

# Managing a Migratory Species That Is Both a Value and a Pest

*Anders Skonhøft and Jon Olaf Olaussen*

---

**ABSTRACT.** *Wild animals can represent both value and nuisance. We consider the moose (*Alces alces*), which due to seasonal migration causes browsing damage in some areas, while creating hunting value in other areas. We first explore a situation when harvesting, following today's practice in Norway, only takes place in the fall. Next, the season is extended to include winter harvesting. It is shown how this redistributes harvesting benefits between areas and landowners, and under which conditions total net benefit increases. The model is illustrated by a real life example from the Swe-Nor moose region some 250 kilometers north of Oslo, Norway. (JEL Q26)*

## I. INTRODUCTION

### *Background*

In many cases, wild animals create benefits for humans. Quite frequently, however, we also find that wild species are a nuisance. Rodents damaging agricultural production may be a typical example (see, e.g., Stenseth et al. 2003). In other instances, wild animals are both a nuisance and valuable. Some marine species may be of this type, such as whales that prey upon, or compete with, commercially valuable species like cod (Flaaten and Stollery 1996). An elephant population causing grazing damage, but at the same time also creating consumption and non-consumption values, is another example (see, e.g., Bulte and van Kooten 1999). Because of the fugitive nature of the species, however, we can also see that species may cause damage in some areas while being valuable in other areas. Consequently, different agents, or groups of people, may consider the same wild animals both valuable and a pest. An elephant population (a park manager and the local

people, see, e.g., Schulz and Skonhøft 1996) and a whale population (whale hunters and cod fishers, again, see Flaaten and Stollery 1996) may again serve as examples. In this paper we consider the moose (*Alces alces*), which causes browsing damage in some areas, while creating hunting values in other areas. The analysis is carried out in a Scandinavian institutional, economic, and ecological setting.

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 the Scandinavian countries, and in Norway and Sweden about 40,000 and 100,000 animals, respectively, are shot every year (Saether et al. 1992). This hunting, which takes place in September and October, is also an important social and cultural event in a large number of rural communities. However, the moose population also causes various costs. There is a high incidence of moose-vehicle collisions, and there is browsing damage during the winter when young pine trees are an important food source. This damage may be considerable (Storaas et al. 2001). Because of large spatial variations in densities during the winter season, the browsing damage is, however, quite unevenly distributed between different areas. Migration and concentration are two important factors explaining these differences, as some sub-populations tend to leave their summer ranges

---

The authors are, respectively, professor and PhD student, Department of Economics, Norwegian University of Science and Technology, Trondheim. The authors thank Bernt-Erik Saether for discussions initiating this research and Anne Borge Johannesen, Jan Tore Solstad, and two anonymous reviewers for critical and constructive comments on earlier drafts. We are also indebted to The European Commission for funding through the BIOECON project.

and graze in specific winter ranges due to snow and forage conditions (Ball, Nordengen, and Wallin 2001). Hence, as hunting takes place in the fall before the yearly migration, there is often an asymmetry between areas where the benefit of harvesting is obtained and areas with heavy browsing damage; that is, for some landowners the moose creates value while for other landowners it is merely a pest (see, e.g., Saether et al. 1992 for more details).

#### *The Scope of the Analysis*

The scope of this paper is to analyze this problem within a model framework that links two strands of studies within the bio-economic literature: spatial dispersal studies and pest and nuisance studies. Recently, there has been a strong emphasis on bio-economic models with spatial distribution as a key element, in most instances formulated within the context of marine reserves (see, e.g., Conrad 1999; Sanchirico and Wilen 2001; Anderson 2002). These models have, among others, analyzed under what ecological and economic conditions, and to what extent, marine reserve creation may increase aggregate biomass and change the profitability of a fishery. A somewhat different type of study is Skonhøft, Yoccoz, and Stenseth (2002), who analyzed the optimal management of a chamois population moving between a protected area and a surrounding hunting area. Yet another example is Huffaker, Bhat, and Lenhart (1992) who analyze a beaver population in a two-patch system managed by two different landowners, where the beaver population represents no value but is a nuisance (damage on timber stands) and costly to hunt in one of the areas. Bhat, Huffaker, and Lenhart (1996) presents another analysis of basically the same model. These last two papers also have some similarities with a more recent paper by Zivin, Hueth, and Zilberman (2000), which studies the optimal management of the Californian feral pig that represents both value and a pest. In Zivin, Hueth, and Zilberman however, there is no explicitly formulated spatial model.

The following analysis of moose as valuable and a pest utilizes a stylized bio-economic framework where we consider two areas of fixed size, two landowners, and two sub-populations of moose. The fact that the moose is partly a migratory species is modeled by allowing a fraction of one of the sub-populations to migrate from one of the areas to the other during the winter season, and hence causing forestry damage here. The present analysis is most similar to that of Huffaker, Bhat, and Lenhart (1992). However, the dispersal is not density dependent in our study (see below), and the moose is both valuable and a pest, not only a pest. Because of the dispersal and because the moose is valuable *and* a pest, there will be an economic interdependency between the sub-populations, the two areas and the two landowners. We analyze the externalities following this interdependency within a unified management scheme where the wildlife manager (the planner) aims to find harvesting quotas that maximize profit, harvesting income minus forestry damage, of the two areas taken together in biological equilibrium. This management goal is more or less in accordance with the actual management policy in Norway and in Scandinavia, but migration is not taken directly into account.<sup>1</sup> The wildlife manager therefore sets quotas for the areas based on an overall economic and ecological assessment, and the cost and benefits streams of the landowners, that is, the property rights over the wildlife (see, e.g., Bromley 1991), are accordingly controlled by the wildlife manager.

<sup>1</sup> According to Norwegian wildlife law, the state through the Directorate for Wildlife and Nature Management, Direktoratet for Naturforvaltning, determines the number of animals to be hunted within each management area. The size of the management area depends on both institutional and ecological factors. In a next step, the total quota is distributed between the landowners within the management area. These owners form a hunting board and decide how to harvest and share the quota. In the present analysis, the two areas, with two different landowners, represent the management area. The management goal is usually to maximize the meat value in ecological equilibrium (Saether et al. 1992). While grazing damage is normally taken into account, this is often in an ad-hoc manner. Costs related to traffic damage are rarely considered.

Two different harvesting schemes, implying different cost and benefit streams between the areas and landowners, are considered. In Regime 1, analyzed in Section 2, we first explore a situation when harvesting, following today's practice, only takes place in the fall. In Regime 2, analyzed in Section 3, the wildlife manager changes this practice and extends the season to include winter harvesting as well. The moose is then potentially harvested both in the fall and in the winter, and we have sequential harvesting. Still under the assumption that the profit of the two areas is maximized within a unified management scheme, we study how this new practice may change harvesting and profitability. Section 4 illustrates the two regimes numerically by a real life example from the so-called Sweenor moose region some 250 kilometers north of Oslo, Norway.

## II. THE POPULATION EQUATIONS, THE COST AND BENEFIT FUNCTIONS, AND REGIME 1 MANAGEMENT

### General Functional Forms

As noted, we consider two areas of fixed size, areas 1 and 2, with two different landowners, owners 1 and 2, and two sub-populations of moose, sub-populations 1 and 2. Saether et al. (1992) make a distinction between three migration patterns of *Alces alces*. We focus on the most common one, namely sub-populations with a distinct and more or less fixed yearly migration pattern between a summer range and a winter range. This pattern is modeled by letting a fixed fraction of one of the sub-populations migrate in a density-independent manner during the winter.<sup>2</sup> Because of the snow and forage conditions, it is assumed that the dispersal runs from area 1 to area 2.<sup>3</sup> These

two areas are considered a closed system, and after winter, all the migratory moose return to their summer range. The regular hunting season is September and October, before the yearly migration. We thus have harvesting benefits that are directly related to the summer range of the two sub-populations, while the migrating fraction of sub-population 1 causes browsing damage in area 2 during the winter season but not vice versa since sub-population 2 is stationary throughout the year. Because hunting and browsing damage take place sequentially, but more importantly because sequential harvesting is also considered (Section 3), the population model is formulated in a time-discrete manner and harvesting activity is represented by fractions, not by absolute number of animals.

