

**Balancing cost and income in red deer management –
a case study from Norway**

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Abstract

In this paper a cost-benefit analysis of a red deer population in a Norwegian institutional and ecological context is presented. The red deer population is structured in five categories of animals (calves, female and male yearlings, and adult females and adult males). This population is managed by a well-defined manager, typically consisting of many landowners operating in a cooperative manner, with the goal of maximizing the present-value hunting related income while taking browsing and grazing damages into account. The numerical analysis, represented by a case study from an area in the Western part of Norway, shows that while quite different ways to compose the harvest may produce more or less identical economic outcomes, the benefits per harvested animal may differ substantially.

1. Introduction

The management of deer have become in focus with recent large increases in population sizes in many areas of both Europe and North America (Gordon et al. 2004). Increased abundances increases potential yields. However, costs related to traffic incidents, damage to forestry and agriculture and concern for overgrazing and general ecosystem impact increases (Myserud 2006). Large herbivores are termed ecological keystone species because of their ability to affect vegetation community patterns and ecosystem functioning (Hobbs 1996, Côté et al. 2004). Deer management decisions concerning population development are therefore important issues that generally influence both ecological and economic aspects.

A good example of the above described development is the Norwegian red deer (*Cervus elaphus*) population, which has increased and spread substantially during the last few decades. The red deer has become the most numerous wild ungulate in Norway measured as number of harvested animals (Statistics Norway 2010). In 1970 the total number of harvested red deer was about 2,800, and animals were mainly found in scattered and low density populations along the south-western part of the country (Figure 1). In 2010, on the other hand, red deer are found in nearly all municipalities of southern Norway, and the total number of shot animals exceeded 39,000 animals (Figure 1). However, the main populations are still situated in the core western areas and more than 90 % of the red deer harvested are shot within five counties along the south-western coast. The national population increase is therefore mainly due to increased densities in these core areas.

Figures 1 about here (Maps 1970 and 2009)

Red deer are extensively utilized as a game species, and the management strategy in Norway has traditionally been related to meat hunting rather than trophy oriented (Milner et al. 2006). Large deer populations both represent a potential source of income for the landowners possessing the hunting rights, as well as a potential cost related to damages from grazing and browsing. The harvest-related incomes are typically associated to sale of meat and hunting rights, whereas additional services or products (cabin rental, guiding, etc.) generally represent a modest income source. The cost account is normally associated to a reduced production, in terms of quality or quantity loss, from harvested agricultural crops (mostly grass production). There might also be some browsing damage to economically important tree species, mainly

Norway spruce (*Picea abies*), but these are considered to be of less general importance relative to the agricultural damages (Thorvaldsen et al. 2010). There are clearly also costs related to traffic incidents (Mysterud 2004). Such costs are both complex to quantify (Bissonette et al. 2008) and paid by the general public and hence therefore external to the landowners.

The present paper aims to analyze the economy of the deer hunting where a five-stage model (calves, female and male yearlings, adult females and adult males) is formulated. All the time we have a landowner perspective. The meat value is assumed to be given by a fixed meat price, and the unit costs related to grazing damage are assumed to be constant as well. The landowner, typically consisting of more landowners acting as a single agent through a landowner association, is assumed to be rational and well-informed aiming to maximize profit, and hence the trade-off between meat value and grazing cost damage is considered. The main goal is to analyze the basic driving forces behind the harvesting composition in the various harvesting scenarios. We find that differences in meat value per animal together with the survival rates of the different categories of animals are instrumental in determining the optimal harvesting composition. The similarity with the results in the seminal Reed (1980) paper is apparent. In addition, we explicitly model a female-calf harvest restriction as the current code of conduct among hunters prevent that calves are left without their mother their first winter (section four), which is common in many countries (Mysterud 2011). A restriction on the male harvest is also included.

The paper is organized as follows. In the next section, deer hunting in Norway is briefly described. This section also includes a more detailed description of our study area, Flora and Gloppen, which are two municipalities in the county of Sogn and Fjordane, Norway (see map below). In section three the population model is formulated while the cost and benefit functions is formulated in section four. In section five the landowner exploitation is studied when the hunting is steered by the traditional landowner goal of maximizing meat value only. This section proceeds to analyze what happens with the optimal harvest and sex and age composition when the grazing and browsing damage are taken into account as well. Section seven illustrates the models by numerical simulations using data from the western part of Norway. Section eight summarizes our findings.

2. Red deer hunting in Norway

The red deer hunting in Norway is taking place in the fall, starting September 10th and ending November 15th (in some areas December 23rd). Hunting is most often practised either in rather dense forest or on open agricultural pastures during early morning, late evening or even during night if snow and moon light. Hunting on agricultural pastures is typically carried out by single hunters from stands or ground blinds. Hunting in forest during daytime is more often organized as drive hunts for a team of hunters, sometimes with the aid from a dog on leach or a barking dog. Some stalking occurs also in the forest habitat, especially during the rutting season when males are roaring (Meisingset 2008).

Decisions related to the management of red deer populations in Norway involve various levels of the management hierarchy. General hunting periods and regulations are decided by the Directorate for Nature Management. Within this framework, municipalities (local governments) are given authority to limit the hunting period and to regulate the “minimum area required” (the basis for quotas) to adapt policy to local management aims, population situation and current challenges. Each municipality is responsible of developing a management plan which acts as a framework for private management. Among other things, the municipality also has the responsibility for coordinating local management plans, deciding hunting quotas and licence fees, and reporting harvest result to Statistics Norway.

The hunting right belongs to the landowners. This means that landowners can benefit from hunting-related activities and products that relates to his or her property. Quotas are related to the total area of suitable red deer habitat within an area, and the municipalities define the “minimum area required” needed for each licence. The quota is typically found by dividing the total area of suitable red deer habitat within an area by the minimum area required. The minimum area required does not differ between red deer sex and age classes, but it typically differs between, or within, municipalities due to differences in red deer population density and levels of deer related conflicts. Quotas are thus regulated indirectly by adjusting the minimum area required per license. Since most properties are rather small, association of two or more landowners into cooperative management units is very common. This triggers allocation of more licences, simplifies the practical hunt and stimulates a more uniform management. Larger landowner cooperatives are requested to present multi-annual management plans (3-5 years duration) containing concrete management aims and a detailed harvest plan. These plans need to be approved by the municipality, and harmonized with overall municipal management aims. This system represents a more flexible and locally adapted management alternative

compared to the traditional alternative where the municipality enforce a more detailed and rigid practice.

As mentioned, our particular study area is from the county of Sogn and Fjordane located on the western coast of Norway. It consists of 26 municipalities, and has the overall highest red deer population in the Norway. Flora and Gloppen (approx. 61.5°N and 5.5°E) are two neighbouring municipalities with a common total area of 1721 km². Flora is a coastal municipality, whereas Gloppen is more of a fiord municipality located east of Flora (Figure 2). The topography along the coast is characterized by many islands and fiords with rolling country that change over to narrow valleys with steep slopes leading to higher mountains and mountain range. Small scale agriculture is widespread in the flatter lowlands, and the arable land is mainly cultivated to pastures and meadows for grass production. The forest is dominated by either Scots pine (*Pinus sylvestris*), alder (*Alnus incana*) or birch (*Betula* sp.), while planted Norway spruce (*Picea abies*) dominate locally. Common undergrowth species are juniper (*Juniperus communis*), bilberry (*Vaccinium myrtillus*), heather (*Calluna vulgaris*) and grasses and herbs.

Figure 2 about here

The climate is characterized by the coastal location with annual precipitation between 1100-3500 mm, mean winter (December-February) temperatures between 0-3°C and mean summer (June-August) temperatures between 11-14°C (The Norwegian Meteorological Institute). During winter number of days with snow cover normally increase and temperature decrease with altitude and distance from the coast.

3. Population model

The red deer is a large ungulate. In Norway mean dressed body weight (i.e., live weight minus skin, head, viscera, metapodials and bleedable blood) for males and females 2 years and older is usually between 60-125 kg and 50-70 kg, respectively (Solberg et al. 2010) (see also Table, numerical section). Due to lack of predators natural mortality rates are generally assumed to be low for all age categories (Loison and Langvatn 1998). Still, calf mortality are quite high during particularly harsh winters (Loison et al. 1999). The highest natural mortality rate is found for calves, followed by yearlings, whereas older males and females have the lowest

natural mortality rates (Table 1; Langvatn and Loison 1999). There is no evidence of density-dependent mortality (Loison et al. 1999). On the other hand, fecundity is affected by female density (Langvatn et al. 2004), while the number of males seems to be of negligible importance for a small and modest skewed sex composition (Myrsetrud et al. 2002). However, it may play a role when the male population becomes small accompanied by a highly skewed sex composition (Milner-Gulland et al. 2003).

