim, M., Andersen, R., Rolandsen, C.M., 2009. The genetic structure of moose in Norway. NINA Report 467.
- Solberg, E. J., 2009. Personal communication, email 12.06.2009
- Solbraa, K., 1998. Elg og Skogbruk, biologi, økonomi, beite, taksering, forvaltning. Skogbrukets Kursinstitutt, Biri.
- Solstad, J.T., 2007. The distributional aspect of scarcity. Doctoral thesis NTNU 2007: 216.
- Storaas, T., Gundersen, H., Henriksen, H., and Andreassen, H., 2001. The economic value of moose in Norway. *Alces* 37, 34--50.
- SSB, Statistics Norway, 2009. Hunting Statistics, (http://www.ssb.no/jakt_fiske/).
- Svenska Jägerförbundet, 2009. Viltet. (<http://www.jagareforbundet.se/viltvetande/artpresentation/alghistorik.asp> and <http://www.jagareforbundet.se/Viltet/Viltovervakningen/Algavskjutning/>)
- Wam, H.K., Hofstad, O., 2007. Taking timber browsing damage into account: A density dependent matrix model for the optimal harvest of moose in Scandinavia. *Ecological Economics* 62, 45--55.

Figures and tables

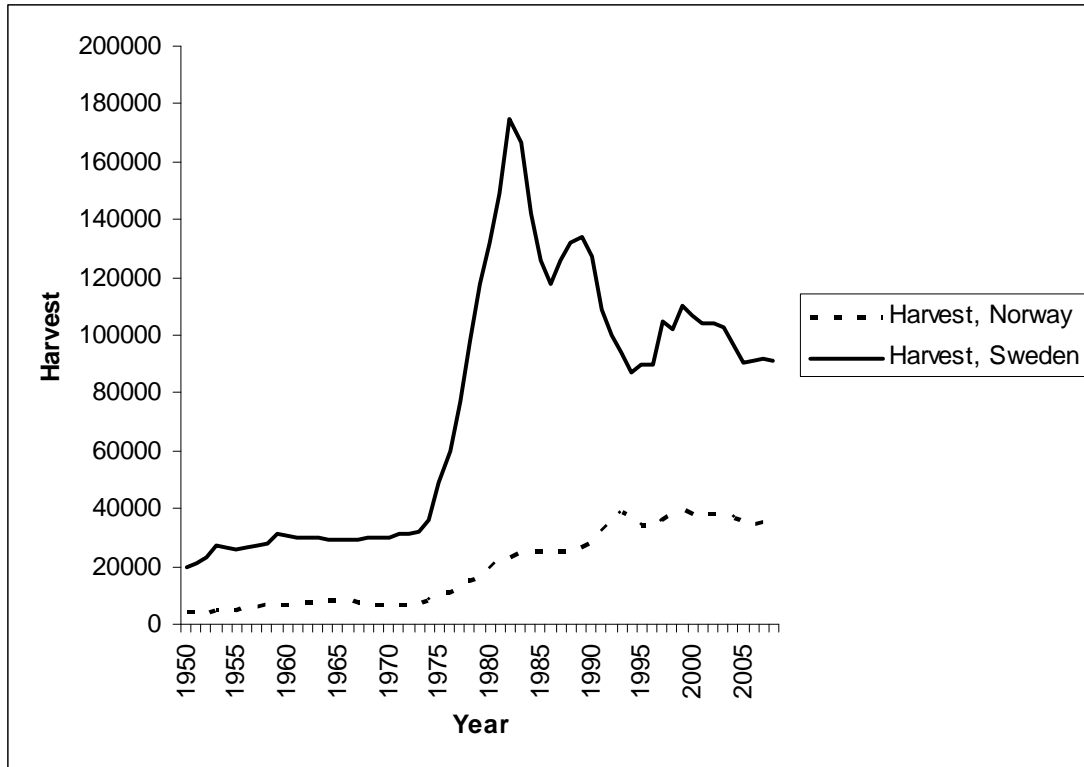


Figure 1: Number of hunted moose Norway and Sweden 1952-2008. Source: SSB, Statistics Norway (2009) and Svenska Jägerförbundet (2009).