Neglecting any stochastic variations in environment and biology, the equations

$$X_{1,t+1} = (1 - h_{1,t})[X_{1,t} + F(X_{1,t})] \quad [1]$$

and

$$X_{2,t+1} = (1 - h_{2,t})[X_{2,t} + G(X_{2,t})] \quad [2]$$

give the population dynamics where  $X_{i,t}$  ( $i = 1, 2$ ) is the size of sub-population  $i$ , measured as biomass (or number of "normalized" animals) year  $t$ ,  $0 \leq h_{i,t} < 1$  is the fraction harvested the same year, and  $F(X_{1,t})$  and  $G(X_{2,t})$  are the density-dependent natural growth functions assumed to be of the logistic type (see below). In more detail,  $X_{1,t}$  is the size of the population after winter in area 1, which determines natural growth as calving happens in May and June (cf. Figure 1). Natural growth takes place before the hunting season in September and October (Saether et al. 1992),  $X_{1,t} + F(X_{1,t})$  is accordingly the biomass before hunting, which is reduced to  $(1 - h_{1,t})[X_{1,t} + F(X_{1,t})]$  after hunting. The fraction of the population migrating from area 1 to area 2 after the hunting season, depending on snow and food conditions, in addition to

<sup>2</sup> The dispersal is density independent because flow between the areas is not related to the relative species density between the areas. As mentioned, such a dispersal pattern is in contrast to Huffaker, Bhat, and Lenhart (1992). See also Sanchirico and Wilen (2001) for a broader discussion.

<sup>3</sup> Normally, the seasonal migratory moose tend to migrate from summer ranges on hilly ground and down to valleys with less snow and where the concentration of moose improves the opportunity to derive advantage

from walking in each other's tracks in order to reduce the cost of locomotion (Ball, Nordengren, and Wallin 2001).

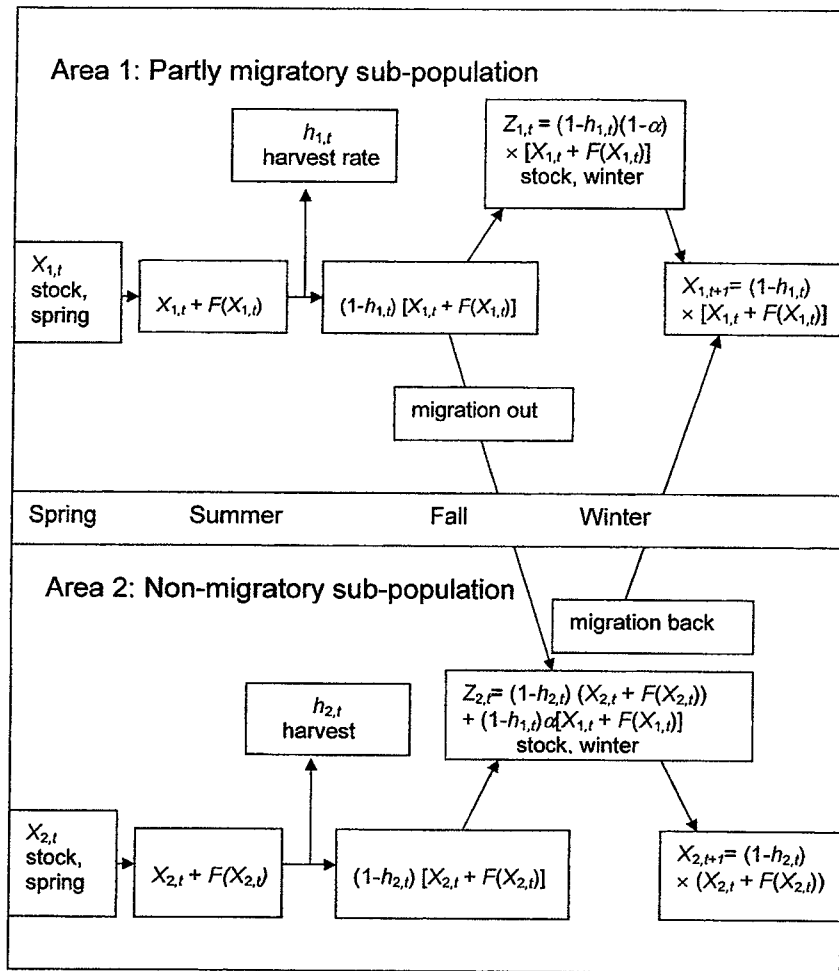


FIGURE 1  
REGIME 1 POPULATION DYNAMICS

the topography and size of the areas, is fixed as  $0 \leq \alpha \leq 1$ . The migratory population out of area 1 is therefore  $(1 - h_{1,t})\alpha[X_{1,t} + F(X_{1,t})]$ , so that the remaining stock browsing here during the winter becomes  $Z_{1,t} = (1 - h_{1,t})(1 - \alpha)[X_{1,t} + F(X_{1,t})]$  (again, see Figure 1). When neglecting natural mortality, which is very low (Saether et al. 1992), and assuming that all animals return after the winter season,  $(1 - h_{1,t})[X_{1,t} + F(X_{1,t})]$  is therefore the size of the sub-population 1 the next year. For sub-population 2 we have the same annual cycle except that there is no dispersal.  $Z_{2,t} = (1 - h_{2,t})[X_{2,t} + F(X_{2,t})] +$

$(1 - h_{1,t})\alpha[X_{1,t} + F(X_{1,t})]$  is, hence, the winter stock browsing in area 2 during the winter season (Figure 1). Notice that there is no biological interdependency between the two sub-populations because there is no density-dependent mortality during the winter and no winter harvesting (see below).

All the time we assume stable populations. In ecological equilibrium we have  $X_{i,t+1} = X_{i,t} = X_i$  and  $h_{i,t} = h_i$  ( $i = 1, 2$ ), and [1] and [2] write  $X_1 = (1 - h_1)[X_1 + F(X_1)]$  and  $X_2 = (1 - h_2)[X_2 + G(X_2)]$ , respectively. When replacing the harvesting fractions, the winter populations may then be

written as  $Z_1 = (1 - h_1)(1 - \alpha)[(X_1 + F(X_1))] = (1 - \alpha)X_1$  and  $Z_2 = (1 - h_2)[X_2 + G(X_2)] + (1 - h_1)\alpha[X_1 + F(X_1)] = X_2 + \alpha X_1$ . As forest damage to pine trees occurs during winter, these winter stocks determine the browsing damage. The damage functions are given by  $D_i = D_i(Z_i)$ , with  $D_i(0) = 0$ ,  $\partial D_i / \partial Z_i = D_i' > 0$  and  $D_i'' \leq 0$  ( $i = 1, 2$ ) (Storaas et al. 2001). The damage may vary between areas due to different quality of the timber stands, or simply different productivity of the forests.<sup>4</sup> The equilibrium number of animals harvested is  $H_1 = h_1[X_1 + F(X_1)] = F(X_1)$  and  $H_2 = h_2[X_2 + G(X_2)] = G(X_2)$ , respectively. The unit hunting license price, identical in the two areas, is assumed to be independent of the amount harvested and the stock sizes.<sup>5</sup> Following the practice in Scandinavia, one license allows the buyer to kill one animal, which is paid only if the animal is killed. When further assuming that the cost of the landowners of organizing the hunting is constant per animal shot and hence stock independent, the "net" license price is fixed as  $p$ . The yearly net-benefit in the two areas in biological equilibrium read therefore  $\pi_1 = pF(X_1) - D_1((1 - \alpha)X_1)$  and  $\pi_2 = pG(X_2) - D_2(X_2 + \alpha X_1)$ .

Because of the dispersal, but also because the moose is a pest and not only a value, there is an economic interdependency between the two sub-populations and the two areas. As mentioned, we analyze the harvest and browsing externalities following this interdependency within a unified management scheme, and the wildlife manager aims to find hunting quotas for the areas that maximize the total profit. Hence,  $\pi = (\pi_1 + \pi_2)$

<sup>4</sup> The damage may take place immediately and damaged young pine trees may be replaced directly. Often, however, there is a time lag between browsing and the occurrence of damage. In such instances, discounting is not taken explicitly into account in the present exposition.

<sup>5</sup> Mattson (1994) observed a positive stock-dependent willingness to pay for hunting licenses in Sweden while an ambiguous effect was observed between the price and the number of animals hunted. See also Johansson, Kriström, and Mattsson (1988). The present assumption of a fixed harvesting price can be justified by the presence of competition between different suppliers of hunting licences.

is to be maximized. The first order conditions of this problem read:<sup>6</sup>

$$F'(X_1^*) = \frac{1}{p}[(1 - \alpha)D_1'((1 - \alpha)X_1^*) + \alpha D_2'(X_2^* + \alpha X_1^*)] \quad [3]$$

and

$$G'(X_2^*) = \frac{1}{p}D_2'(X_2^* + \alpha X_1^*), \quad [4]$$

and where superscript "\*" denotes the optimal stock sizes. The biomass harvested, or hunting quotas, may next be calculated as  $H_1^* = F(X_1^*)$  and  $H_2^* = G(X_2^*)$  while the harvesting fractions follow as  $h_1^* = F(X_1^*) / [(X_1^* + F(X_1^*))]$  and  $h_2^* = G(X_2^*) / [(X_2^* + G(X_2^*))]$ .