In the present analysis, where the goal is to analyze some basic principles of red deer management, the population at time (year) t is structured in just five stages; calves

$X_{c,t}$ ($yr < 1$), female yearlings $X_{yf,t}$ ($1 \leq yr < 2$), male yearlings $X_{ym,t}$, adult females $X_{f,t}$ ($yr \geq 2$) and adult males $X_{m,t}$. The total population hence

reads $X_t = X_{c,t} + X_{yf,t} + X_{ym,t} + X_{f,t} + X_{m,t}$. The population is measured in spring before calving. All stages may be harvested. All natural mortality is assumed to take place during the winter, after the hunting season (September–December), as the natural mortality throughout summer and fall is regarded to be small.

Neglecting any stochastic variations in biology and environment, and any possible dispersal in and out of the considered area, the number of calves (recruitment) is first governed

by $X_{c,t} = r_{yf,t} X_{yf,t} + r_{f,t} X_{f,t}$ so that $r_{yf,t}$ is the fertility rate of the yearlings and $r_{f,t}$ is for the adults. As already mentioned, the male abundance and sex composition are of negligible importance if the number of males does not become extremely low. Therefore, in what follows, we assume that only the number of females, yearlings and adults, influence the fertility rates; that is, $r_{yf,t} = r_{yf}(X_{yf,t})$ with $r_{yf}(0) > 0$ and $\partial r_{yf} / \partial X_{yf,t} = r_{yf}' < 0$ for the yearlings. In a similar manner we have $r_{f,t} = r_f(X_{f,t})$ with $r_f(0) > 0$ and $r_f' < 0$ for the females.

The recruitment function then yields:

$$(1) \quad X_{c,t} = r_{yf}(X_{yf,t})X_{yf,t} + r_f(X_{f,t})X_{f,t}.$$

The number of female and male yearlings follows next as:

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

and

$$(3) \quad X_{ym,t+1} = (1 - \psi) s_c (1 - h_{c,t}) X_{c,t}$$

where s_c is the fixed calf natural survival rate (fraction) and ψ is the proportion of female calves. Usually, the proportion of female and male calves born are quite equal, i.e., $\psi \approx 0.5$. $0 \leq h_{c,t} \leq 1$ is the calf harvesting rate. Finally, the abundance of adult females and males become:

$$(4) \quad X_{f,t+1} = s_{yf}(1-h_{yf,t})X_{yf,t} + s_f(1-h_{f,t})X_{f,t}$$

and

$$(5) \quad X_{m,t+1} = s_{ym}(1-h_{ym,t})X_{ym,t} + s_m(1-h_{m,t})X_{m,t},$$

respectively. s_f is the fixed natural survival rate for adult females while s_m is for males, and where $s_f = s_m$ (see also section two above). s_{yf} and s_{ym} are the yearling survival rates, also with $s_{yf} > s_{ym}$. $0 \leq h_{yf,t} \leq 1$ and $0 \leq h_{ym,t} \leq 1$ are the harvesting rates of female and male yearlings, respectively, while $0 \leq h_{f,t} \leq 1$ and $0 \leq h_{m,t} \leq 1$ are the harvesting rates of the two adult stages. Note that it is possible to hunt all adult females in a given year and still get production of calves in the next year. There are two reasons for this. First, it is an inflow of females from the yearling class which becomes reproductive. Second, the yearling class is also reproductive.

The population model (1) - (5) has a recursive structure, and when inserting equation (1) into (2) we find:

$$(6) \quad X_{yf,t+1} = \psi s_c (1-h_{c,t}) [r_{yf}(X_{yf,t})X_{yf,t} + r_f(X_{f,t})X_{f,t}].$$

When further inserting equation (1) into (3), the number of male yearlings may be written as $X_{ym,t+1} = (1-\psi)s_c(1-h_{c,t})[r_{yf}(X_{yf,t})X_{yf,t} + r_f(X_{f,t})X_{f,t}]$ which combined with (6) yields:

$$(7) \quad X_{ym,t} = [(1-\psi)/\psi]X_{yf,t}.$$

Therefore, equations (4) – (6) and with (5) written as:

$$(5') \quad X_{m,t+1} = s_{ym}(1-h_{ym,t})[(1-\psi)/\psi]X_{yf,t} + s_m(1-h_{m,t})X_{m,t}$$

yields a reduced form model in three stages and five harvesting rates, and where all equations are first order difference equations. We employ this system of equations when studying exploitation below. When this system is included and solved through the optimization, the number of calves and male yearlings follow readily from equations (1) and (7), respectively. With $\psi = 0.5$ (see Table 1 numerical section), the number of female and male yearlings will all the time be similar.

In biological equilibrium it is possible to say something about adult sex ratio in our population model. Combing (4), (5^{*}) and (6) when $X_{i,t+1} = X_{i,t} = X_i$ ($i = c, yf, ym, f, m$) for fixed harvesting rates, gives this sex ratio as

$X_m / X_f = [(1-\psi) / \psi][(1-s_f(1-h_f))s_{ym}(1-h_{ym})] / [(1-s_m(1-h_m))s_{yf}(1-h_{yf})]$ after some straightforward manipulations. Therefore, harvest of all the different categories of yearlings and adults influence the adult equilibrium sex ratio. However, the calf harvest plays no role because there is no distinction between female and male calf harvest in our model. With unprofitable yearling harvest and $h_{ym} = h_{yf} = 0$, the adult sex ratio reduces to

$X_m / X_f = [(1-\psi) / \psi](1-s_f(1-h_f))s_{ym} / (1-s_m(1-h_m))s_{yf}$. For identical female and male yearling survival rates together with similar proportion of female and male calves entering the yearling stages, $\psi = 0.5$, we find $X_m / X_f = [(1-s_f(1-h_f))] / [(1-s_m(1-h_m))]$. Therefore, under these assumptions, sex-skewed adult harvesting rates directly translate into sex-skewed adult abundance. This last relationship may also be written as

$h_f = (1/s)(1-s)(X_m / X_f - 1) + (X_m / X_f)h_m$ where $s_m = s_f = s$ (Table 1). Therefore, in

biological equilibrium, or steady state, we find that a skewed sex ratio like, say,

$X_m / X_f = 0.5$, can be met with hunting rates in the ranges $(1-s) / s \leq h_m < 1$ together with

$0 \leq h_f < (s-0.5) / s$.

4. The landowner costs and benefits

The traditional landowner management goal has been directed towards maximising the population productivity in order to produce meat, but also with a strong recreational component (Milner et al. 2006). Typically, hunters have been local people, the landowners and their families and friends, and the hunting has had some flavour of subsistence hunting (Olaussen and Mysterud 2011). It has been a gradual shift towards more commercialization of the hunting during the last two decades. This is due both to higher red deer populations and of increased awareness of the economic potentials of red deer hunting and related products and activities (e.g., cabin renting and guiding; see, e.g., Skogeierforbundet 2005), but also due to easier access to the various hunting areas and increased income among people. This has caused increased introduction of non-local hunters and a higher willingness to pay among all hunters regardless of local belonging. Still, the most important motivation for hunting among the local people is the prospect for meat and recreation (Olaussen and Mysterud 2011), and

only this type of hunting is considered here (but see Naevdal et al. 2010 who analyzes moose trophy hunting). Therefore, we assume that the landowner, or a landowner association acting as a single agent, are hunting for meat where the meat value, but also the recreational value, are taken into account. Additionally, the grazing damage cost is included as well. We start to look at the hunting benefits.

Because natural mortality basically occurs during the winter after the hunting season (section two above), the number of animals removed in year t is defined as

$H_{i,t} = h_{i,t} X_{i,t}$ ($i = c, yf, ym, f, m$). The price per kg harvested meat \hat{p} is assumed to be independent of number of animals hunted, population density and animal category, as well as assumed to be fixed over time. The current gross meat hunting value is accordingly

$\hat{p}(w_c h_{c,t} X_{c,t} + w_{yf} h_{yf,t} X_{yf,t} + w_{ym} h_{ym,t} X_{ym,t} + w_f h_{f,t} X_{f,t} + w_m h_{m,t} X_{m,t})$ and where

$w_c < w_{yf} \leq w_{ym} < w_f < w_m$ are the (average) body dressed weights (kg per animal) of the different categories of animals (see also Table 1 numerical section). For every animal shot the landowner (or landowner association) pays a fixed fee q_i (NOK per animal) to the municipality which typically is smallest for the calves (see Table 2). Therefore, the yearly *net* landowner hunting meat value benefit is defined as:

$$(8) \quad V_t = p_c h_{c,t} X_{c,t} + p_{yf} h_{yf,t} X_{yf,t} + p_{ym} h_{ym,t} X_{ym,t} + p_f h_{f,t} X_{f,t} + p_m h_{m,t} X_{m,t},$$

and where $p_i = (\hat{p}w_i - q_i)$ ($i = c, yf, ym, f, m$) is the net per animal hunting value (NOK per animal).

