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# The costs and benefits of a migratory species under different management schemes

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**Abstract**

This paper analyses how different management schemes influence the exploitation and economics of a wildlife population—the moose (*Alces alces*)—that is both a value (harvesting income) and a pest (forestry damage). Two regimes are explored; the unified management scheme where the wildlife manager aims to find harvesting quotas that maximise the overall benefit of the moose population, and the market solution where the landowners follow their narrow self-interests and maximise their private profit. Because the moose is partly a migratory species, these regimes will differ both with respect to harvesting income and browsing damage, and the landowners will experience different profit. The unified scheme is very similar to the actual Scandinavian management, while the market solution is closer to the management policy one finds in North America. In the first part of the paper it is shown how the harvesting quotas and browsing damage under these two regimes are influenced by dispersal as well as other ecological and economic factors. In the last part of the paper it is demonstrated that under the unified management regime the present practice of neglecting migration may lead to sub-optimally sized populations of migrating moose and an overall economic loss. It is also shown that neglecting migration leads to a substantial profit transfer among the landowners. The model is supported by a real life numerical example.


*Keywords:* Migratory species; Management; Bioeconomic analysis

## 1. Introduction

In this paper, the way different management regimes influence the exploitation and economics of a wildlife population—the moose (*Alces alces*)—that is both a value and pest is analysed. Two regimes are explored; the unified management regime and the market solution. Because the moose is a partly migratory species, these regimes will differ with respect to harvesting income and browsing damage, and the landowners will gain different profit. The unified management scheme is very close to the management scheme one finds in Norway and Scandinavia, while the market solution is close to the management policy one finds in North-America (Saether et al., 1992). All the time, however, we will analyse the exploitation with reference to a Scandinavian ecological setting where we focus on sub-populations with a distinct and more or less fixed yearly migration pattern between a summer range and a winter range.

The moose 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). The hunt, taking place in September/October, is also an important social and cultural event in a large number of rural communities. However, the moose population also causes various costs. A high incidence of moose-vehicle collisions takes place, and there is browsing damage during the winter when young pine trees are an important food source. The browsing damage may be considerable (Storaas et al., 2001), but because of large spatial variation in moose densities during winter, it is unevenly distributed. Migration and concentration are two important explanatory factors because some sub-populations tend to leave their summer ranges and graze in specific winter ranges due to snow and forage conditions (Ball et al., 2001). Hence, as hunting takes place in the fall before the yearly migration, there is often an asymmetry between areas where the harvesting benefit is obtained and

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areas with high browsing damage; that is, for some landowners the moose represents a value while being basically a pest for others (see, e.g. Saether et al. (1992) for more details).

The following analysis of moose as a value and pest utilises a stylised bio-economic biomass framework that links two strands of studies within the bio-economic literature; spatial studies (see, e.g. Huffaker et al. (1992), Conrad (1999), Sanchirico and Wilen (2001) and Skonhoft et al. (2002)), and pest and nuisance studies (see, e.g. Zivin et al. (2000) and Huffaker et al. (1992)). We consider two areas of fixed size, two landowners and two sub-populations of moose. A fraction of one of the sub-populations migrates from its home range to the other area during the winter season where it causes forest damage. The present analysis is most similar to the Huffaker et al. (1992) study and Skonhoft et al. (2002), although dispersal is not density dependent (see below), and the moose is both a value and pest. Furthermore, in contrast to Huffaker et al., but in line with Skonhoft et al., different institutions, and hence management schemes, are studied.

As a consequence of dispersal and the moose being a pest, there will be an economic interdependency between the sub-populations, the two areas and the two landowners; that is, harvesting that takes place in one of the areas will generally influence the stock size and economic outcome in the other area, and vice versa. We study this economic interdependency in two ways. First, we analyse the situation where the landowners follow their narrow self-interests and maximise their private profit, harvesting income minus forestry damage. This first management scheme, the 'North American model', is referred to as the market solution. Next, we study the unified management scheme where the wildlife manager, the planner in the economic jargon, aims to find harvesting quotas that maximise the profit of the two areas viewed together. The harvesting policy in this 'Scandinavian model' is then based on an overall economic and ecological assessment. Both regimes assume stable populations.

We start by formulating the population equations and the cost and benefit functions in Section 2. Next, in Section 3, the market solution is studied while the unified management scheme is analysed in Section 4. Section 5 illustrates the two regimes numerically by a real life example from the so-called Swe–Nor moose region some 250 km north of Oslo, Norway. In Section 6, we study the economic consequences of neglecting dispersal when setting the harvesting quotas within the unified management scheme. As will be shown, the solution of this scheme then becomes more similar to the market solution.