Condition [3] indicates that harvesting should take place up to the point where the marginal natural growth is equal to the marginal grazing damage, evaluated at the hunting license price, and where the damage in both areas is taken into account due to the dispersal. Multiplying by  $p$ , it is also seen that this condition says that the stock should be kept at the point where the marginal harvesting value is exactly balanced by the marginal damage. Because the right hand side of condition [3] is positive, the population size  $X_1^*$  will always be below that of  $F'(X_1^*) = 0$ , or  $X_1^* < X_1^{msy}$ . The interpretation of condition [4] is exactly the same, except that there is no spillover of browsing damage.  $X_2^* < X_2^{msy}$  will also hold.

By taking the total differential of the two first order conditions the comparative static results can be found. A positive shift in the harvesting price gives a higher sub-population 1, and hence  $X_1^*$  moves closer to  $X_1^{msy}$  while the sub-population 2 effect is ambiguous. The direct effect is that browsing damage, measured in terms of the harvesting price, decreases, and hence both sub-

<sup>6</sup> It can easily be shown that when the natural growth functions are strictly concave and the damage cost functions are convex (as here), the second order conditions are fulfilled. Furthermore, under these conditions, the solution is unique as well.

populations increase. But when sub-population 1 increases accompanied by more dispersal, the damage in area 2 shifts up, and thus the total effect here is unclear (but see next sub-section). On the other hand, an upward shift in the marginal damage cost always means lower stock size. The dispersal coefficient has also generally ambiguous stock effects. A shift in  $\alpha$  works through the damage functions, and the direct effect on sub-population 1 is unclear, as the marginal damage in both areas has to be taken into account. Because of the ambiguous sub-population 1 effect, the sub-population 2 effect is ambiguous as well. The number of moose harvested  $H_i^*$  will change in the same direction as the stock because  $X_i^* < X_i^{msy}$ , while it can easily be demonstrated that harvesting rates  $h_i^*$  will change in the opposite direction.

These last comparative static results imply that today's management practice of neglecting dispersal (cf. the Introduction) has ambiguous stock as well as harvesting effects. On the other hand, the total profit will clearly be lower when harvesting rates and stock sizes are implemented *as if* there were no dispersal. The present management policy may also redistribute profit between areas, and thus influence the economic outcome of the landowners compared to a situation where dispersal is ignored. To see how this works, we specify the functional forms. Later, in Section 4, additional insight is demonstrated by running numerical examples.

#### Specific Functional Forms

We specify logistic natural growth functions,  $F(X_1) = rX_1(1 - X_1/K_1)$  and  $G(X_2) = rX_2(1 - X_2/K_2)$ , with  $r > 0$  as the maximum-specific growth rate, assumed to be identical for both sub-populations, and  $K_i > 0$  as carrying capacity. We use linear damage functions so that  $D_1(Z_1) = a_1Z_1 = a_1(1 - \alpha)X_1$ , with  $a_1 > 0$ , is for area 1, while  $D_2(Z_2) = a_2Z_2 = a_2(X_2 + \alpha X_1)$ , with  $a_2 > 0$ , is for area 2 (but see Appendix 2 for convex cost functions). Inserted into the first order conditions [3] and [4], we obtain  $F'(X_1^*) = [a_1(1 - \alpha) + a_2\alpha]/p$  and  $G'(X_2^*) = a_2/p$ . When solving for stock size, the results are

$$X_1^* = \frac{K_1}{2r} \left[ r - \frac{a_1(1 - \alpha) + a_2\alpha}{p} \right] \quad [5]$$

and

$$X_2^* = \frac{K_2}{2r} \left[ r - \frac{a_2}{p} \right], \quad [6]$$

respectively.

These first order conditions represent two independent equations, and hence, when the damage functions are linear, each sub-population may be managed separately in the present meaning of efficiency. On the other hand, when deciding stock size in area 1, the dispersal coefficient plays a role because it determines the marginal damage by stock 1 when the marginal damage in each area differs. Accordingly, if the marginal damages are equal, the dispersal rate vanishes from equation [5]. Notice also that the dispersal parameter does not affect the stock decision in area 2. This result hinges again on the constant marginal damage assumption (again see Appendix 2). When combining [5] and [6] it is seen that optimal stock density in area 1 will be above that of area 2 if the marginal grazing damage is lower there; that is,  $X_1^*/K_1 > X_2^*/K_2$  if  $a_2 > a_1$  for all  $0 \leq \alpha < 1$ . This is quite an intuitively appealing result as the harvesting price is the same in the two areas. With the same cost assumption, we also find  $H_1^*/K_1 > H_2^*/K_2$ .

Under these specific functional forms, a higher hunting license price means more animals in both areas. More productive ecological conditions, that is, higher carrying capacities and a higher maximum species growth rate, work in the same direction. As noted,  $\alpha$  has no sub-population 2 effect, but the sub-population 1 effect is still ambiguous as we have  $\partial X_1^*/\partial \alpha < 0$  if  $a_2 > a_1$  since more migration then increases the overall damage. The profitability effects are generally unclear. Differentiation of  $\pi_1^* = pF(X_1^*) - a_1(1 - \alpha)X_1^*$ , and using the first order condition yields  $\partial \pi_1^*/\partial \alpha = (pF' - a_1(1 - \alpha))(\partial X_1^*/\partial \alpha) + a_1X_1^* = a_2\alpha(\partial X_1^*/\partial \alpha) + a_1X_1^*$ . The area 2 profit  $\pi_2^* = pG(X_2^*) - a_2(X_2^* + \alpha X_1^*)$  is also affected, and the crucial point is what happens to  $X_1^*$  and, hence, the num-

ber of migratory species, since  $\partial\pi_1^*/\partial\alpha = -a_2(X_1^* + \alpha(\partial X_1^*/\partial\alpha))$ . Adding these, the effect on total profit is simply  $\partial\pi^*/\partial\alpha = (a_1 - a_2)X_1^*$ . In line with intuition, more dispersal, therefore, means lower total profit suggested that  $a_2 > a_1$ . Hence, under this cost assumption, total cost increases with more dispersal and dominates any possible upward shift in harvesting income.

Given these functional forms, today's practice of neglecting dispersal also has some clear profitability implications most conveniently demonstrated for area 2, as  $\pi_2^* = pG(X_2^*) - a_2(X_2^* + \alpha X_1^*)$  is only influenced by  $a_2\alpha X_1^*$ , since  $X_2^*$  is not affected by  $\alpha$  (cf. equations [5] and [6]). The area 2 profit change may then simply be written as  $a_2\alpha[X_1^0 - X_1^*]$ , where  $X_1^0$  is the optimal chosen stock size if there had been no dispersal while  $X_1^*$  is the optimal stock size subject to the actual dispersal rate. From equation [5], we observed that  $X_1^*$  decreases with  $\alpha$  suggesting that  $a_1 < a_2$ . Under this browsing cost difference assumption,  $X_1^0$  dominates  $X_1^*$  for all  $0 < \alpha \leq 1$  and the above expression therefore represents a loss of profitability. Additional insight will be demonstrated when presenting the numerical examples in Section 4.

### III. REGIME 2 MANAGEMENT WITH SEQUENTIAL HARVESTING

We have modeled the harvesting benefit and damage cost specific to the area and not the landowner. However, if the hunting quotas, in number of animals (or biomass), are distributed to landowner 1 and 2, respectively, and landowner 1 bears the damage cost taking place in area 1 while landowner 2 bears the cost in area 2, the area-specific profit coincides with landowner profit. As already indicated, such a property rights scheme is more or less in line with the present management practice in Norway, even if it may cause substantial asymmetries between the cost and benefit between landowners. Irrespective of such asymmetries, however, the general rule is that the quotas set by the wildlife manager are respected, and it is close to no cheating

or illegal harvesting.<sup>7</sup> The important reason for this is the strong social control of Scandinavian moose hunting which, as already mentioned, is a crucial social event taking place in a large number of rural communities (see, e.g., Saether et al. 1992). However, due to asymmetries, various compensation schemes may be established. Following the logic of our model, landowner 1 can pay for some (or all) of the grazing damage caused by sub-population 1 on landowner 2's property. Granting area 1 hunting licenses to landowner 2 may be another type of compensation scheme, and this is what actually takes place within the Swe-Nor moose region (cf. Section 4 below).