In addition to the meat value, the hunters also obtain a recreational value related to the hunting. Studies from elk hunting in US (USWS 2003) reports net consumer surplus for resident elk hunters (total willingness to pay minus actual fees and costs) of about \$60 per day in Wyoming. Empirical studies from Sweden (Boman et al. 2010) also indicates that time spent on hunting is valuable. In what follows, only the hunting time is considered as an indicator for recreational value and hence all other valuable aspect of the hunting, except of the meat value, is lumped into this indicator. When using a production function approach and where the production (harvesting) function is assumed to be of the standard Schaefer type with perfect selectivity (e.g., Clark 1990), the number of hunted animals of category i can be written as $H_{i,t} = \theta_i N_{i,t} X_{i,t}$ ($i = c, yf, ym, f, m$). $N_{i,t}$ indicates the hunting effort, measured in

number of hunting days, and θ_i is the catchability (productivity) coefficient (1/hunting days)¹.

The catchability coefficient will typically differ somewhat between the various categories of animals, but probably not too much. In what follows, it is assumed to be similar. Therefore, with z as the recreational value (NOK per hunting day) assumed to be fixed and independent of the number of days hunted and category of animal hunted, the recreation value writes

$$B_t = z(N_{c,t} + N_{yf,t} + N_{ym,t} + N_{f,t} + N_{m,t}), \text{ or}$$

$$(9) \quad B_t = (z / \theta)(h_{c,t} + h_{yf,t} + h_{ym,t} + h_{f,t} + h_{m,t})$$

when substituting for the harvesting functions. The total yearly hunting benefit is hence described as $(V_t + B_t)$. Notice that formulation (9) implies that the sum of all the harvesting rates should be included in the assessment of the recreational value. This is due to the fact that we assume perfect harvesting selectivity.

Damage costs related to deer populations is a multidimensional and complex issue (see introductory section). As this study is considering landowner costs and benefits, only damages related to agriculture and forestry are taken into account. These damages depend generally on a number of factors such that the amount of agricultural land, type and value of crops, in addition to the size and composition of the red deer population. In our study area the most common agricultural product are grasses produced for winter fodder of cattle and sheep either dried or as ensilage. There is no production of grain in our study area. More vulnerable and economically valuable productions like fruit farming and commercial production of berries are often fenced in to avoid browsing damage.

As agricultural land and crop damage take place during the spring, summer and fall, and hence basically before the crop harvest, it is the population size *before* hunting that is relevant. When assuming separate damage functions for every category of animals, these cost functions may therefore be written as $D_i(X_{i,t})$ ($i = c, yf, ym, f, m$), and where no animals means zero damage and more animals more damage; that is, $D_i(0) = 0$ and $dD_i / dX_{i,t} = D_i' > 0$. Except for these two properties, we do not know very much about these damage cost functions (but see Wam and Hofstad 2007 for an assessment of forest damage costs). They may be concave or convex, or partly concave and convex. As a compromise, and for simplicity, linear

¹ If the male stock is, say, 6 animals and the number of hunted animals is 2 with an effort use of 10 hunting days, the male catchability coefficient equalizes 2/60 (1/hunting days).

functions are used, $D_i(X_{i,t}) = d_i X_{i,t}$. The damage will, as indicated, vary for the different categories of animals, and where the per animal damage of adult males typically is larger than that of the yearlings and calves (see Table 2) so that $d_c < d_{yf} \leq d_{ym} < d_f < d_m$ is the fixed per animal damage cost (NOK per animal). The agricultural damage costs are thus:

$$(10) \quad D_t = d_c X_{c,t} + d_{yf} X_{yf,t} + d_{my} X_{my,t} + d_f X_{f,t} + d_m X_{m,t}.$$

Therefore, the landowner yearly net benefit is described by:

$$(11) \quad R_t = V_t + B_t - D_t$$

5. Optimal management

5.1 Harvest value only included

We first study the situation where the landowner, or the landowner association, maximizes the harvest value only, comprising the sum of the meat and recreational value, $(V_t + B_t)$. The goal

is then to find harvesting rates that maximizes the present-value $\max_{h_{c,t}, h_{yf,t}, h_{my,t}, h_{f,t}, h_{m,t}} \sum_{t=0}^{t=\infty} \rho^t (V_t + B_t)$

subject to the biological growth equations (4), (5') and (6). $\rho = 1/(1 + \delta)$ is the discount factor with $\delta \geq 0$ as the (yearly) discount rate.

In addition to the above biological constraints, a female – calf harvest restriction is included because of the common hunting code of conduct is to never shoot an adult female without also harvesting her calf (Olaussen and Skonhøft 2011). Since red deer hardly ever get more than one calf per reproductive event, this restriction is included simply as:

$$(13) \quad h_{f,t} X_{f,t} \leq h_{c,t} X_{c,t}.$$

A restriction on the number of harvested adult males is also included to avoid a too skewed sex ratio. Such restriction may also in some cases be due to the common hunting code of conduct, but where the question of evolutionary trait changes also may be of importance (Mysterud and Bischof 2010). One way to include this restriction is simply to impose an upper limit on the male harvesting fraction:

$$(14) \quad h_{m,t} \leq \bar{h}_m.$$

This male harvesting restriction may be strengthened if we additionally also include a similar restriction on the male yearling hunting; that is:

$$(14') \quad h_{m,t} \leq \bar{h}_m \text{ and } h_{ym,t} \leq \bar{h}_m.$$

Yet another way to impose a restriction on male harvest is to demand that the adult male – female sex ratio should exceed a certain lower level. In other words, we may write:

$$(14'') \quad X_{m,t} / X_{f,t} \geq \bar{x} .$$

In the Appendix the first order necessary control conditions are stated. Particularly due to the inclusion of the hunter recreation value, we find that it is difficult to draw conclusions about the harvest composition based on these conditions. Without this value included it is, however, possible to say something about the basic driving forces steering the harvest composition. We now discuss these driving forces first by disregarding the code of conduct constraints (13) and (14) (or 14' or 14'').

We first find that yearling harvest together with female adult harvest at the same time is not a possible option. We also find that male yearling harvest together with male adult harvest at the same time neither is a possible option (see Appendix). Next, it can easily be shown that positive female yearling harvest together with zero adult female harvest implies

$p_{yf} / s_{yf} > p_f / s_f$; that is, the ‘biological discounted’ female yearling hunting value (in NOK per animal) exceeds the ‘biological discounted’ adult female hunting value. Because the adult category is more valuable than the yearling category, $p_f > p_{yf}$, and the survival rates s_{yf} and s_y do not differ too much (Tables 1 and 2, numerical section), this inequality represents a contradiction. In the same manner, we also find that positive male yearling harvest together with zero adult male harvest implies $p_{ym} / s_{ym} > p_m / s_m$ which also represent a contradiction for reasonable parameter values. Therefore, positive female yearling harvest and zero female adult harvesting and positive male yearling harvest and zero adult male harvesting are not a possible option when the code of conduct constraints (13) and (14) are not binding and when the harvest recreation value is small and negligible.

These results show that the marginal harvesting values (in NOK per animal) and the survival rates (‘biological discount’ rates) are instrumental in determining the optimal harvest composition (see also Olaussen and Skonhøft 2011 and Reed 1980). Since, the ‘biological discounted’ value for the calf category is lower than for the yearlings, $p_c / s_c < p_i / s_i$ ($i = yf, ym$) (see Tables 1 and 2), we may also suspect that calf harvest together with zero adult harvest will not represent an optimal harvesting policy when the code of conduct

constraint (13) is not binding. It is not possible to prove this by only using the first order necessary control conditions, but numerical solutions demonstrate that this will be the case.

On the other hand, when the female – calf constraint (13) and the male harvesting constraint (14) (or 14' or 14'') still do not bind and when the harvest recreation value is small, we find that zero yearling harvest together with positive harvest of one, or both, of the adult categories do not contradict the optimality conditions. The reason for this outcome, in line with the above reasoning, is simply that the per animal values are higher for the adults than the yearling category while the survival rates do not differ too much. However, based on the above optimality conditions it is difficult to say something definitely about the harvest composition among the adults. There are two obvious effects involved here. First, a direct economic effect working through the relative hunting valuation of females and males, and where males are more valuable due to a higher net per animal hunting value. Secondly, only the females contribute to reproduction (under our assumption of a not too skewed sex ratio). Both these effects pull in the direction of a more aggressive male than female hunting.

However, if both adult females and males are harvested in the unbinding case, this result may change when the restrictions (13) and (14) (or 14' or 14'') are included. First suppose that restriction (13) is included, while we still neglect restriction (14) and the hunter recreation value. If females are harvested, the code of conduct restriction (13) indicates that at least the same number of calves must be harvested. Since the restriction is unbinding if more calves than females are harvested, we already know from the unbinding case that no calves should be harvested. Therefore, harvesting more calves than females represents a contradiction both in the unbinding as well as the binding case. Hence, the only remaining case to be considered is the case when the restriction binds; that is, the number of calves and females harvested are similar, or zero.