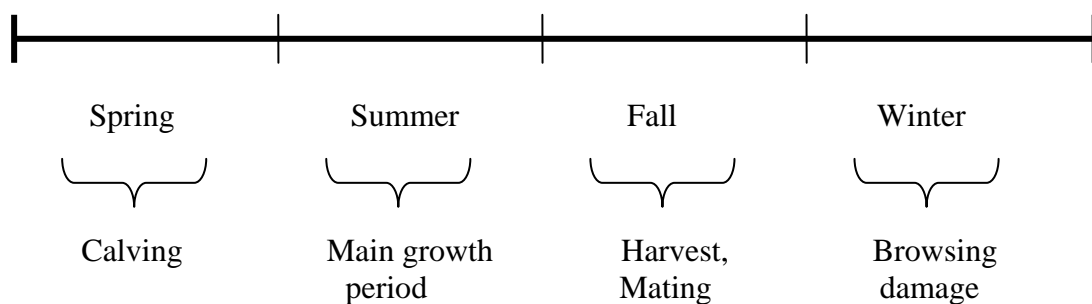


Figure 2: Seasonal pattern and course of major events Scandinavian moose.

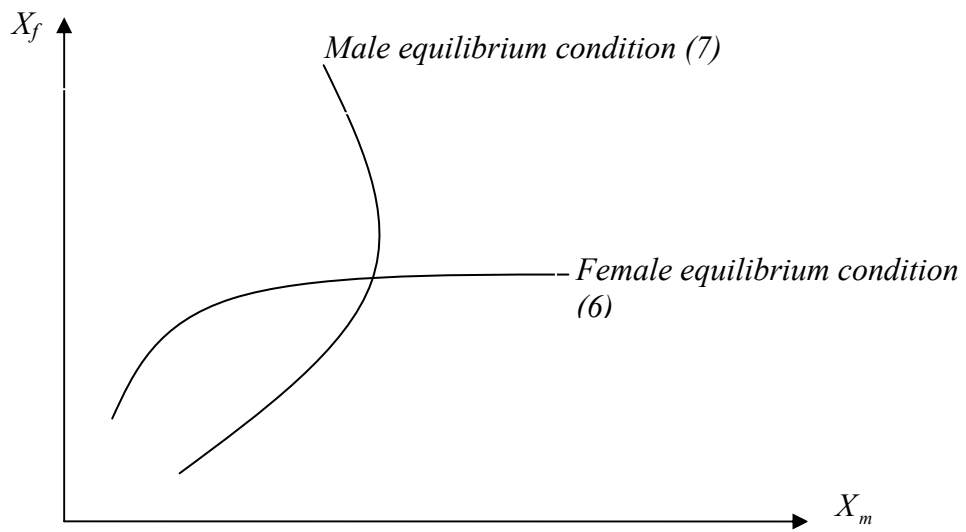


Figure 3: *Biological equilibrium male and female population stages. Fixed harvest rates.*