Instead of analyzing such compensation schemes, we will assume that the wildlife manager changes the present practice of hunting only in the fall and extends the harvesting season to include winter harvesting as well. The moose is then potentially harvested both in the fall and in the winter, and we will explore, still under the assumption of unified management, whether this (institutional) change may induce more correspondence between landowners' costs and benefits, while still assuming that area-specific profits coincide with landowner profits. Moreover, we want to study under what conditions total profitability may, in fact, increase. Winter harvesting is taking place in Sweden, but is not yet an option in Norway (Olaussen 2000).

<sup>7</sup> In the present context, landowner 2 will typically argue that landowner 1 profits at his expense. However, this argument is somewhat obscure because harvesting of sub-population 1 always reduces grazing pressure and damage taking place in area 2. In line with this, it should also be noticed that a property rights scheme following the above unified management scheme makes landowner 2 better off compared to the private solution where both landowners maximize current profit separately and reap the profit accordingly. The private solution yields first order conditions as [3] and [4], except that the term  $\alpha D_2(\cdot)$  is absent in equation [3]. In the linear version of the model, the term  $a_2\alpha$  is therefore missing on the right hand side of equation [5]. As a consequence,  $X_1$  will be higher and  $X_2$  generally lower compared to the unified management scheme. Hence, landowner (and area) 1 profit rises while landowner (and area) 2 profit falls compared to the unified management scheme when area-specific profit coincides with landowner profit.

When introducing winter harvesting we have so-called sequential harvesting.<sup>8</sup> Because the dispersal runs from area 1 to area 2, only area 2 winter harvesting is considered. Moreover, quite intuitively, if sequential harvesting should be of any economic interest, it must take place before the moose cause any substantial damage in the winter grazing area, that is., in December and January. Since the moose then typically stay within a very limited part of the winter habitat, an effective winter off take is possible. Two harvesting options in area 2 are present. One possibility is that all the harvest takes place in the winter, meaning that only the migratory moose from area 1 are sequentially harvested. Another possibility is to hunt in area 2 in the fall as well, so that both the remaining fraction of sub-population 2 and the migratory population 1 are exposed to sequential hunting. Both these possibilities are considered.

If  $y_t$  represents the fraction harvested in area 2 during the winter, both of the migratory and stationary animals are harvested as it is not possible to select between them, the population dynamics [1] and [2] (cf. also Figure 1) change to

$$X_{1,t+1} = (1 - h_{1,t})(1 - \alpha) + (1 - y_t)\alpha[X_{1,t} + F(X_{1,t})] \quad [7]$$

and

$$X_{2,t+1} = (1 - y_t)(1 - h_{2,t})[X_{2,t} + G(X_{2,t})]. \quad [8]$$

Equation [7] indicates that the sub-population 1 harvest in area 2 during the winter is  $y_t(1 - h_{1,t})\alpha[X_{1,t} + F(X_{1,t})]$ , so that the number of animals returning back to the summer range after the winter is  $(1 - y_t)(1 - h_{1,t})\alpha[X_{1,t} + F(X_{1,t})]$ . Equation [8] implies that the winter harvest of sub-population 2 is  $y_t(1 - h_{2,t})[X_{2,t} + G(X_{2,t})]$ . The winter stock in area 1 is the same as in the case without winter harvesting,  $Z_{1,t} = (1 - h_{1,t})(1 - \alpha)[X_{1,t} + F(X_{1,t})]$ , while winter

stock causing browsing damage in area 2 now becomes  $Z_{2,t} = (1 - y_t)\{(1 - h_{2,t})[X_{2,t} + G(X_{2,t})] + (1 - h_{1,t})\alpha[X_{1,t} + F(X_{1,t})]\}$  when winter harvesting takes place *before* the damage. In contrast to the previous model, the migration coefficient  $\alpha$  now influences the ecology, but only sub-population 1, and this happens indirectly through harvesting.

In ecological equilibrium, equations [7] and [8] read  $X_1 = (1 - h_1)(1 - y\alpha)[X_1 + F(X_1)]$  and  $X_2 = (1 - y)(1 - h_2)[X_2 + G(X_2)]$ , respectively. Because the harvesting rate  $h_1$  will always be positive, while  $h_2$  may be positive or zero (see below), the most convenient way to study the solution of this model seems to be to substitute  $h_1$  away from the profit functions by using the sub-population 1 equilibrium condition and introduce the sub-population 2 equilibrium condition as a constraint. When still assuming linear damage functions, the area 1 equilibrium profit function may be written as  $\pi_1 = \frac{p[(1 - y\alpha)F(X_1) - y\alpha X_1]}{(1 - y\alpha)}$

when  $h_1$  is replaced (see Appendix 1 for details). The first term on the RHS gives harvesting profit while the second term yields browsing damage. When  $q > 0$  is the winter harvesting license price, assumed to be fixed and independent of the stock size and also a 'net' price of the landowners, area 2 profit may in the same manner be written as  $\pi_2 = \frac{p h_2 [X_2 + G(X_2)] + q y \{(1 - h_2)[X_2 + G(X_2)] + \frac{\alpha X_1}{(1 - y\alpha)}\} - a_2 (1 - y) \{(1 - h_2)[X_2 + G(X_2)] + \frac{\alpha X_1}{(1 - y\alpha)}\}}{(1 - y\alpha)}$ , where the first RHS term gives the harvesting profit in the fall, the second term is the winter harvesting profit while the last term yields the damage cost.

The hunting license price is presumably lower in the winter than in the fall because of, *inter alia*, a thinner market for hunting licenses.<sup>9</sup> Accordingly,  $p \geq q$  is assumed to

<sup>8</sup> Among others, Laukkanen (2001) analyses a sequential fishery model. However, we are not aware of any bio-economic analysis of this type for land-based resources.

<sup>9</sup> A thinner market is expected due to unfavorable hunting conditions (snow and cold weather). In addition, the trophy value aspect is less as the male moose has lost his antlers.



hold in the following. The economic objective is still to maximize total profit  $\pi = (\pi_1 + \pi_2)$ . The Lagrangian of this maximization problem can be written as  $L = (\pi_1 + \pi_2) + \lambda\{(1 - y)(1 - h_2)[X_2 + G(X_2)] - X_2\}$ , when the sub-population 2 equilibrium condition is introduced as a constraint so that  $\lambda$  may be interpreted as the sub-population 2 shadow price. Because both sub-populations create both positive and negative value and the license prices are stock-independent, harvest will take place in both areas, i.e.,  $h_1^* > 0$  and  $(h_2^* + y^*) > 0$ . Generally, there are three possibilities in area 2; a)  $h_2^* > 0$ ,  $y^* > 0$ , b)  $h_2^* = 0$ ,  $y^* > 0$  and c)  $h_2^* > 0$ ,  $y^* = 0$ . We study these cases in turn and we start with case a.

#### Case a

Appendix 1 demonstrates that case a) with  $h_2^* > 0$ ,  $y^* > 0$  occurs when

$$X_1^* = \frac{K_1}{2r} \left[ r - \frac{a_1(1 - \alpha) + a_2(1 - y^*)\alpha + (p - q)y^*\alpha}{p(1 - y^*\alpha)} \right], \quad [9]$$

$$X_2^* = \frac{K_2}{2r} \left[ r - \frac{(p - q)y^* + a_2(1 - y^*)}{p(1 - y^*)} \right], \quad [10]$$

and

$$(p - q) = \frac{(a_2 - a_1)(1 - \alpha)}{1 + \frac{(1 - y^*\alpha)^2 X_2^*}{(1 - y^*)^2 \alpha X_1^*}} \quad [11]$$

hold. These three equations jointly determine  $X_1^*$ ,  $X_2^*$  and  $y^*$ , while  $h_1^*$  and  $h_2^*$  follow from the ecological equilibrium conditions. The harvesting quotas, in number of animals (or biomass), can then be found. Under the present assumption of  $p \geq q$ , equation [11] is fulfilled under two main conditions; either when  $p = q$  is accompanied by  $a_1 = a_2$  or  $\alpha = 1$ , or when  $p > q$  holds together with  $a_2 > a_1$  and  $0 < \alpha < 1$ . We discuss these two sub-cases, a.i) and a.ii), respectively, in turn.