## 2. The population equations and the cost and benefit functions

We consider two areas of fixed size, area 1 and 2, with two different landowners, owner 1 and owner 2, and two sub-populations of moose, sub-population 1 and 2 and where there is seasonal dispersal. Saether et al. (1992) discuss the various migration patterns of *Alces alces*. As already indicated, we focus on the most common one, at least in a Scandinavian context, namely sub-populations with a distinct and more or less fixed yearly migration pattern between a summer range and a winter range. All the time the dispersal is modelled by letting a fixed fraction of one of the sub-populations migrate in a density independent manner during the winter. Because of the snow and forage conditions, it is assumed that the dispersal runs from area 1 to area 2.[1] These two areas are considered a closed system, and after the winter all the migratory moose return to their summer range. The hunting season is September/October, before the yearly migration. Harvesting income is therefore directly related to the summer range of the two sub-populations while the migrating fraction of sub-population 1 causes forestry damage in area 2 during the winter season, but not vice versa since sub-population 2 is non-migratory.

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 'normalised' animals) in year $t$ after winter, $0 \le h_{i,t} < 1$ 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). Natural growth occurs at calving in May/June, so taking place before the hunting in September/October (Saether et al., 1992), $X_{1,t}+F(X_{1,t})$ is accordingly the biomass before hunting which reduces 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 depends on snow and food conditions, in addition to the topography and the size of the areas, and is fixed as $0 \le \alpha \le 1$. The population migrating out of area 1 is therefore $(1-h_{1,t})\alpha[X_{1,t}+F(X_{1,t})]$, and hence $(Z_{1,t} = (1-h_{1,t})(1-\alpha)[X_{1,t}+F(X_{1,t})]$ is the remaining population browsing in area 1 during the winter. When neglecting natural winter mortality, which is very low (Saether et al., 1992), and assuming that all animals return after winter $(1-h_{1,t})[X_{1,t}+F(X_{1,t})]$, is therefore the size of sub-population 1 the next year. For sub-population 2 we have the same annual cycle except that there is no dispersal out. The winter stock size browsing in area 2 is therefore $Z_{2,t} = (1-h_{2,t})\,[X_{2,t}+G(X_{2,t})] + (1-h_{1,t})\alpha[X_{1,t}+F(X_{1,t})]$.

[1] Normally, the seasonal migratory moose tends to migrate from summer ranges on hilly ground and down to valleys with less snow and where the concentration of moose improves the opportunity of deriving advantage from walking in each other's tracks in order to reduce the cost of locomotion (Ball et al., 2001).

Notice that there is no biological interdependency between the two sub-populations because there is no density dependent mortality during the winter.

All the time we assume stable populations, $X_{i,t+1}=X_{i,t}=X_i$ and $h_{i,t}=h_i$ ($i=1,2$). (1) and (2) reduce then to $X1(1-h_1)[X_1+F(X_1)]$ and $X2(1-h_2)[X_2+G(X_2)]$, respectively. When replacing the harvesting fractions, the winter populations read $Z_1=(1-h_1)(1-\alpha)[(X_1+F(X_1)]=(1-\alpha)X_1$ 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 damage to pine happens during the winter, these winter stocks determine the browsing damage with damage functions given as $D_i=D_i(Z_i)$ ($i=1,2$) with $D_i(0)=0$ and $\partial D_i/\partial Z_i=D_i'>0$ (Storaas et al., 2001). The damage may vary between the areas due to differences in the quality of the timber stands, or simply different productivities of the forests. The damage may take place immediately and damaged young pine trees may be replaced directly. Usually, however, there is a time lag between the occurrence of browsing and the economic loss of the damage. In such instances, discounting is not taken explicitly into account in the present exposition. The equilibrium number of animals harvested are $H_1=h_1[X_1+F(X_1)]=F(X_1)$ and $H_2=h_2[X_2+G(X_2)]=G(X_2)$. The hunting income follows as $pF(X_1)$ and $pG(X_2)$ with $p$ as the unit hunting licence price, assumed to be identical in the two areas. Mattsson (1994) observed a positive stock dependent willingness to pay for hunting licences in Sweden while an ambiguous effect was observed between the price and the number of animals hunted. However, here it is assumed that $p$ is fixed and independent of the harvest and stock size. This is justified by the fact that there generally is competition among a large number of suppliers of hunting licences. Following the practice in Norway, one licence allows the buyer to kill one animal, which is paid only if the animal is killed.