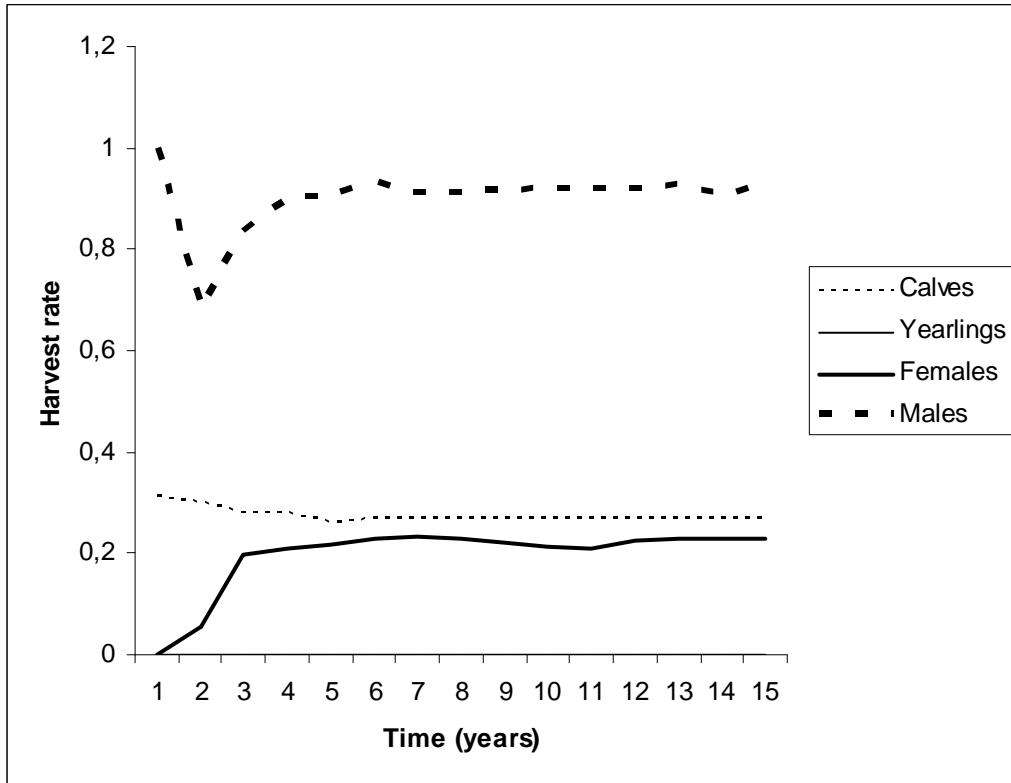


Figure 4: Harvest rates overall management scenario (OM). Baseline parameter values.

Table 1: Baseline biological and economic parameter values

Parameters	Description	Value	Reference/source
\tilde{r}	maximum specific growth rate	1.15	Nilsen et al. (2005),
K	female stock level where density dependent factors dominates density independent factors	80,000 animal	Calibrated
a	male density recruitment factor	0.00024	Calibrated
b	density compensation parameter	2	Nilsen et al. (2005)
w_c	average weight calve	65 kg/animal	SSB (2004)
w_y	average weight young	135 kg/animal	SSB (2004)
w_f	average weight females	150 kg/animal	SSB (2004)
w_m	average weight male	170 kg/animal	SSB (2004)
s_c	survival rate calves	0.90	Nilsen et al. (2005)
s_y	natural mortality young	0.95	Nilsen et al. (2005)
s	natural mortality female and male	0.95	Nilsen et al. (2005)
p	meat price	75 NOK/kg	Storaas et al. (2001)
d_c	marginal browsing damage, calf	250 NOK/calf	Larsen (2007)
d_y	marginal browsing cost, yearling	500 NOK/yearling	Larsen (2007)
d_f	marginal browsing cost, female	750 NOK/female	Larsen (2007)
d_m	marginal browsing cost, male	750 NOK/male	Larsen (2007)
t_c	marginal traffic cost, calf	800 NOK/calf	Solstad (2007)
t_y	marginal traffic cost, yearling	1,700NOK/yearling	Solstad (2007)
t_f	marginal traffic cost, female	1,900 NOK/female	Solstad (2007)
t_m	marginal traffic cost, male	2,100 NOK/male	Solstad (2007)
δ	discount rate	0	

Table 2: Steady state different management regimes, baseline parameter values. *LO* landowner exploitation, *LOF* landowner exploitation taking forest browsing damage into account and *OM* overall management taking both browsing costs and traffic damage costs into account. Current reflects actual harvesting data. X_c , number of calves, X_y , number of yearlings, X_f , number of adult females, X_m , number of adult males, X total number of animals, H_c number of calf harvest, H_y , number of yearling harvest, H_f number of female harvest, H_m number of male harvest and H total harvest. Corresponding harvest rates in brackets.