In sub-case a.i, with equal harvesting prices  $p = q$  and equal marginal damage in the two areas  $a_1 = a_2 = a$ , we have

one degree of freedom in the system as equation [11] vanishes and gives no information.<sup>10</sup> At the same time, conditions [9] and [10] reduce to  $X_1^* = (K_1/2r)(r - a/p)$  and  $X_2^* = (K_2/2r)(r - a/p)$ , respectively. Consequently, as in the linear model without winter harvesting, equilibrium stock sizes are determined independently of each other. In equilibrium, the sub-population 2 equation [8] may be written as  $(1 - y^*)(1 - h_2^*) = X_2^*/[X_2^* + G(X_2^*)]$ . Since  $X_2^*$  is determined from the above reduced version of condition [10] alone, this means that all combinations of  $h_2^*$  and  $y^*$  being in accordance with the population equilibrium condition, represent efficient harvesting rates. The area 2 harvesting rates are therefore *not* uniquely determined due to the fact that there is one degree of freedom in the system. The economic reason for this result is that when there are no price or cost differences, overall profitability is not affected when the moose is harvested in area 2. For a given  $y^*$  in accordance with the sub-population 2 equilibrium condition and with  $X_1^*$  fixed by the first order condition [9], the area 1 harvesting rate follows next from the sub-population 1 equilibrium condition as  $h_1^* = 1 - X_1^*/\{(1 - y^*\alpha)[X_1^* + F(X_1^*)]\}$ . A numerical illustration is given below.

Sub-case a.ii, when  $y^* > 0$  and  $h_2^* > 0$ , follows when  $p > q$  holds together with  $a_2 > a_1$  and  $0 < \alpha < 1$ . In this case, equation [11] does not vanish, and the first order condition [9], [10], and [11] simultaneously determine  $X_1^*$ ,  $X_2^*$ , and  $y^*$ . This sub-case can be considered somewhat more general than a.i), as a strictly lower winter harvesting license price seems more realistic (cf. footnote 9). Higher profit when the winter harvesting price is lower seems counterintuitive. The reason is, however, quite simple as winter harvesting means that it is possible to separate the harvest of the migratory and the stationary fraction of sub-population 1, and thus hunt the fraction of the migratory sub-population causing most

<sup>10</sup> Obviously,  $\alpha = 1$  produces the same result as  $a_1 = a_2$  since  $a_1$  is irrelevant when the whole sub-population 1 migrates out of area 1 (see main text below).

severe browsing damage more efficiently.<sup>11</sup> As above, it can be shown that the dispersal coefficient has no effect on the sub-population 2 stock. On the other hand, just as in the model without winter harvesting, we find  $\partial X_1^*/\partial\alpha < 0$ , as more migration means increased grazing damage, and hence it is economically beneficial to reduce the number of migratory animals.

#### Cases b and c

We then have case b) with  $h_2^* = 0$  and  $y^* > 0$  so it is profitable to only harvest sequentially the migratory species from area 1. In Appendix 1, it is shown that the economic and ecological conditions for this result is that

$$(p - q) < \frac{(a_2 - a_1)(1 - \alpha)}{1 + \frac{(1 - y^*\alpha)^2 X_2^*}{(1 - y^*)^2 \alpha X_1^*}} \quad [12]$$

should hold. Hence, if  $p = q$  is accompanied by  $a_2 > a_1$ , and  $0 < \alpha < 1$ , area 2 harvesting in the fall is not profitable. The reason is obvious as there is no price effect due to the lower harvesting value counteracting the gain of selective harvesting. On the other hand, if  $p > q$ , there must be a certain gap between the marginal damage costs if it is to be economically beneficial, with the entire area 2 harvest taking place during the winter (see also the numerical illustrations given below).

This leads us to the final case c) with  $h_2^* > 0$  and  $y^* = 0$ , and no sequential harvesting at all. Hence, we are back in the previous Regime 1 management situation. The stock sizes are then found by [9] and [10], coinciding with equations [5] and [6], respectively. The economic and ecological conditions leading to this outcome may be stated as

<sup>11</sup> As pointed out by one of the referees, higher profit might also be seen in light of Le Chatelier's principle as introducing winter harvesting means more flexibility as the previous Regime 1 (tacitly) imposed constraint of no winter harvesting is eliminated.

$$(p - q) > \frac{(a_2 - a_1)(1 - \alpha)}{1 + \frac{X_2^*}{\alpha X_1^*}} \quad [13]$$

(again, see Appendix 1). Consequently, if  $p > q$  holds, together with  $a_2 = a_1$ , and  $0 < \alpha < 1$ , no sequential harvesting is profitable, as these economic conditions obviously produce no gain from selective harvesting. Moreover, even if there is a selection gain, and we have  $a_2 > a_1$ , the same may happen if the loss due to lower harvesting price in the winter dominates the potential gain from selection.

When  $X_1^*$  and  $X_2^*$  are replaced by equations [9] and [10] with  $y^* = 0$ , or equally by [5] and [6], it is possible to say something more definite as [13] then yields

$$(p - q) > \frac{(a_2 - a_1)(1 - \alpha)}{1 + \frac{K_2 \left[ r - \frac{a_2}{p} \right]}{\alpha K_1 \left[ r - \frac{(1 - \alpha)a_1 + a_2}{p} \right]}} = v. \quad [13']$$

Hence,  $v$  yields the smallest price difference that ensures  $y^* = 0$ . When  $a_2 > a_1$  and  $v > 0$ , situation c) with  $h_2^* > 0$  and  $y^* = 0$  therefore occurs when  $q < (p - v)$ . This case is also illustrated numerically below.

#### IV. NUMERICAL ILLUSTRATIONS

Our theoretical models will now be illustrated by data from the so-called Swe-Nor moose region on the border between Sweden and Norway, some 250 kilometers north of Oslo. The Swe part of the region, located in Torsby municipality (Sweden), covers 43,600 ha, while the Nor part of the region, located in Trysil municipality (Norway), covers 78,300 ha, altogether 121,900 ha. This region fits well with the present assumption of winter migration. Due to snow and forage conditions, the winter migration moves from Nor to Swe. It is estimated that about 30% of the moose browsing in the Swe area in the winter are migratory moose from the Nor area, and the forestry damage here is con-

TABLE 1  
REGIME 1. STOCK SIZES (NUMBER OF MOOSE), HARVESTING RATES, AND PROFIT  
(1,000 NOK) FOR DIFFERENT MIGRATION RATES

	Migration Rate ( $\alpha$ )					
	0.0	0.2	0.4	0.6	0.8	1.0
Stock, area 1 $X_1^*$	1,158	1,009	860	711	562	413
Stock, area 2 $X_2^*$	231	231	231	231	231	231
Total stock $X^*$	1,389	1,240	1,091	942	793	644
Harvest rate, area 1 $h_1^*$	0.26	0.27	0.28	0.28	0.29	0.30
Harvest rate, area 2 $h_2^*$	0.30	0.30	0.30	0.30	0.30	0.30
Profit, area 1 $\pi_1^*$	900	1,188	1,357	1,406	1,337	1,148
Profit, area 2 $\pi_2^*$	64	-440	-797	-1,003	-1,060	-969
Total profit $\pi^*$	964	748	561	404	276	179

Parameter values:  $a_1 = 1,500$  NOK per moose;  $a_2 = 2,500$  NOK per moose;  $p = 6,500$  NOK per moose;  $r = 0.47$ ;  $K_1 = 4,550$  number of moose;  $K_2 = 2,540$  number of moose.

siderable. A unified management plan for the whole area is worked out, and harvesting quotas are allocated to the Nor part and the Swe part proportionally to the number of animals in the areas before migration takes place. The presence of dispersal and damage in the Swe area is reflected by the fact that Swe landowners are given hunting licenses in the Nor area; that is, a kind of side-payment is present (for more details, see Olaussen 2000). The harvest in both areas takes place before the winter migration.

As above, we specify logistic natural growth functions and use linear damage functions. All parameter values in the simulations are based on Olaussen (2000). The maximum species growth rate is given as  $r = 0.47$  while  $K_1 = 4,550$  and  $K_2 = 2,540$  (number of moose) are the carrying capacities, assumed to be proportional to the size of the areas, so that area 1 is referring to Nor while area 2 is Swe. The price of the fall hunting license is  $p = 6,500$  (NOK per moose, 1999 prices) while the marginal damage cost is higher in Swe than in Nor as Swe is mainly located at a lower altitude with a more productive forestry. In the baseline calculations, the marginal damage costs are given as  $a_1 = 1,500$  and  $a_2 = 2,500$  (NOK per moose, 1999 prices). The baseline migration parameter is assumed to be  $\alpha = 0.2$ . However, because of the importance of dispersal, we also study the effects of other values. Table 1 reports the

results for various values of  $\alpha$  when we have management Regime 1 and hence no winter harvesting.