It is assumed that the area-specific cost and benefit streams correspond to the landowner cost and benefit streams. The number of animals harvested and the harvesting income in area $i$ are therefore distributed to landowner $i$ under both the unified management scheme (more details below), and the market solution. Furthermore, under both management schemes landowner $i$ bears the damage cost taking place in area $i$. The yearly profits of the two landowners at biological equilibrium therefore read

$$\pi_1=pF(X_1)-D_1((1-\alpha)X_1) \tag{3}$$

and

$$\pi_2=pG(X_2)-D_2(X_2+\alpha X_1). \tag{4}$$

## 3. The market solution

When there is no unified resource policy the landowners follow their narrow self-interest. They each balance the income of the moose against its cost, and we assume that they aim to maximise this difference. However, because of the dispersal and because the moose is also a pest, there is an economic interdependency between the landowners. This interdependency, or externality, is, however, unidirectional because only sub-population 1 leaves its summer range. As a consequence, the harvesting activity of landowner 1 influences sub-population 2 and the harvesting activity of landowner 2, but not vice versa. Technically, the solution to the management problem of individual profit maximisation occurs when landowner 1 maximises (3), and then, given the activity of landowner 1, landowner 2 maximises (4).

Maximisation of (3) yields[2]

$$F'(X_1^*)=\frac{1}{p}\left[(1-\alpha)D_1'((1-\alpha)X_1^*)\right] \tag{5}$$

where superscript '*' indicates the market solution. This equation alone determines the stock size $X_1^*$. The harvesting rate follows then as $h_1^*=F(X_1^*)/[X_1^*+F(X_1^*)]$ while the biomass harvested is $H_1^*=F(X_1^*)$. Condition (5) indicates that harvesting should take place up to the point where the marginal natural growth is equal to the area 1 marginal damage, evaluated at the harvesting price. Multiplying with $p$ it is also seen that this condition says that the stock size should be kept at the point where the marginal *private* harvesting income is exactly balanced by the *private* marginal damage cost as only the area 1 damage is taken into account. The right hand side of condition (5) is non-negative, $X_1^*$ will therefore always be found as $F'(X_1^*)\geq 0$, or $X_1^*\leq X_1^{msy}$.

Landowner 2 is also profit maximising, but the size of the sub-population 1 causing browsing damage has to be taken into account. Accordingly, the profit function (4) is maximised subject to $X_1=X_1^*$. The first order condition of this problem reads:

$$G'(X_2^*)=\frac{1}{p}D_2'(X_2^*+\alpha X_1^*). \tag{6}$$

As above, the harvesting rate and the number of hunted animals (biomass), follow as $h_2^*=G(X_2^*)/[X_2^*+G(X_2^*)]$ and $H_2^*=G(X_2^*)$. The interpretation of condition (6) is exactly the same as condition (5), but the migratory stock generally influences the harvesting decision of landowner 2 (but see below). Because $G'(X_2^*)>0$ always holds, we also find $X_2^*<X_2^{msy}$.

When taking the total differential of the two first order conditions (5) and (6), the economic and ecological forces influencing the population sizes can be found. This suggests that when $\alpha<1$, a positive shift in the harvesting price gives a larger sub-population 1 and hence, $X_1^*$ moves closer to $X_1^{msy}$. However, the effect on sub-population 2 is ambiguous. The direct effect is that the browsing damage, measured in

[2] 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. For these reasons, the solution is unique as well.

terms of the harvesting price, decreases and hence, works in the direction of a higher stock size. But when an increase in sub-population 1 is accompanied by more dispersal, the damage in area 2 shifts up and thus, the total effect is unclear. On the other hand, an upward shift in the marginal damage cost always means lower stock sizes. The dispersal coefficient has an unambiguous stock size 1 effect, and a higher $\alpha$ means a larger stock as the damage in area 1 then decreases. If the damage cost is strictly convex, the stock size 2 effect will be in the opposite direction because of a larger migratory population. However, when the cost function is linear, there will be no stock 2 effect as then the marginal conditions do not change (see below). The number of moose harvested $H_i^*$ will change in the same direction as the stock sizes because $X_i^* \le X_i^{\text{msy}}$ while it can easily be demonstrated that the harvesting rates $h_i^*$ change in the opposite direction.