When constraint (13) binds, it will certainly also influence the various possibilities of yearling harvest together with adult female and male harvest. We may hence find that yearling harvest together with male harvest occurs in the optimal solution. When condition (14) binds and $h_{m,t} = \bar{h}_m$, this will generally also influence the various optimal harvest options. Less adult male harvest may spill over to male yearling harvest, but possible also female yearling harvest. When also including the harvest recreation value, we find that the picture will be even more

complicated. The reason for this is that the population sizes will be included also in the first order control conditions (see Appendix). This inclusion of the population sizes may be of particular importance if the recreation value is significant; that is, the value per hunting day z is ‘high’. Summing up, we have demonstrated that differences in the ‘biological discounted’ value of various animal categories are the basic driving forces behind the optimal harvest composition, but that certain modifying forces related to common code of conduct constraints as well as the harvesting recreation value are present.

5.2. Grazing damage taken into account

We then look at the problem when also the grazing damage costs are taken into account. This cost component is often neglected in real life management situations. One important reason for this is that it may arise a mismatch between hunting values and damage costs for the various landowners because of the migration pattern of the animals (see Skonhøft and Olausen 2005). When taking the damage costs into account, the current net benefit is defined by equation (11). Therefore, the problem now is to find the harvesting strategy that

$$\max_{h_{c,t}, h_{y,t}, h_{f,t}, h_{m,t}} \sum_{t=0}^{t=\infty} \rho^t (V_t + B_t - D_t),$$
 again subject to the biological growth equations (4), (5’) and (6) and the code of conduct constraints (13) and (14) (or 14’ or 14’’). The solution to this problem gives the ‘overall’ optimal solution for the landowners.

Because the damage cost function (10) is not directly related to the harvesting activity, as the damage takes place *before* the harvest, the first order necessary control conditions will be similar to the above problem of maximizing the harvesting value only (see Appendix). Therefore, the equations determining the structure of the harvesting composition remain unchanged. On the other hand, we find that a new term reflecting the fixed marginal damage costs will be included in all the first order necessary portfolio conditions. Therefore, the harvest of the different stages and the harvest composition will generally change. One reason for this is that the shadow prices of the various restrictions, including the female–calf harvest constraint, change. Moreover, just as in biomass models (e.g., Clark 1990), we may suspect that the harvest will be more aggressive and the numbers of animals lower when damage costs are included (see, e.g., Skonhøft and Olausen 2005). This is confirmed by the numerical results.

7. Numerical results

7.1 Data and specific functional forms

The exploitation will now be illustrated numerically by applying recent ecological and economic data from the western part of Norway.

The fertility rate is expressed as a sigmoid function predicting increased degree of density dependence at high population densities (Mysterud et al. 2002). The function reads:

$$(15) \quad r_{i,t} = r_i(X_{i,t}) = \frac{\tilde{r}_i}{1 + (X_{i,t} / K_i)^{b_i}}; \quad (i = yf, f)$$

with $\hat{r}_i > 0$ as the intrinsic growth rate (maximum number of calves per female) and $K_i > 0$ as the female population level for which density-dependent fertility is equal to density-independent fertility (female ‘carrying capacity’). Thus, for a population level above K_i 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 $b_i > 0$ indicates to what extent density-independent effects compensate for changes in the stock size.

Equation (15) implies a recruitment function (1) as

$X_{c,t} = \tilde{r}_{yf} X_{yf,t} / [1 + (X_{yf,t} / K_{yf})^{b_{yf}}] + \tilde{r}_f X_{f,t} / [1 + (X_{f,t} / K_f)^{b_f}]$ and is of the so-called Shepherd type. With $b > 1$, which is assumed (Table 1), we have the Ricker version meaning that $\partial X_{c,t} / \partial X_{i,t} < 0$ ($i = yf, f$) for a high female density. However, for obvious reasons, this will not hold in an optimal harvesting programme without positive animal stock values (as here)². Table 1 gives the baseline parameter values for this function as well as the other biological parameter values. As already indicated, the parameters K_i ($i = yf, f$) are scaled for our study area with 2000 for the yearling females as well as for the adult females.

Table 2 gives the economic values used in the numerical calculations where

$p_i = (\hat{p}w_i - q_i)$ ($i = c, yf, ym, f, m$) is the net per animal hunting value (NOK per animal). The fee q_i is found in guidelines given by the Directorate for Nature Management, and is normally set to 210 NOK for calves and 350 NOK for older individuals (yearlings as well as older females and males) while the meat value is assumed similar for all categories of animals

² It can be shown that this recruitment function will be strictly concave in the actual range of utilization, i.e., when $\partial X_{c,t} / \partial X_{i,t} < 0$ (see also Olaussen and Skonhøft 2011).

and is assumed to be 75 NOK/kg³. We assume a zero discount rent in the baseline scenario. As already mentioned, this means that the steady state of the dynamic optimization problem coincides with the problem of maximizing the current net animal benefit in biological equilibrium.

Tables 1 and 2 about here

7.2 Results

The basic dynamic harvesting results are not very surprising⁴. Due to the strong degree of linearity in the model together with density dependent regulating through the recruitment function, we find the model to approach a stable equilibrium. 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. We find that a positive discount rent (5 %), not surprisingly, yields somewhat higher harvest rates and lower total stock value while the dynamics does not change qualitatively. The effects of other initial stock values were examined as well without changing the qualitative structure of the dynamics; neither was other steady – state values found (‘ergodic’ dynamics). These and other dynamic sensitivity results are available from the authors upon request.

With the baseline parameter values, the equilibrium results are given in Table 3. Case 1 describes where the landowner only takes meat value and recreational hunting benefits into account, and hence, grazing damage costs are neglected. In this situation, the only objective of the landowner is hence to maximise the hunting benefits. All stages except the yearling males are harvested. In addition, it should be noted that the adult males are harvested up to the limit of male harvest due to the male/female recruitment restriction discussed above, $\bar{h}_m = \bar{h}_{y,m} = 0.55$. The resulting adult male/female sex ratio in Case 1 is 0.15. Note that the identical yearling male and yearling female stock is simply a consequence of the stock being measured in the spring, before calving, and hence it owes directly to the calf harvest rate and the sex ratio of calves being 0.5 (see Table 1).

³ 1EUR ≈ 8.0 NOK

⁴ The dynamic optimization was performed with the Premium Solver Platform from Frontline Systems.

In Case 2, the manager takes both hunting benefits as well as browsing damage costs into account. The harvest rates for calves, yearling female, adult females, and adult males are changed only moderately, but the harvest rate for yearling males increases up to the upper limit. As a consequence, the female and male adult population are reduced. Moreover, the total population size is reduced by about 22%. The resulting adult male/female sex ratio is increased to 0.20.

In Case 3, the male/female sex ratio restriction is included more directly. Here, the restriction is set such that the male-female ratio never is below 0.30, hence $X_m/X_f \geq 0.30$. Again, the effect on the calf, yearling female, and adult female harvest rates are modest, while the yearling and adult male harvest rates become zero and 0.91, respectively. The overall population is reduced by about 29% compared to Case 1.

Table 3 about here

Table 4 shows that the meat hunting benefits (V) are highest in Case 1, where the manager (landowner??) aims at maximising the meat and recreational value. It is reduced by about 10% (from 3,016 to 2,700; in 1000 NOK) in Case 2 where browsing damage costs (D) are taken into account. On the other hand, the pure recreational value of hunting turns out to be higher in Case 2 than in Case 1, while the landowner yearly net benefit (R) is 1,726 in Case 1 and 1,956 (1000 NOK) in Case 2. Hence, since the browsing damage costs are substantially higher in Case 1, the yearly net benefit (R) is about 13% higher in Case 2 than in Case 1. Note that the overall yearly net benefit obtained in Case 3 is only marginally (1%) lower than in Case 2, while the adult male/female sex ratio is 0.30 in Case 3 and 0.20 in Case 2. Hence, this shows that quite different ways to compose the harvest are able to produce quite similar economic results. However, if we look at the yearly benefit per harvested animal (R/H), it is about 10% and 37% higher in Case 3 than in Case 2 and Case 1, respectively. Finally, the yearly net benefit per animal (R/X) is about 7% and 56% higher in Case 3 than in Case 2 and Case 1, respectively.

Table 4 about here

7.3 Sensitivity analysis:

The numerical analysis presented above is of course only as good as the parameter values chosen (see Table 1). Even if the baseline parameter values represent our best estimates, at least some of them are associated with uncertainty. Moreover, some parameters may also show substantial stochastic variation, or be subject to changes due to management policy. For these reasons, it is interesting to look if the results obtained in Table 3 and 4 are sensitive to parameter changes. If the results turns out to be very sensitive to some parameter values, this must of course be taken further into consideration before management practise can be suggested. For this end we present sensitivity analyses for the most uncertain parameters as well as for the limit on the male harvest rate.