Sub-population 1 falls with increased migration because  $a_2 > a_1$  while sub-population 2 is unaffected, cf. equations [5] and [6] above. Under the given cost assumption, it is then profitable to reduce the total stock compared to a scenario without dispersal. Furthermore, area 1 profit initially increases when  $\alpha$  shifts up and then decreases,<sup>12</sup> while area 2 profit exhibits the opposite pattern. Total profit falls. It is also seen that  $\pi_2^*$  becomes negative when  $\alpha$  exceeds a certain (small) value. However, it should be noted that this is a calculated loss, as the forest damage in most instances represents future profit loss (cf. Section 2). In Appendix 2 we demonstrate what happens when the damage cost functions are strictly convex.

Today's practice of ignoring migration may also be illustrated. As an example, assume that 20% of sub-population 1 stays in area 2 during winter (baseline assumption),  $\alpha = 0.2$ , but this is not taken into account and stock sizes are managed as if no migration is present,  $\alpha = 0$ . This has no consequences for the efficient allocation of sub-population 2, while sub-population 1

<sup>12</sup> The decreasing area 1 profit when  $\alpha$  exceeds a certain level may seem counterintuitive. At this level, reduced browsing damage is outweighed by an even higher reduction in harvesting income.

TABLE 2  
REGIME 2, CASE A.1). STOCK SIZES (NUMBER OF MOOSE), HARVESTING RATES, AND  
PROFIT (1,000 NOK) FOR VARIOUS AREA 2 WINTER HARVESTING RATES

	Winter Harvest Rate ( $y^*$ )					
	0.00	0.05	0.10	0.15	0.20	0.25
Stock, area 1 $X_1^*$	786	786	786	786	786	786
Stock, area 2 $X_2^*$	439	439	439	439	439	439
Total stock $X^*$	1,224	1,224	1,224	1,224	1,224	1,224
Harvest rate, area 1 $h_1^*$	0.28	0.27	0.27	0.26	0.25	0.24
Harvest rate, area 2 $h_2^*$	0.28	0.24	0.20	0.15	0.10	0.04
Profit, area 1 $\pi_1^*$	729	664	599	532	464	394
Profit, area 2 $\pi_2^*$	-83	-19	47	114	182	252
Total profit $\pi^*$	646	646	646	646	646	646

Parameter values:  $a_1 = a_2 = a = 2,000$  NOK per moose;  $p = q = 6,500$  NOK per moose;  $\alpha = 0.2$ ;  $r = 0.47$ ;  $K_1 = 4,550$  number of moose;  $K_2 = 2,540$  number of moose.

becomes too high;  $X_1^0 = 1,158$  animals instead of  $X_1^* = 1,009$  (Table 1), cf. also the analytical demonstration in Section 2. Using the actual migration rate,  $\alpha = 0.2$ , this stock size gives an annual profit of 1,248 (1,000 NOK) in area 1 and -515 in area 2.<sup>13</sup> The area 1 profit is thus 60 (1,248 - 1,188) higher than if dispersal had been taken into account, while area 2 profit is 75 (-515 - (-440)) lower. Hence, the profit loss in area 2 dominates the gain in area 1, resulting in an overall annual loss of 15. The area 1 net gain is due to an addition of 238 in harvesting benefit, dominating an additional loss of 178 in grazing damage. The area 2 loss reflects more grazing damage caused by the migratory species, as the size of sub-population 2 is unchanged.

As demonstrated, the consequence of neglecting migration translates into a substantial profit transfer between the areas while the overall loss is quite modest (just 2%). With more dispersal, the profit transfer and the total loss increase, and for  $\alpha = 0.4$  and  $0.6$  the overall loss is about 10% and 33%, respectively. Generally, the loss increases for higher grazing damage and more substantial cost differences (see also Section 2 above). It is also important to realize that no ecological mechanism re-

veals this type of allocation error as the dispersal does not influence the ecology; that is, all corresponding harvesting rates and stock levels in Table 1 fit the sub-population 1 ecological-equilibrium condition,  $X_1 = (1 - h_1)[X_1 + F(X_1)]$ . Moreover, as the grazing damage basically represents future calculated profit losses, there is no clear economic signal indicating allocation errors. These two features may explain today's practice of ignoring migration.

We now illustrate the Regime 2 winter harvesting management. We start with the situation when both sub-populations are sequentially harvested given the same harvesting prices winter and fall, together with the same marginal damage cost in both areas. This was referred to as case a.i in the above Section 3, and it was demonstrated that all combinations of area 2 winter and fall harvesting in accordance with the population equilibrium represented efficient harvesting rates. Table 2 gives an illustration for various values of  $y^*$ .

While  $X_1^*$  and  $X_2^*$  are independent of the harvesting composition in area 2, both  $h_2^*$  and  $h_1^*$  decrease when  $y^*$  increases. Total profit,  $\pi^*$ , is also unaffected by the area 2 harvesting composition as all harvest rates in accordance with the biological equilibrium for sub-population 2 represent profit maximizing allocations. Because winter harvesting affects the harvest rate in area 1, the distribution of the fixed total profit

<sup>13</sup> For area 1 we obtain  $pF(X_{10}) - a_1(1 - \alpha)X_{10} = 6,500 \cdot 0.47 \cdot 1,158(1 - 1,158/4,550) - 1,500 \cdot (1 - 0.2) \cdot 1,158 = 1,248$  (1,000 NOK).

TABLE 3  
REGIME 2. STOCK SIZES (NUMBER OF MOOSE), HARVESTING RATES, AND  
PROFIT (1,000 NOK) FOR VARIOUS AREA 2 HARVESTING SCHEMES

	Winter Harvesting Price ( $q$ )		
	6000 Case c): $h_2^* > 0, y^* = 0$	6150 Case a.ii): $h_2^* > 0, y^* > 0$	6500 Case b): $h_2^* = 0, y^* > 0$
Stock, area 1 $X_1^*$	1,009	1,018	1,047
Stock, area 2 $X_2^*$	231	209	231
Total stock $X^*$	1,240	1,227	1,278
Harvest rate, area 1 $h_1^*$	0.27	0.25	0.22
Harvest rate, area 2 $h_2^*$	0.30	0.20	0.00
Winter harvest rate $y^*$	0.00	0.13	0.30
Profit, area 1 $\pi_1^*$	1,188	984	692
Profit, area 2 $\pi_2^*$	-440	-235	110
Total profit $\pi^*$	748	749	802

Parameter values:  $a_1 = 1,500$  NOK per moose;  $a_2 = 2,500$  NOK per moose;  $p = 6,500$  NOK per moose;  $\alpha = 0.2$ ;  $r = 0.47$ ;  $K_1 = 4,550$  number of moose;  $K_2 = 2,540$  number of moose.

between  $\pi_1^*$  and  $\pi_2^*$  changes for various values of  $y^*$ , and in line with intuition, more winter harvesting increases area 2 profit at the expense of area 1 profit.

When landowner profit coincides with area-specific profit, profit may be redistributed between landowners by implementing winter harvesting without affecting total profitability. Under the given price and cost conditions, this is obviously a very effective instrument for redistribution, and it is possible to attain a close correspondence between the costs and benefits facing landowners. In addition, we find that the migration coefficient influences neither the equilibrium populations, harvesting rates,  $h_2^*$  and  $y^*$ , nor total profit. On the other hand,  $h_1^*$  is affected by the dispersal pattern, and a higher  $\alpha$  reduces  $\pi_2^*$  and increases  $\pi_1^*$ .

Finally, Table 3 illustrates the other cases of sequential harvesting, referred to as b and c together with a.ii, where the fall harvesting price is still fixed as  $p = 6,500$ . Together with the other parameter values, we then find that the smallest price difference that ensures  $y^* = 0$  becomes  $v = 373$  (NOK per moose), cf. equation [13']. Accordingly, winter harvesting is not profitable when  $q < (p - v) = 6,127$ , and the table demonstrates this case when  $q = 6,000$  (see also Table 1). On the other

hand,  $y^* > 0$  is optimal when  $q > 6,127$ , and simulations demonstrate that we have situation a.ii with  $y^* > 0$ , as well as  $h_2^* > 0$  up to  $q = 6,183$ . Table 3 illustrates this case when  $q = 6,150$ . As demonstrated in Section 3 (above), case b) with  $h_2^* = 0$  and  $y^* > 0$ , takes place for an even higher value of  $q$ . Table 3 illustrates this case when  $q = 6,500$ .