## 4. The unified management scheme

Within the unified management scheme, the wildlife manager (the social planner) aims to find area-specific hunting quotas that maximise overall profit. The hunting quotas are then distributed to the landowners. Because the landowners also now bear the damage cost taking place in their respective areas, there is still a correspondence between the landowner profit and the area profit (see also above). The profit of the landowners, i.e. the property rights, is accordingly controlled by the wildlife manager (Bromley, 1991).[3] It can easily be verified that the first order conditions when maximising the sum of (3) and (4), $\pi=(\pi_1+\pi_2)$, will be

$$F'(X_1^{\text{u}}) = \frac{1}{p}\left[(1-\alpha)D_1'((1-\alpha)X_1^{\text{u}}) + \alpha D_2'(X_2^{\text{u}} + \alpha X_1^{\text{u}})\right] \tag{7}$$

in addition to the above condition (6), now as

$$G'(X_2^{\text{u}}) = \frac{1}{p}D_2'(X_2^{\text{u}} + \alpha X_1^{\text{u}}) \tag{6'}$$

and where superscript 'u' indicates the unified management scheme. The only difference between (7) and (5) is that the browsing damage caused by the migratory stock in the area 2 is taken into account as well; that is, the damage now reflects the *social* marginal cost.

Because the social value, and not only the private value, of the damage caused by sub-population 1 is taken into account, we find $X_1^{\text{u}} < X_1^*$. Accordingly, we also have $X_2^{\text{u}} \ge X_2^*$. The results for the harvesting rates will therefore be the opposite. Moreover, the profit of landowner 1 will be lower than that of the market solution, $\pi_1^{\text{u}} < \pi_1^*$, while we have $\pi_2^{\text{u}} > \pi_2^*$ due to less browsing damage. Hence, the unified management scheme makes landowner 2 better off and landowner 1 worse off compared to the market solution. Due to the very nature of the optimisation problems, we also have $\pi^{\text{u}} = (\pi_1^{\text{u}} + \pi_2^{\text{u}}) > \pi^* = (\pi_1^* + \pi_2^*)$. We obtain the same comparative static effects as in the market solution except that the dispersal coefficient now generally has an ambiguous stock 1 effect because the marginal damage in both areas has to be taken into account when determining $X_1^{\text{u}}$. This fact implies that a unified management practice of neglecting dispersal (cf. Section 1) has ambiguous stock as well as harvesting effects (Section 6 below gives the details).

## 5. Specific functional forms and numerical illustrations

The model will now be illustrated by data from the so-called Swe–Nor moose region on the border between the two countries Sweden and Norway, some 250 km 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, and due to the snow and forage conditions the one-way migration runs from Nor to Swe. It is estimated that about 30% of the moose grazing in the Swe area in the winter are migratory moose from the Nor area, and the forestry damage here is considerable (for more details, see Olaussen (2000)).

The natural growth functions are specified logistic with sub-populations 1 and 2 growth as $F(X_1)=rX_1(1-X_1/K_1)$ and $G(X_2)=rX_2(1-X_2/K_2)$, respectively. $r>0$ is the maximum specific growth rate, assumed to be identical for both sub-populations, and $K_i>0$ $(i=1,2)$ are the carrying capacities. Whether the damage functions are concave or convex are unclear (see above). As a compromise we use linear functions (but see below), such that we have $D_1(Z_1)=a_1Z_1=a_1(1-\alpha)X_1$, with $a_1>0$, in area 1, and $D_2(Z_2)=a_2Z_2=a_2(X_2+\alpha X_1)$, with $a_2>0$, in area 2. Inserted into the first order conditions (5) and (6), we find $F'(X_1^*)=a_1(1-\alpha)/p$ and $G'(X_2^*)=a_2/p$, respectively. When solving for the stock sizes, the market solution reads

$$X_1^* = \frac{K_1}{2r}\left[r - \frac{a_1(1-\alpha)}{p}\right] \tag{8}$$

[3] As mentioned, such a scheme is more or less in accordance with the actual management policy in Norway and in Scandinavia. Even if the property rights following such a scheme may cause substantial asymmetries between the cost and benefit among the landowners (but at a smaller extent than that of the market solution, see below), the general rule is that the quotas set by the wildlife manager (the hunting board) are respected, and there is almost no cheating or illegal harvesting. The important reason for this is the strong social control of the Scandinavian moose hunting which, as already mentioned, is one of the most important social and cultural yearly events taking place in many rural communities (see, e.g. Saether et al. (1992)). However, in some instances, various compensation schemes may be established. However, such schemes are not analysed here.