Table 5 presents the results when the upper male harvest rate limit is 0.65, 0.75, and 0.85. Note first that both the overall number of animals harvested as well as the overall population sizes is only moderately changed. The major change is that the adult male population is substantially reduced compared with the baseline results. Moreover, as Table 6 shows, the economic outcome is not very sensitive to the male harvest rate limit either. In fact, the overall hunting meat value and recreational benefits ($V+B$) in Case 1 increases by only about 7% when the harvest rate limit is increased from 0.55 to 0.85. However, by allowing more adult male harvest, the overall benefit are increased more due to the fact that this category both represents more meat value and is associated with the highest browsing damage costs. Hence, the overall benefits (R) in Case 1 increases by about 25%. This is also reflected in Case 2 where the overall benefit (R) is increased by about 21% when the male harvest limit is increased from 0.55 to 0.85.

Table 5 and 6 about here

Table 7 and 8 demonstrate what happens when the landowners are able to charge a higher meat price for adult males, e.g. because there is an extra trophy value price associated with male harvest. When the male meat price is increased to NOK $\hat{p}_m = 100$ (NOK per kg), the harvest pattern stays similar to the baseline scenario in both cases. Due to the higher value of males, it turns out that the harvest pattern in Case 2 changes when the male meat price becomes NOK 125 per kg. Since the relative value of adult males increases compared with yearlings, it is no longer optimal to harvest yearling males in Case 2. Hence, while the harvest rates and population sizes in Case 1 turns out to be quite insensitive to changes in the male harvest price, the overall population size in Case 2 increases by about 21% (from 3 204 to

3 893) when the male meat price doubles from NOK 100 to NOK 200. This occurs since the adult male stock is increased substantially in Case 2 while it stays quite stable in Case 1. The explanation for this difference is that in Case 2, where browsing damages are taken into account, the browsing damages become relatively less important compared to the meat price when the meat price increases, and therefore, the harvesting regimes in Case 1 and 2 become more similar. This is also reflected in Table 9 where the overall economic outcome (R) becomes less different, the more the adult permit price increases.

Table 7 and 8 about here

Finally, Table 9 and Table 10 demonstrate how the harvest pattern and economic performance changes under different recreational harvest value levels. First, when the recreational value is zero, the harvest pattern is quite similar to the baseline results, while the overall benefits drops due to the missing recreational value. Next, when the recreational harvest value is twice the baseline value ($z=100$), the harvest pattern changes in Case 1 where male yearling harvest rate increases from 0 to 0.55. In addition, the net benefits increases by about 50% (from 1000 NOK 1,726 to NOK 2,580). In Case 2, an increase from $z=0$ to $z=100$ changes the harvest pattern substantially. More calves and yearling females are harvested at the expense of zero adult female harvest. This is also reflected if we look at a scenario where the recreational harvest value increases by four times the baseline value ($z=200$). While the harvest pattern in Case 1 is only modestly affected, it changes substantially in Case 2. Generally, more calves, and yearling females are harvested while the adult female harvest drops to zero. Again the net benefits increases substantially to the recreational value.

Table 9 and 10 about here

8. Concluding remarks

In this paper we have analyzed costs and benefits of a red deer population within a five stage model with density-dependent fertility and density independent mortality and where the cost and benefit functions are approximated by linear functions. Two basic landowner exploitation schemes, maximizing the present harvest value and maximizing harvest value plus grazing damage, have been studied. The different ways to compose the harvest, e.g. in yearlings or

females, and how the various management schemes induce different composition of the harvest are highlighted. Without a restriction on the female – calf harvest and without restrictions on the male harvest, we find the optimal harvest composition to be determined basically by the same factors as in Reed (1980). With the female – calf restriction included, we find it to bind. As a consequence, the harvest composition will be substantially different from the situation without this constraint. Therefore, the same number of calves and females should always be harvested (zero or positive) in the optimal solution, irrespective of harvesting scheme.

The numerical section illustrates the predictions from the theoretical model. To be written....

Comparing to current harvesting practices....

Our study is a restricted type of cost-benefit analysis because some values, like non-use values and existence values, are neglected. However, due to the recent high deer population in Scandinavia, such values, on the margin, are probably quite modest and will hence only have small influence on the optimal harvest composition. Traffic damages.....

All our basic conclusions drawn about the harvesting composition is based on linear damage cost and benefit functions. However, when relaxing the linearity assumptions, numerical results indicate that the harvest pattern does not change dramatically. We have also calculated the net benefit when our optimal selective harvesting pattern is replaced by an ‘optimal’ uniform pattern where an ‘animal is an animal’ as considered in the traditional bioeconomic models. We find that such harvesting pattern reduce the economic benefit considerably.

Appendix

The maximization problem

The Lagrangian of the problem of maximizing the present value harvest value $(V_t + D_t)$ given the biological constraints plus constraints (13) and (14) can be written as

$$L = \sum_{t=0}^{\infty} \rho^t \left\{ \left[p_c h_{c,t} [r_{yf}(X_{yf,t})X_{yf,t} + r_f(X_{f,t})X_{f,t}] + [p_{yf} h_{yf,t} + p_{ym} h_{ym,t} (1-\psi) / \psi] X_{yf,t} + p_f h_{f,t} X_{f,t} + p_m \right] \right. \\ \left. + (z / \theta)(h_{c,t} + h_{yf,t} + h_{ym,t} + h_{f,t} + h_{m,t}) - \rho \eta_{t+1} [X_{yf,t+1} - \psi s_c (1-h_{c,t}) [r_{yf}(X_{yf,t})X_{yf,t} + r_f(X_{f,t})X_{f,t}]] \right. \\ \left. - \rho \lambda_{t+1} [X_{f,t+1} - s_{yf} (1-h_{yf,t}) X_{yf,t} - s_f (1-h_{f,t}) X_{f,t}] - \rho \mu_{t+1} [X_{m,t+1} - [s_{ym} (1-h_{ym,t}) (1-\psi) / \psi] X_{yf,t} - s_m] \right. \\ \left. - \rho \omega_{t+1} [h_{f,t} X_{f,t} - h_{c,t} [r_{yf}(X_{yf,t})X_{yf,t} + r_f(X_{f,t})X_{f,t}]] - \rho \zeta_{t+1} (h_{m,t} - \bar{h}_m) \right\}$$

$\eta_t > 0, \lambda_t > 0, \mu_t > 0$ are the shadow prices of the female yearling constraint (6), adult female constraint (4) and adult male population constraint (5'), respectively, while $\omega_t \geq 0$ is the shadow price of the female – calf harvesting restriction (13) and $\zeta_t \geq 0$ is the shadow price of the male harvesting restriction (14). Notice that the population constraint shadow prices, in contrast to the two harvesting constraints (13) and (14), always will be strictly positive because these constraints always binds (Kuhn-Tucker theorem).

The first-order necessary 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 assumed not to be possible (section three above). These control conditions with $X_{i,t} > 0$ ($i = c, yf, ym, f, m$) read:⁵

$$(A1) \quad \frac{\partial L}{\partial h_{c,t}} = [r_{yf}(X_{yf,t})X_{yf,t} + r_f(X_{f,t})X_{f,t}] (p_c + z / \theta X_{c,t} - \rho \eta_{t+1} \psi s_c + \rho \omega_{t+1}) \leq 0 ; 0 \leq h_{c,t} < 1,$$

$$(A2) \quad \frac{\partial L}{\partial h_{yf,t}} = X_{yf,t} (p_{yf} + z / \theta X_{yf,t} - \rho \lambda_{t+1} s_{yf}) \leq 0 ; 0 \leq h_{yf,t} < 1,$$

$$(A3) \quad \frac{\partial L}{\partial h_{ym,t}} = X_{ym,t} (p_{ym} + z \psi / (1-\psi) \theta X_{yf,t} - \rho \mu_{t+1} s_{ym}) \leq 0 ; 0 \leq h_{ym,t} < 1,$$

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 when no positive stock values are included.

$$(A4) \quad \frac{\partial L}{\partial h_{f,t}} = X_{f,t}(p_f + z / \theta X_{f,t} - \rho \lambda_{t+1} s_f - \rho \omega_{t+1}) \leq 0; 0 \leq h_{f,t} < 1$$

and

$$(A5) \quad \frac{\partial L}{\partial h_{m,t}} = X_{m,t}(p_m + z / \theta X_{m,t} - \rho \mu_{t+1} s_m - \rho \xi_{t+1} / X_{m,t}) \leq 0; 0 \leq h_{m,t} < 1.$$

The portfolio conditions with are rather messy and are not stated (available from the authors upon request).