The calculations reported in Table 3 again indicate that introduction of winter harvesting may be a very powerful tool for redistribution of profit between areas and landowners while the total profit and the stock sizes are only modestly affected. In case a.ii, the selection gain more than outbalances the loss due to lower harvesting price, and for the given parameter values this is accompanied by a quite significant redistribution of profit between areas and landowners, compared to situation c with no winter harvesting. This redistribution is further strengthened when  $q$  shifts up, and we have case b with only winter harvesting in area 2. The redistribution is always governed by large shifts in harvesting rates.

## V. CONCLUDING REMARKS

In this paper, we have analyzed a species that is both valuable and a pest and where there is an economic interdependency be-

tween different landowners utilizing the species due to dispersal. Management is studied within a unified framework, where the wildlife manager (the planner) aims to find area-specific harvesting quotas that maximize the net economic benefit of harvesting income and forestry damage to the areas taken together in biological equilibrium. The wildlife manager, therefore, sets quotas for the areas based on an overall economic and ecological assessment. The cost and benefit streams are controlled by the wildlife manager and distributed to landowners. Such a property rights structure is more or less in line with present management practice in Norway and Scandinavia.

In the first part of the paper—the Regime 1 situation where harvesting of the *Alces alces* only takes place in the fall—we show how dispersal influences stock sizes, harvesting quotas, and browsing damage. It is also demonstrated that the present practice of neglecting migration leads either to too large or to too small populations of migrating moose. By taking migration into account when setting harvesting quotas, a larger degree of accordance between harvesting income and browsing damage between the different landowners is attained. In addition, the total economic viability of the moose populations generally increases.

In the second part of the paper, still under a unified management scheme, we analyze the Regime 2 situation where it is opened up for winter harvesting and sequential harvesting in the area where the browsing damage is most substantial. It is demonstrated that winter harvesting may improve total profitability, even if the harvesting license price is lower in the winter than in the fall. Increased overall profitability with a lower hunting license price in the winter is a counterintuitive result. The explanation is that through winter harvesting it is possible to separate the harvest of the migratory and the stationary fraction of the migratory sub-population, and thus more efficiently hunt the fraction of the migratory sub-population that causes most severe grazing damage. This selection

gives a potential overall profitability gain, while the reduced hunting license price represents a potential loss. A substantial difference in harvesting prices reduces the efficiency of winter harvesting as a tool in wildlife management while a substantial difference in browsing damage works in the opposite direction.

It is also shown that winter harvesting seems to be a very effective measure to redistribute harvesting income in accordance with browsing costs between areas and landowners. Winter harvesting is, however, only one possible way to redistribute profit. The above mentioned compensation scheme in the Swe-Nor region allowing the Swe landowners to hunt in the Nor area is another possibility, and represents a type of side-payment. One obvious argument for the winter harvesting alternative is that such a scheme may increase overall profit. One argument against this alternative is that it introduces an additional uncertainty as the assumption of the same harvesting fraction of the migratory and stationary animals during the winter may be violated. Hence, when this happens and if the resulting stock level in the winter harvesting area becomes low, the question of inbreeding and the threat of depletion may arise. In such situations, neglecting stochastic elements, as we have done, is a critical assumption. The existing side payment compensation scheme may therefore be better suited to handle uncertainties with low population levels.

Models are only approximations of how we conceive reality, and they are only as good as the assumptions on which they are based. Environmental and biological stochastic variations are neglected, and potentially instability problems are not studied. The analysis is carried out in ecological equilibrium where current profit is maximized. Maximizing present-value profit is an obvious alternative management goal. Under the given cost and benefit assumptions, such a problem is linear in the harvesting rates controlling the dynamics, and hence it is of the “singular” type (Clark 1990). The analysis of the long-term equilibrium (steady-state) of this problem, however, does not add much compared to

the present analysis as the two equilibrium solutions coincide when the rate of discount is equal to zero (see, e.g., Munro and Scott 1985). On the other hand, there is a fundamental difference between these two approaches as the present exposition of maximizing profit in ecological equilibrium implies that the moose stock as a capital asset is neglected. Hence, when the discount rate is equal to zero, the opportunity cost of capital is zero as well. Our analysis is also carried out in an aggregate manner because the moose population is considered as biomass. The reality is obviously more complex as there are selective harvesting schemes with different harvesting values between males, females, and calves, and there are variations in grazing pressure and damage between the different sex and age groups. The migration pattern may clearly also be more complex than just seasonal migration. However, by making all these simplifications, it is possible to reveal some important driving forces that we will also find in a more complex, and hence realistic, setting. The present model framework may also be applicable in other economic, ecological and institutional settings when studying fugitive species representing positive and negative value enjoyed by different agents or groups of people.

## APPENDIX 1

### REGIME 2 MANAGEMENT

As  $Z_1 = (1 - h_1)(1 - \alpha)[X_1 + F(X_1)]$  is the equilibrium area 1 winter stock, the area 1 equilibrium profit writes  $\pi_1 = ph_1[X_1 + F(X_1)] - a_1(1 - h_1)(1 - \alpha)[X_1 + F(X_1)]$  under the assumption of a linear damage function. When replacing  $h_1$  by use of sub-population 1 equilibrium condition  $h_1 = 1 -$

$\frac{X_1}{(1 - y\alpha)[X_1 + F(X_1)]}$ , the expression for  $\pi_1$  in the main text is obtained.

The size of the equilibrium winter stock in area 2 becomes  $Z_2 = (1 - y)\{(1 - h_2)[X_2 + G(X_2)] + (1 - h_1)\alpha[X_1 + F(X_1)]\}$ . The winter harvest of sub-population 1 is  $y(1 - h_1)\alpha[X_1 + F(X_1)]$  while the winter harvest of sub-population 2 is  $y(1 - h_2)[X_2 + G(X_2)]$ . The area 2 profit function there-

fore reads  $\pi_2 = ph_2[X_2 + G(X_2)] + qy\{(1 - h_2)[X_2 + G(X_2)] + (1 - h_1)\alpha[X_1 + F(X_1)]\} - a_2(1 - y)\{(1 - h_2)[X_2 + G(X_2)] + (1 - h_1)\alpha[X_1 + F(X_1)]\}$ . When again replacing  $h_1$  by the sub-population 1 equilibrium condition, we obtain  $\pi_2$  as given in the main text.

The first order conditions of the maximization problem  $L = (\pi_1 + \pi_2) + \lambda\{(1 - y)(1 - h_2)[X_2 + G(X_2)] - X_2\}$  (cf. the main text) reads

$$\begin{aligned} \frac{\partial L}{\partial X_1} &= 0 \rightarrow F'(X_1) \\ &= \frac{a_1(1 - \alpha) + a_2(1 - y)\alpha + (p - q)y\alpha}{p(1 - y\alpha)}, \quad [\text{A1}] \end{aligned}$$

$$\begin{aligned} \frac{\partial L}{\partial X_2} &= 0 \rightarrow G'(X_2) \\ &= \frac{\lambda}{ph_2 + [qy + (\lambda - a_2)(1 - y)](1 - h_2)} - 1, \quad [\text{A2}] \end{aligned}$$

$$\frac{\partial L}{\partial h_2} \leq 0 \rightarrow [p - qy + (a_2 - \lambda)(1 - y)] \leq 0; h_2 \geq 0 \quad [\text{A3}]$$

and

$$\begin{aligned} \frac{\partial L}{\partial y} &\leq 0 \rightarrow \frac{(a_2 - a_1)(1 - \alpha) - (p - q)}{(1 - y\alpha)^2} \\ &\quad - (\lambda - q - a_2)(1 - h_2) \frac{X_2 + G(X_2)}{\alpha X_1} \leq 0; \\ y &\geq 0. \quad [\text{A4}] \end{aligned}$$

In addition, we have the biological equilibrium constraint for sub-population 2:

$$(1 - y)(1 - h_2)[X_2 + G(X_2)] = X_2. \quad [\text{A5}]$$

The above system yields five conditions between five variables,  $X_1$ ,  $X_2$ ,  $h_2$ ,  $y$  and  $\lambda$ . The area 1 harvesting fraction follows then recursively through the sub-population 1 equilibrium condition:

$$X_1 = (1 - h_1)(1 - y\alpha)[X_1 + F(X_1)]. \quad [\text{A6}]$$

When the ecological and economic conditions lead to possibility a with  $h_2^* > 0$  and  $y^* > 0$ , [A3] as well as [A4] hold as equations. When manipulating [A3] slightly the shadow price may be written as  $\lambda^* = a_2 + p + \frac{(p - q)y^*}{(1 - y^*)}$ . Substitution into