	X_c	X_y	X_f	X_m	X	H_c	H_y	H_f	H_m	H
LO	45,580	41,020	74,520	20,860	181,980	0 ($h_c=0$)	33,190 ($h_y=0.81$)	0 ($h_f=0$)	2,816 ($h_m=0.14$)	36,006
LOF	44,450	29,740	65,790	17,480	157,460	11,420 ($h_c=0.26$)	0 ($h_y=0$)	11,380 ($h_f=0.17$)	13,950 ($h_m=0.80$)	36,750
Current	44,510	32,620	65,660	17,960	160,750	8,279 ($h_c=0.19$)	9,166 ($h_y=0.28$)	8,273 ($h_f=0.13$)	10,780 ($h_m=0.60$)	36,498
OM	39,010	25,800	48,530	13,040	126,380	10,340 ($h_c=0.27$)	0 ($h_y=0$)	10,340 ($h_f=0.24$)	12,210 ($h_m=0.94$)	32,890

Table note: H_c differs slightly from H_f due to rounding errors.

Table 3: Steady state different management regimes, baseline parameter values. *LO* landowner exploitation, *LOF* landowner exploitation taking browsing damages into account and *OM* overall management taking both forest browsing and traffic damage costs into account. Current reflects actual harvesting data. *D* is total forest browsing damage cost, *T* is total traffic damage cost and *Q* is hunting value. All values in thousand NOK.

	<i>D</i>	<i>T</i>	<i>Q</i>	$(Q - D - T)$
LO	84,740	229,300	371,900	57,860
LOF	66,580	187,800	361,600	107,220
Current	69,210	193,000	363,600	101,390
OM	49,340	141,100	322,300	131,860

Table 4: Steady state different management regimes, 10% increase of traffic and damage costs compared to baseline parameter values. LO landowner exploitation, LOF landowner exploitation taking browsing damages into account, Current reflects actual harvesting data, OM overall management taking both browsing costs and traffic damage costs into account. X_c number of calves (in 1,000 animals), X_y number of young (in 1,000 animals), X_f number of females (in 1,000 animals), X_m number of males (in 1,000 animals), X is total number of moose, H_c harvest of calves (in 1,000 animals), H_y harvest of young (in 1,000 animals), H_f harvest of females (in 1,000 animals), H_m harvest of males (in 1,000 animals), H is total harvest (in 1,000 animals). Corresponding harvest rates in brackets.

	X_c	X_y	X_f	X_m	X	H_c	H_y	H_f	H_m	H
LO	45,580	41,020	74,520	20,860	181,980	0 ($h_c=0$)	33,190 ($h_y=0.81$)	0 ($h_f=0$)	2,816 ($h_m=0.14$)	36,006
LOF	44,310	29,630	65,010	17,250	156,200	11,390 ($h_c=0.26$)	0 ($h_y=0$)	11,380 ($h_f=0.18$)	13,900 ($h_m=0.81$)	36,670
Current	44,510	17,960	65,660	32,620	160,750	8,279 ($h_c=0.19$)	9,166 ($h_y=0.28$)	8,273 ($h_f=0.13$)	10,780 ($h_m=0.60$)	36,498
OM	38,000	25,110	46,430	12,610	122,140	10,120 ($h_c=0.27$)	0 ($h_y=0$)	10,110 ($h_f=0.22$)	11,890 ($h_m=0.94$)	32,120

Table note: H_c differs slightly from H_f due to rounding errors.

Table 5: Steady state different management regimes, 10% increase of traffic and damage costs compared to baseline parameter values. LO landowner exploitation, LOF landowner exploitation taking browsing damages into account, Current reflects actual harvesting data, OM overall management taking both browsing costs and traffic damage costs into account. D is total forest browsing damage costs, T is total traffic damage costs, Q is meat value, OS is overall surplus taking hunting income, traffic damage and browsing damage costs into account. All values in thousand NOK.

	D	T	Q	$(Q - D - T)$
LO	93,210	252,200	371,900	26,490
LOF	72,360	204,200	360,800	84,240
Current	76,130	212,300	363,600	75,170
OM	52,030	149,100	314,800	113,670