Condition (A1) says that calf harvest should take up to the point where marginal harvest income plus marginal recreation value is equal to, or below, the cost in term of reduced yearling growth of both categories evaluated at their shadow prices while also taking the discounting 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 (A2) and (A3) indicate that harvesting of the yearling female (male) category should take place up to the point where the marginal benefit is equal to, or below, the cost in terms of reduced population of adult females (males). The female and male adult conditions (A4) and (A5), respectively, can be given a similar interpretations, but the shadow cost of the female - calf harvesting constraint is included in the female condition (A4) while the shadow cost of the male harvesting rate is included in condition (A5).

These first order control conditions together the portfolio conditions and the biological constraints comprise a complex dynamic system with 12 unknowns and 12 equations. It is therefore difficult, if not impossible, to assess the dynamics analytically. However, based on the control conditions, it is possible to draw some important conclusions about the harvesting composition. To see this, we look away from the constraints (13) and (14) and assume that the hunting recreation value is small and negligible. The above conditions are then simplified to:

$$(A1') \quad \frac{\partial L}{\partial h_{c,t}} = [r_{yf}(X_{yf,t})X_{yf,t} + r_f(X_{f,t})X_{f,t}](p_c - \rho \eta_{t+1} \psi s_c) \leq 0; 0 \leq h_{c,t} < 1,$$

$$(A2') \quad \frac{\partial L}{\partial h_{yf,t}} = X_{yf,t}(p_{yf} - \rho \lambda_{t+1} s_{yf}) \leq 0; 0 \leq h_{yf,t} < 1,$$

$$(A3') \quad \frac{\partial L}{\partial h_{ym,t}} = X_{ym,t}(p_{ym} - \rho \mu_{t+1} s_{ym}) \leq 0; 0 \leq h_{ym,t} < 1,$$

$$(A4') \quad \frac{\partial L}{\partial h_{f,t}} = X_{f,t}(p_f - \rho\lambda_{t+1}s_f) \leq 0; 0 \leq h_{f,t} < 1$$

and

$$(A5') \quad \frac{\partial L}{\partial h_{m,t}} = X_{m,t}(p_m - \rho\mu_{t+1}s_m) \leq 0; 0 \leq h_{m,t} < 1.$$

From these conditions it is straightforward to find that harvesting female yearlings and females at the same time can not represent a possible optimal policy. To see this, assume first that female yearling harvest is optimal. (A2') (with $X_{yf,t} > 0$) holds then as $p_{yf} = \rho\lambda_{t+1}s_{yf}$. In a similar manner, assume next that female harvest is optimal. With $X_{f,t} > 0$ (A4') then reads $p_f = \rho\lambda_{t+1}s_f$. Combining these two equation yields then $p_{yf} / s_{yf} = p_f / s_f$. As only parameters are included here, this equation holds only by accident, Therefore, harvesting both these two stages at the same time cannot represent an optimal solution when the constraints (13) and (14) (or 14' or 14'') are not binding and when the harvest recreation value is not included. When combining (A3') and (A5') we can draw a similar type of conclusion; that is, harvesting male yearlings and males at the same time is not in accordance with the optimality conditions. In the main text (section 5.1) more discussions based on (A1') – (A5') are found. For example, harvesting female yearlings together with zero adult female harvesting yields $p_{yf} / s_{yf} > p_f / s_f$ which represents a contradiction due to the structure of the parameter values.

When including grazing damage $D_t = d_c X_{c,t} + d_{fy} X_{fy,t} + d_{my} X_{my,t} + d_f X_{f,t} + d_m X_{m,t}$, the

'overall' problem is hence to $\max_{h_{c,t}, h_{fy,t}, h_{my,t}, h_{f,t}, h_{m,t}} \sum_{t=0}^{t=\infty} \rho^t (V_t + B_t - D_t)$, again subject to the biological growth equations (4), (5') and (6) together with constraints (13) and (14) (or 14' or 14''). It is easily recognized that the control conditions of this problem will be similar to that of (A1) – (A5).

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Wam and Hofstad 2007??

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Table 1: Baseline biological parameter values

| Parameters | Description | Value | Reference/source |
|------------------|--|--------------------|----------------------------|
| \tilde{r}_{yf} | maximum specific growth rate yearlings | 0.6 | Langvatn et al. (2004) |
| \tilde{r}_f | maximum specific growth rate adults | 0.96 | Langvatn et al. (2004) |
| K_{yf} | carrying capacity yearlings | 2000 animals | Calibrated |
| K_f | carrying capacity adults | 2000 animals | Calibrated |
| b_{yf} | density compensation parameter yearlings | 2 | Nilsen et al. (2005) |
| b_f | density compensation parameter adults | 2 | Nilsen et al. (2005) |
| w_c | mean weight calves | 24.8 kg/animal | Solberg et al. (2010) |
| w_{yf} | mean weight female yearlings | 50.9 kg/animal | Solberg et al. (2010) |
| w_{ym} | mean weight male yearlings | 63.5 kg/animal | Solberg et al. (2010) |
| w_f | mean weight females | 58 kg/animal | Solberg et al. (2010) |
| w_m | mean weight male | 85.1 kg/animal | Solberg et al. (2010) |
| s_c | survival rate calves | 0.75 | Langvatn and Loison (1999) |
| s_{yf} | survival rate female yearlings | 0.92 | Langvatn and Loison (1999) |
| s_{ym} | survival rate male yearlings | 0.87 | Langvatn and Loison (1999) |
| s_f | survival rate adult females | 0.93 | Langvatn and Loison (1999) |
| s_m | survival rate adult males | 0.93 | Langvatn and Loison (1999) |
| θ | catchability coefficient | 0.0001/hunting day | Calibrated from SSB (2004) |

Table 2: Baseline economic parameter values

| Parameters | Description | Value | Reference/source |
|------------|--|-------------------|-----------------------------------|
| \hat{p} | meat price | NOK 75/kg | Olaussen and Mysterud (2011) |
| qc | hunting fee calf | NOK 210/animal | Directorate for Nature Management |
| qyf | hunting fee yearling female | NOK 350/animal | Directorate for Nature Management |
| qym | hunting fee yearling male | NOK 350/animal | Directorate for Nature Management |
| qf | hunting fee female | NOK 350/animal | Directorate for Nature Management |
| qm | hunting fee male | NOK 350/animal | Directorate for Nature Management |
| dc | marginal grazing damage cost calves | NOK 265/animal | Olaussen and Mysterud (2011) |
| d_{yf} | marginal grazing cost female yearlings | NOK 545/animal | Olaussen and Mysterud (2011) |
| d_{ym} | marginal grazing cost male yearlings | NOK 680/animal | Olaussen and Mysterud (2011) |
| df | marginal grazing cost female adults | NOK 620/animal | Olaussen and Mysterud (2011) |
| dm | marginal browsing cost male adults | NOK 910/animal | Olaussen and Mysterud (2011) |
| z | recreational hunting value | NOK 50/day | Thorvaldsen et al (2010) |
| δ | discount rate | 0 | |

Table 3: Red deer harvest rates and stock size, h_c , h_{ym} , h_{yf} , h_f , and h_m are harvest rates of calves, male yearlings, female yearlings, females and males respectively. H is total yearly harvest in number of animals while X_c , X_{ym} , X_{yf} , X_f , and X_m are the population sizes (in number of animals) of calves, male yearlings, female yearlings, females and males respectively. X is total yearly population size.

| | Case 1 | Case 2 | Case 3 |
|----------|--------|--------|--------|
| h_c | 0.11 | 0.12 | 0.12 |
| h_{yf} | 0.33 | 0.37 | 0.38 |
| h_{ym} | 0 | 0.55 | 0 |
| h_f | 0.08 | 0.11 | 0.12 |
| h_m | 0.55 | 0.55 | 0.91 |
| H | 752 | 682 | 613 |
| X_c | 1 176 | 1 021 | 935 |
| X_{yf} | 392 | 336 | 307 |
| X_{ym} | 392 | 336 | 307 |
| X_f | 1 720 | 1 137 | 972 |
| X_m | 264 | 227 | 292 |
| X | 3 944 | 3 057 | 2 813 |

Table note:

Case 1: Meat and recreational benefits only: No browsing damage costs, upper limit on adult male harvest, $\bar{h}_m = 0.55$

Case 2: Meat benefits, recreational benefits and browsing damage, upper limit on adult male harvest, $\bar{h}_m = 0.55$

Case 3: Meat benefits, recreational benefits and browsing damage, adult male/female sex ratio restriction $\bar{x} = 0.30$.