TABLE A1  
REGIME 1. STRICTLY CONVEX GRAZING COSTS, STOCK SIZES  
(NUMBER OF MOOSE), HARVESTING RATES, AND PROFIT  
(1,000 NOK) FOR DIFFERENT MIGRATION RATES

	Migration Rate ( $\alpha$ )					
	0.0	0.2	0.4	0.6	0.8	1.0
Stock, area 1 $X_1^*$	664	688	653	542	373	197
Stock, area 2 $X_2^*$	188	134	84	59	69	110
Total stock $X^*$	852	822	737	601	442	307
Harvest rate, area 1 $h_1^*$	0.29	0.29	0.29	0.29	0.30	0.31
Harvest rate, area 2 $h_2^*$	0.30	0.31	0.31	0.32	0.31	0.31
Profit, area 1 $\pi_1^*$	1,002	1,178	1,277	1,220	964	576
Profit, area 2 $\pi_2^*$	71	-266	-606	-795	-715	-425
Total profit $\pi^*$	1,073	912	671	425	249	150

Parameter values:  $a_1 = 1,100$  NOK per moose;  $a_2 = 2,300$  NOK per moose;  $b_1 = b_2 = 1.6$  NOK per moose<sup>2</sup>;  $p = 6,500$  per moose;  $r = 0.47$ ;  $K_1 = 4,550$  number of moose;  $K_2 = 2,540$  number of moose.

[A2] gives  $G'(X_2^*) = \frac{(p-q)y^* + a_2(1-y^*)}{p(1-y^*)}$ , and

solving for the stock size under logistic growth yields the main text equation [10] while the main text equation [9] follows directly from [A1]. Combination of [A3] and [A4] as equities and [A5] yield condition [11].

Possibility b) with  $h_2^* = 0$  and  $y^* > 0$  happens with [A3] as an inequality and [A4] as an equality. [A3] then states the shadow price as  $\lambda^* > a_2 + p + \frac{(p-q)y^*}{(1-y^*)}$ . Combination of conditions [A3]-[A5] gives the main text inequality [12].

Finally, we have possibility c) with  $h_2^* > 0$  and  $y^* = 0$ . [A3] then holds as equality while [A4] is an inequality. [A3] now therefore yields the shadow price as  $\lambda^* = a_2 + p$ . Hence, adding one more sub-population 2 moose to be hunted increases overall profitability with the amount of  $a_2 + p$  due to reduced area 2 damage cost and increased hunting profit. Combination of conditions [A3]-[A5] gives the main section inequality [13].

first order conditions [5] and [6] are then replaced by

$$X_2^* = \frac{\left[ r - \frac{a_1(1-\alpha) + a_2\alpha + b_2\alpha X_2^*}{p} \right]}{\left[ \frac{2r}{K_1} + \frac{b_1(1-\alpha)^2 + b_2\alpha^2}{p} \right]} \quad [\text{A5}']$$

and

$$X_2^* = \frac{1}{\left[ \frac{2r}{K_2} + \frac{b_2}{p} \right]} \left[ r - \frac{a_2 + b_2\alpha X_2^*}{p} \right], \quad [\text{A6}']$$

respectively. In contrast to the linear cost case, these conditions are interdependent. Moreover, the migration coefficient affects both sub-populations.

Table A1 demonstrates some numerical results where the parameters in the damage functions are calibrated so that the average damage cost in both areas are close to the average (= marginal) cost in the linear case for the baseline migration coefficient  $\alpha = 0.2$ . The average damage cost is 1,500 (NOK per moose) in area 1 and 2,500 in area 2 when  $X_1^* = 614$  and  $X_2^* = 139$ .

Table A1 shows that when having convex damage functions we obtain lower stock sizes for the same average damage costs as in the linear case because the marginal damage costs now are higher. The profitability distribution among the two areas, however, follows much of the same pattern as in the linear case in Section 4.

## APPENDIX 2

### CONVEX DAMAGE COST FUNCTIONS REGIME 1 MANAGEMENT

Strictly convex grazing damage costs are introduced by specifying the cost functions as  $D_i = a_i Z_i + \frac{b_i}{2} Z_i^2$  with  $a_i > 0$  and  $b_i > 0$  ( $i = 1, 2$ ). The



## References

- Anderson, L. G. 2002. "A Bioeconomic Analysis of Marine Reserve." *Natural Resource Modeling* 15 (3): 311-34.
- Ball, J. P., C. Nordengren, and K. Wallin. 2001. "Partial Migration by Large Ungulates: Characteristics of Seasonal Moose *Alces alces* Ranges in Northern Sweden." *Wildlife Biology* 7 (1): 39-47.
- Bhat, M. G., R. G. Huffaker, and S. M. Lehnhart. 1996. "Controlling Transboundary Wildlife Damage: Modeling under Alternative Management Scenarios." *Ecological Modelling* 92 (2-3): 215-24.
- Bromley, D. 1991. *Environment and Ecology*. Oxford, U.K.: Blackwell.
- Bulte, E., and G. C. van Kooten. 1998. "Economics of Antipoaching Enforcement and the Ivory Trade Ban." *American Journal of Agricultural Economics* 81 (2): 453-66.
- Clark, C. 1990. *Mathematical Bioeconomics*. 2nd ed. New York: John Wiley.
- Conrad, J. M. 1999. "The Bioeconomics of Marine Sanctuaries." *Journal of Bioeconomics* 1 (2): 205-17.
- Flaaten, O., and K. Stollery. 1996. "The Economic Cost of Biological Predation." *Environment and Resource Economics* 8 (1): 75-95.
- Huffaker, R. G., M. G. Bhat, and S.M. Lehnhart. 1992. "Optimal Trapping Strategies for Diffusing Nuisance-Beaver Populations." *Natural Resource Modeling* 6 (1): 71-97.
- Johansson, P.-O., B. Kriström, and L. Mattsson. 1988. "How Is the Willingness To Pay for Moose Hunting Affected by the Stock of Moose? An Empirical Study of Moose-Hunters in the County of Västerbotten." *Journal of Environmental Management* 26 (3): 163-71.
- Laukkanen, M. 2001. "A Bioeconomic Analysis of the Northern Baltic Salmon Fishery: Coexistence versus Exclusion of Competing Sequential Fisheries." *Environmental and Resource Economics* 18 (3) 293-315.
- Mattsson, L. 1994. "Att Kvantifiera Viltets Jaktvärde." *Arbetsrapport nr. 192*. Umeå, Sweden: Sveriges Lantbruksuniversitet.
- Munro, G., and A. Scott. 1985. "The Economics of Fishery Management." In *Handbook of Natural Resource and Energy Economics*, vol. 2, ed. A. V. Kneese and J. L. Sweeney. Amsterdam: Elsevier Science.
- Olaussen, J. O. 2000. "Forvaltning av en Migrenderende Viltressurs. En Bioøkonomisk Analyse av Elg." Master's thesis, Department of Economics, Norwegian University of Science and Technology, Trondheim, Norway.
- Sanchirico, J., and J. Wilen. 2001. "A Bioeconomic Model of Marine Reserve Creation." *Journal of Environmental Economics and Management* 42 (3): 257-76.
- Saether, B-E., K. Solbraa, D. P. Sødal, and O. Hjeljord. 1992. "Sluttrapport Elg-Skog-Samfunn." *Forskningsrapport nr. 28*. Trondheim, Norway: Norwegian Institute for Nature Research.
- Schulz, C. E., and A. Skonhoft. 1996. "Wildlife Management, Land-Use and Conflicts." *Environment and Development Economics* 1 (3): 265-80.
- Skonhoft, A., N. Yoccoz, and N. C. Stenseth. 2002. "Management of a Chamois (*Rupicapra rupi-capra*) Moving between a Protected Area and a Hunting Area." *Ecological Applications* 12:1199-1211.
- Stenseth, N. C., H. Leirs, A. Skonhoft, S. A. Davis, R. P. Pech, H. P. Andreassen, G. R. Singleton, M. Loma, R. S. Machang, R. H. Makundi, Z. Zhang, P. R. Brown, D. Shi, and X. Wan. 2003. "Mice, Rats and People: The Bio-Economics of Agricultural Rodent Pests." *Frontiers in Ecology and the Environment* 1 (7): 367-75.
- Storaas, T., H. Gundersen, H. Henriksen, and H. Andreassen. 2001. "The Economic Value of Moose in Norway—A Review." *Alces* 37 (1): 97-108.
- Zivin, J., B. M. Hueth, and D. Zilberman. 2000. "Managing a Multiple-Use Resource: The Case of Feral Pig Management in California Rangeland." *Journal of Environmental Economics and Management* 39 (2): 189-204.