and

$$X_2^* = \frac{K_2}{2r}\left[r - \frac{a_2}{p}\right]. \tag{9}$$

A special feature of this solution is that these two first order conditions are independent. Hence, when the damage functions are linear, landowner 2 may manage sub-population 2 separately in an optimal way without being influenced by the harvesting decision of the other landowner.[4] Notice also that the dispersal parameter does not affect the harvesting decision of landowner 2. This result hinges again on the constant marginal damage assumption. When combining (8) and (9) it is seen that the optimal stock density in area 1 will be above that of the area 2 density if the marginal grazing damage is lower here; that is, $X_1^*/K_1 > X_2^*/K_2$ if $(1-\alpha)a_1 < a_2$ for all $0 \le \alpha < 1$. This is a quite intuitive result as the harvesting price is the same in the two areas.

Under these specific functional forms, a higher harvesting price means more animals in both areas. More productive ecological conditions, i.e. higher carrying capacities and a higher maximum specific growth rate, work in the same direction. These results are, however, far from obvious as long as the species, as here, is both a value and pest. The dispersal coefficient has an unambiguous landowner 1 profitability effect as differentiation of $\pi_1^* = pF(X_1^*) - a_1(1-\alpha)X_1^*$ yields $\partial\pi_1^*/\partial\alpha = [pF' - a_1(1-\alpha)](\partial X_1^*/\partial\alpha) + a_1X_1^* = a_1X_1^* > 0$ when using the first order condition. The landowner 2 profit $\pi_2^* = pG(X_2^*) - a_2(X_2^* + \alpha X_1^*)$ is also affected and we find $\partial\pi_2^*/\partial\alpha = -a_2[X_1^* + \alpha(\partial X_1^*/\partial\alpha)] < 0$ because $\partial X_1^*/\partial\alpha$ is positive. This result is also quite obvious as more dispersal means that more of the damage is imposed on area 2.

Under the unified management scheme, the first order condition (7) reads $F'(X_1^u) = [a_1(1-\alpha) + a_2\alpha]/p$. Accordingly, when solving for the stock size, we find

$$X_1^u = \frac{K_1}{2r}\left[r - \frac{a_1(1-\alpha) + a_2\alpha}{p}\right]. \tag{10}$$

In addition, we also have Eq. (9), now as:

$$X_2^u = \frac{K_2}{2r}\left[r - \frac{a_2}{p}\right]. \tag{9'}$$

Hence, within the unified management scheme, the stock sizes are determined independently of each other as well. Compared to the market solution the only difference is the term $\alpha a_2$ in Eq. (10) reflecting the fact that the damage cost facing landowner 1 should add up to the social cost. As a consequence, the effect of higher dispersal is ambiguous, and we only have $\partial X_1^u/\partial\alpha > 0$ if $a_1 > a_2$ since more migration then reduces the overall marginal damage. The profitability effects are therefore ambiguous as well, and we find $\partial\pi_1^u/\partial\alpha = a_2\alpha(\partial X_1^u/\partial\alpha) + a_1X_1^u$ and $\partial\pi_2^u/\partial\alpha = -a_2(X_1^u + \alpha(\partial X_1^u/\partial\alpha))$ when again using the first order conditions, while the total profit changes simply as $\partial\pi^u/\partial\alpha = (a_1 - a_2)X_1^u$. In line with intuition, more dispersal means lower total profit suggesting that $a_2 > a_1$.

As already seen, we have $\pi_1^u < \pi_1^*$ together with $\pi_2^u > \pi_2^*$ and $\pi^u > \pi^*$. However, because the sub-population 2 stock will be the same under the two management schemes and hence, the landowner 2 harvesting income will be the same as well, we find $\pi_2^u > \pi_2^*$ because of lower browsing damage under the unified management scheme. Moreover, $\pi_1^u < \pi_1^*$ holds because reduced harvesting income dominates reduced area 1 browsing damage. Finally, we have $\pi^u - \pi^* = p[F(X_1^u) - F(X_1^*)] - [a_1(1-\alpha) + a_2\alpha](X_1^u - X_1^*) > 0$ because reduced overall grazing damage, the second term, dominates reduced landowner 1 harvesting income, the first term. The profitability gap between the two regimes due to more dispersal shifts according to $\partial(\pi^u - \pi^*)/\partial\alpha = -(a_2 - a_1)(X_1^u - X_1^*) + a_2\alpha(\partial X_1^*/\partial\alpha)$. Because $\partial X_1^*/\partial\alpha > 0$ and $X_1^* > X_1^u$, we therefore find that a higher $\alpha$ increases the total profitability gap between the two regimes when the area 2 marginal damage is higher than the area 1 damage.