Table 4: Landowner yearly benefits and costs (in NOK). V is net meat hunting income, B is recreational value of hunting, D is browsing damage costs and R net benefits. R/H is net benefits per hunted animal while R/X is the net benefits per live animal in the population before calving.

| | Case 1 | Case 2 | Case 3 |
|-------|-----------|-----------|-----------|
| V | 3 016 000 | 2 700 000 | 2 658 000 |
| B | 809 000 | 850 000 | 765 500 |
| D | 2 099 000 | 1 594 000 | 1 492 000 |
| R | 1 726 000 | 1 956 000 | 1 931 500 |
| R/H | 2 295 | 2 868 | 3 151 |
| R/X | 438 | 640 | 687 |

Table 5: Red deer harvest rates and stock size under different male harvest rate limits, h_c , h_{ym} , h_{yf} , h_f , and h_m are harvest rates of calves, male yearlings, female yearlings, females and males respectively. H is total yearly harvest in number of animals while X_c , X_{ym} , X_{yf} , X_f , and X_m are the stock sizes (in number of animals) of calves, male yearlings, female yearlings, females and males respectively. X is total yearly stock.

| | Case 1 $\bar{h}_m = 0.65$ | Case 2 $\bar{h}_m = 0.65$ | Case1 $\bar{h}_m = 0.75$ | Case 2 $\bar{h}_m = 0.75$ | Case 1 $\bar{h}_m = 0.85$ | Case 2 $\bar{h}_m = 0.85$ |
|----------|------------------------------|------------------------------|-----------------------------|------------------------------|------------------------------|------------------------------|
| h_c | 0.11 | 0.12 | 0.11 | 0.12 | 0.11 | 0.12 |
| h_{yf} | 0.33 | 0.37 | 0.33 | 0.37 | 0.33 | 0.37 |
| h_{ym} | 0.65 | 0.65 | 0.75 | 0.75 | 0.85 | 0.85 |
| h_f | 0.08 | 0.11 | 0.08 | 0.11 | 0.08 | 0.11 |
| h_m | 0.65 | 0.65 | 0.75 | 0.75 | 0.85 | 0.85 |
| H | 761 | 694 | 767 | 704 | 775 | 710 |
| X_c | 1 176 | 1029 | 1 176 | 1033 | 1 175 | 1036 |
| X_{yf} | 392 | 339 | 392 | 341 | 392 | 341 |
| X_{ym} | 392 | 339 | 392 | 341 | 392 | 341 |
| X_f | 1 719 | 1 154 | 1 717 | 1 164 | 1 715 | 1 169 |
| X_m | 177 | 153 | 111 | 96 | 59 | 52 |
| X | 3 856 | 3 014 | 3 788 | 2 975 | 3 733 | 2 939 |

Table note:

Case 1: Meat and recreational benefits only: No browsing damage costs, upper limit on adult male harvest; harvest, $\bar{h}_m = \bar{h}_{y,m} = 0.65$, $\bar{h}_m = \bar{h}_{y,m} = 0.75$, and $\bar{h}_m = \bar{h}_{y,m} = 0.85$.

Case 2: Meat benefits, recreational benefits and browsing damage costs, upper limit on adult male harvest, $\bar{h}_m = \bar{h}_{y,m} = 0.65$, $\bar{h}_m = \bar{h}_{y,m} = 0.75$, and $\bar{h}_m = \bar{h}_{y,m} = 0.85$.

Table 6: Landowner yearly benefits and costs (in NOK) under different male harvest rate limits. V is net hunting income, B is recreational value of hunting, D is browsing damage costs and R net benefits. R/H is net benefits per hunted animal while R/X is the net benefits per animal.

| | Case 1 $\bar{h}_m=0.65$ | Case 2 $\bar{h}_m=0.65$ | Case 1 $\bar{h}_m=0.75$ | Case 2 $\bar{h}_m=0.75$ | Case 1 $\bar{h}_m=0.85$ | Case 2 $\bar{h}_m=0.85$ |
|-------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|
| V | 3 007 000 | 2 709 000 | 2 989 000 | 2 707 000 | 2 963 000 | 2 688 000 |
| B | 909 000 | 948 500 | 1 010 000 | 1 048 000 | 1 109 000 | 1 148 000 |
| D | 2 019 000 | 1 543 000 | 1 958 000 | 1 500 000 | 1 909 000 | 1 464 000 |
| R | 1 897 000 | 2 114 500 | 2 041 000 | 2 255 000 | 2 163 000 | 2 372 000 |
| R/H | 2 493 | 3 047 | 2 661 | 3 203 | 2 791 | 3 341 |
| R/X | 492 | 701 | 539 | 758 | 579 | 807 |

Table 7: Red deer harvest rates and stock size under different male harvest prices, h_c , h_{ym} , h_{yf} , h_f , and h_m are harvest rates of calves, male yearlings, female yearlings, females and males respectively. H is total yearly harvest in number of animals while X_c , X_{ym} , X_{yf} , X_f , and X_m are the stock sizes (in number of animals) of calves, male yearlings, female yearlings, females and males respectively. X is total yearly stock.

| | Case 1 $\hat{p}_m = 100$ | Case 2 $\hat{p}_m = 100$ | Case1 $\hat{p}_m = 125$ | Case 2 $\hat{p}_m = 125$ | Case 1 $\hat{p}_m = 150$ | Case 2 $\hat{p}_m = 150$ |
|----------|-----------------------------|-----------------------------|----------------------------|-----------------------------|-----------------------------|-----------------------------|
| h_c | 0.11 | 0.12 | 0.11 | 0.12 | 0.11 | 0.12 |
| h_{yf} | 0.33 | 0.37 | 0.32 | 0.36 | 0.32 | 0.35 |
| h_{ym} | 0 | 0.55 | 0 | 0 | 0 | 0 |
| h_f | 0.07 | 0.10 | 0.07 | 0.10 | 0.07 | 0.09 |
| h_m | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 |
| H | 711 | 701 | 710 | 694 | 708 | 702 |
| X_c | 1 182 | 1056 | 1 185 | 1 109 | 1 187 | 1 130 |
| X_{yf} | 395 | 348 | 396 | 367 | 397 | 375 |
| X_{ym} | 395 | 348 | 396 | 367 | 397 | 375 |
| X_f | 1 791 | 1 218 | 1 831 | 1 373 | 1 864 | 1 453 |
| X_m | 591 | 234 | 593 | 549 | 595 | 560 |
| X | 4 344 | 3204 | 4 401 | 3 765 | 4 440 | 3 893 |

Table note:

Case 1: Meat and recreational benefits only: No browsing damage costs, upper limit on adult male harvest, $\bar{h}_m = 0.55$.

Case 2: Meat benefits, recreational benefits and browsing damage costs, upper limit on adult male harvest, $\bar{h}_m = 0.55$.

Table 8: Landowner yearly benefits and costs (in NOK) under different male harvest prices. V is net hunting income, B is recreational value of hunting, D is browsing damage costs and R net benefits. R/H is net benefits per hunted animal while R/X is the net benefits per animal.

| | Case 1 $\hat{p}_m = 100$ | Case 2 $\hat{p}_m = 100$ | Case 1 $\hat{p}_m = 125$ | Case 2 $\hat{p}_m = 125$ | Case 1 $\hat{p}_m = 150$ | Case 2 $\hat{p}_m = 150$ |
|-------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| V | 3 943 000 | 3 236 000 | 4 641 000 | 4 404 000 | 5 334 000 | 5 131 000 |
| B | 528 500 | 844 500 | 525 500 | 559 500 | 522 500 | 553 500 |
| D | 2 446 000 | 1 675 000 | 2 475 000 | 2 094 000 | 2 498 000 | 2 169 000 |
| R | 2 025 500 | 2 268 500 | 2 691 500 | 2 869 500 | 3 358 500 | 3 515 500 |
| R/H | 2 849 | 3 236 | 3 791 | 4 135 | 4 744 | 5 008 |
| R/X | 466 | 708 | 612 | 762 | 756 | 903 |

Table 9: Red deer harvest rates and stock size under different recreational harvest values (z), h_c , h_{ym} , h_{yf} , h_f , and h_m are harvest rates of calves, male yearlings, female yearlings, females and males respectively. H is total yearly harvest in number of animals while X_c , X_{ym} , X_{yf} , X_f , and X_m are the stock sizes (in number of animals) of calves, male yearlings, female yearlings, females and males respectively. X is total yearly stock.

Slettet: ,

| | Case 1 $z = 0$ | Case 2 $z = 0$ | Case 1 $z = 100$ | Case 2 $z = 100$ | Case 1 $z = 200$ | Case2 $z = 200$ |
|----------|-------------------|-------------------|---------------------|---------------------|---------------------|--------------------|
| h_c | 0.11 | 0.12 | 0.11 | 0.21 | 0.11 | 0.21 |
| h_{yf} | 0.33 | 0.37 | 0.34 | 0.72 | 0.34 | 0.73 |
| h_{ym} | 0 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 |
| h_f | 0.07 | 0.11 | 0.08 | 0 | 0.08 | 0 |
| h_m | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 |
| H | 712 | 693 | 751 | 668 | 746 | 642 |
| X_c | 1183 | 1 040 | 1 169 | 960 | 1 153 | 918 |
| X_{yf} | 395 | 343 | 389 | 284 | 383 | 271 |
| X_{ym} | 395 | 343 | 389 | 284 | 383 | 271 |
| X_f | 1 794 | 1 179 | 1 662 | 1 056 | 1561 | 981 |
| X_m | 591 | 231 | 262 | 191 | 258 | 182 |
| X | 4 358 | 3 136 | 3 871 | 2 775 | 3 738 | 2 623 |

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Table note:

Case 1: Meat and recreational benefits only: No browsing damage costs, upper limit on adult male harvest, $\bar{h}_m=0.55$.

Slettet: Hunting m

Formatert: Engelsk (USA)

Feltkode endret

Case 2: Meat benefits, recreational benefits and browsing damage, upper limit on adult male harvest, $\bar{h}_m=0.55$.

Formatert: Engelsk (USA)

Slettet: Hunting benefits

Feltkode endret

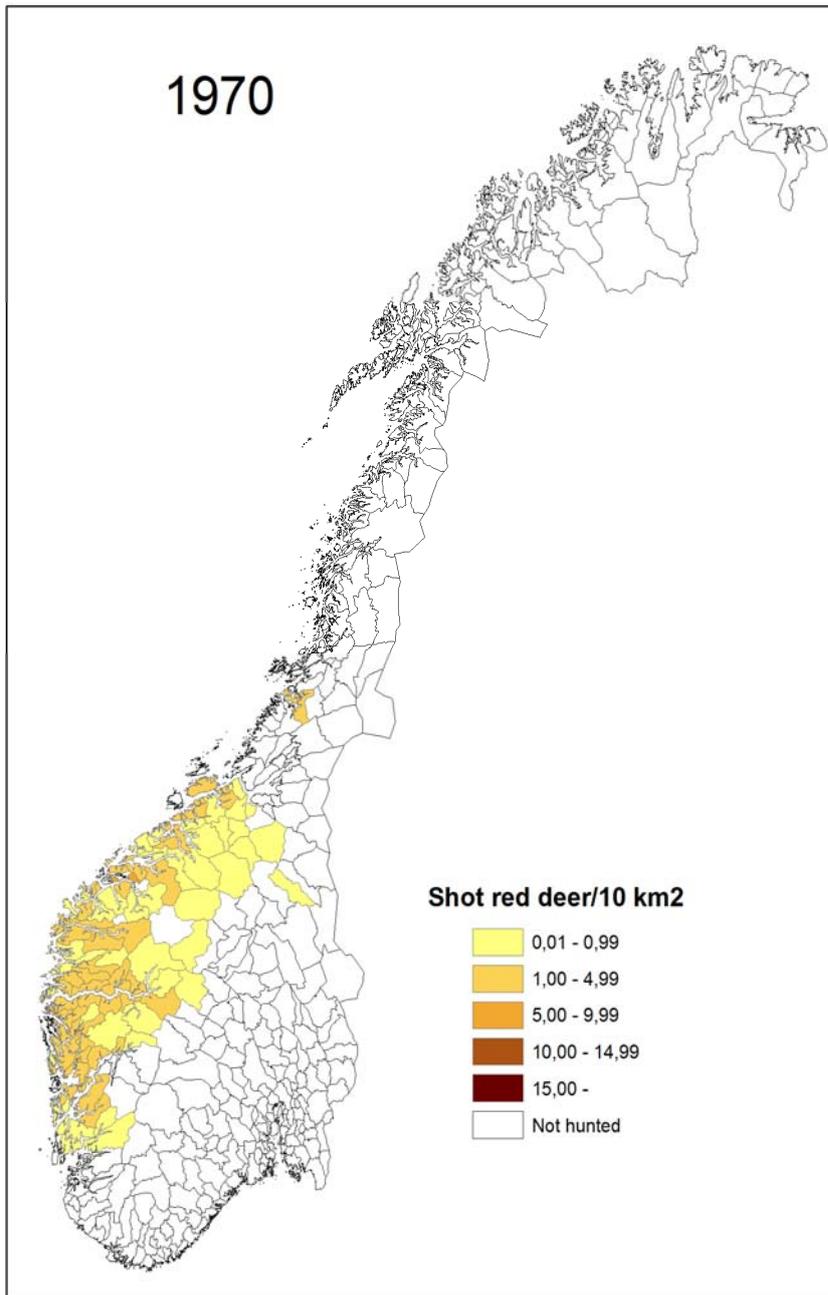
Formatert: Engelsk (USA)

Table 10: Landowner yearly benefits and costs (in NOK) under different recreational harvest values (z). V is net hunting income, B is recreational value of hunting, D is browsing damage costs and R net benefits. R/H is net benefits per hunted animal while R/X is the net benefits per animal.

| | Case 1 $z = 0$ | Case 2 $z = 0$ | Case 1 $z = 100$ | Case 2 $z = 100$ | Case 1 $z = 200$ | Case 2 $z = 200$ |
|-------|-------------------|-------------------|---------------------|---------------------|---------------------|---------------------|
| V | 3 138 000 | 2 745 000 | 3 009 000 | 2 363 000 | 2 982 000 | 2 268 000 |
| B | 0 | 0 | 1 627 000 | 2 029 000 | 3 282 000 | 4 078 000 |
| D | 2 448 000 | 1 636 000 | 2 056 000 | 1 430 000 | 1 977 000 | 1 349 000 |
| R | 690 000 | 1 109 000 | 2 580 000 | 2 962 000 | 4 287 000 | 4 997 000 |
| R/H | 969 | 1 600 | 3 435 | 4 434 | 5 743 | 7 783 |
| R/X | 158 | 353 | 666 | 1 067 | 1 147 | 1 905 |

Formatert tabell

Figure 1: Number of harvested red deer per 10 km² in Norwegian municipalities in 1970 (left) and 2009 (right). The figure illustrates both the change in population density and geographical distribution. Source: Statistics Norway.



2009

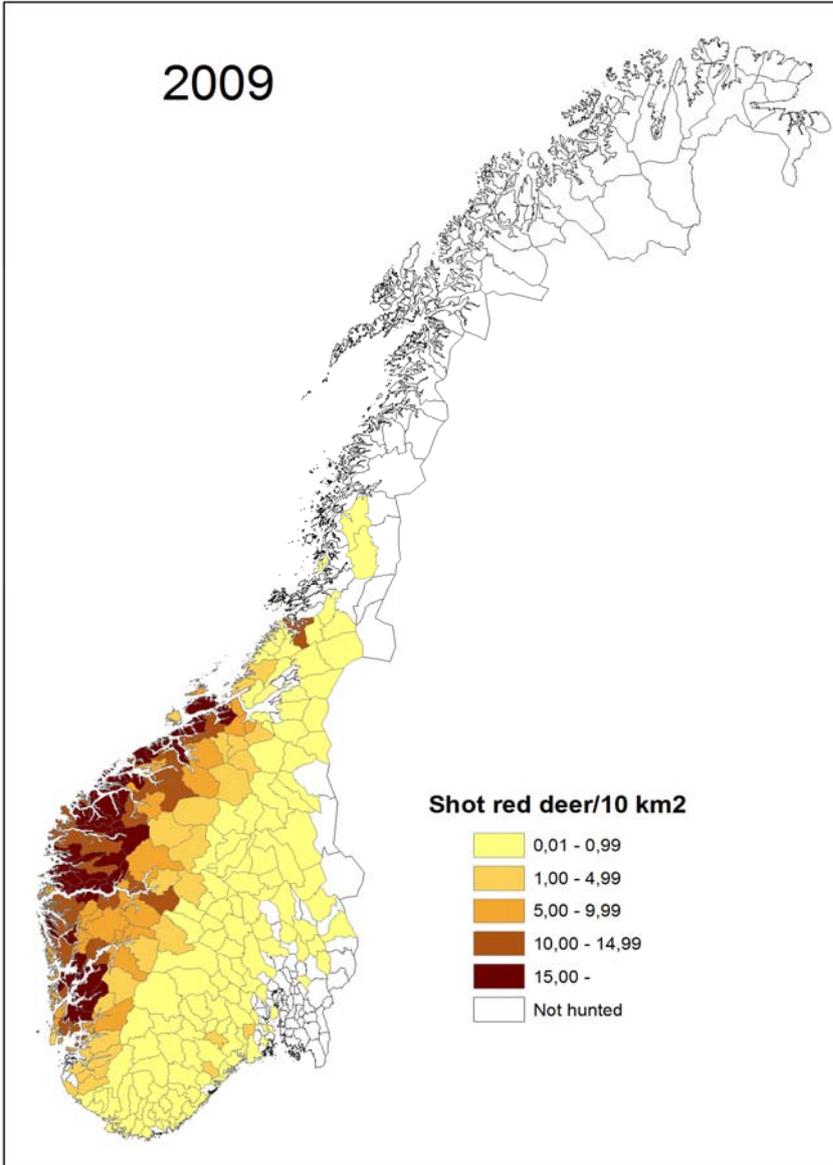


Figure 2: Map study area

The study area consisted of two municipalities, Flora (A) and Gloppen (B), situated on the west coast of Norway.