The numerical results are now reported. All the parameter values in the simulations are based on Olaussen (2000). The maximum specific growth rate is fixed as $r = 0.47$ while the carrying capacities, assumed to be proportional to the size of the areas, are $K_1 = 4550$ and $K_2 = 2540$ (number of moose) so that area 1 is referring to Nor while area 2 is Swe (see above). The price of the hunting licence is $p = 6500$ (NOK per moose, 1999 prices). The marginal damage cost is higher in Swe than in Nor as Swe is mainly located at a lower altitude within more productive forest and it is given as $a_1 = 1500$ and $a_2 = 2500$ (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 when having the market solution while Table 2 is for the unified management scheme.

Under the market solution, sub-population 1 increases with increased dispersal while sub-population 2 is unaffected (Table 1). Under the unified management scheme, the opposite happens for sub-population 1 because $a_2 > a_1$ (Table 2). From a unified management point of view it is accordingly profitable to reduce the total stock compared to a scenario without dispersal. In the market solution, the landowner 1 profit increases steadily with more dispersal while the opposite happens for landowner 2. The total profitability also falls in both regimes, and the total profitability gap widens between the unified management and the market solution. All these results follow the above discussion. It is also seen that $\pi_2^*$ becomes negative when $\alpha$

[4] The model is also illustrated when having strictly convex damage functions, and the first order conditions determining the stock sizes will then be interdependent. Moreover, the dispersal coefficient will influence sub-population 2 as well. This will also be so when having unified management. See Appendix.

Table 1
Market solution

| | Migration rate ($\alpha$) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
| Stock, area 1 $X_1$* | 1158 | 1381 | 1605 | 1828 | 2052 | 2275 |
| Stock, area 2 $X_2$* | 231 | 231 | 231 | 231 | 231 | 231 |
| Total stock $X$* | 1389 | 1612 | 1836 | 2059 | 2283 | 2506 |
| Harvest rate area 1 $h_1$* | 0.26 | 0.25 | 0.23 | 0.22 | 0.21 | 0.19 |
| Harvest rate area 2 $h_2$* | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| Profit, landowner 1 $\pi_1$* | 900 | 1281 | 1729 | 2244 | 2826 | 3475 |
| Profit, landowner 2 $\pi_2$* | 64 | −627 | −1541 | −2678 | −4039 | −5623 |
| Total profit $\pi$* | 964 | 654 | 188 | −434 | −1213 | −2148 |

Stock sizes (number of moose), harvesting rates and profit (1000 NOK) for different migration rates ($a_1=1500$ NOK per moose; $a_2=2500$ NOK per moose; $p=6500$ NOK per moose; $r=0.47$; $K_1=4550$ number of moose; $K_2=2540$ number of moose).

Table 2
Unified management

| | Migration rate ($\alpha$) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
| Stock, area 1 $X_1^{\mathrm{u}}$ | 1158 | 1009 | 860 | 711 | 562 | 413 |
| Stock, area 2 $X_2^{\mathrm{u}}$ | 231 | 231 | 231 | 231 | 231 | 231 |
| Total stock $X^{\mathrm{u}}$ | 1389 | 1240 | 1091 | 942 | 793 | 644 |
| Harvest rate area 1 $h_1^{\mathrm{u}}$ | 0.26 | 0.27 | 0.28 | 0.28 | 0.29 | 0.30 |
| Harvest rate area 2 $h_2^{\mathrm{u}}$ | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| Profit, landowner 1 $\pi_1^{\mathrm{u}}$ | 900 | 1188 | 1357 | 1406 | 1337 | 1148 |
| Profit, landowner 2 $\pi_2^{\mathrm{u}}$ | 64 | −440 | −797 | −1003 | −1060 | −969 |
| Total profit $\pi^{\mathrm{u}}$ | 964 | 748 | 561 | 404 | 276 | 179 |

Stock sizes (number of moose), harvesting rates and profit (1000 NOK) for different migration rates ($a_1=1500$ NOK per moose; $a_2=2500$ NOK per moose; $p=6500$ NOK per moose; $r=0.47$; $K_1=4550$ number of moose; $K_2=2540$ number of moose).

exceeds a certain (small) value. However, it should be noted that this is a calculated loss and not necessarily an actual loss, as the forest damage in most instances represents future profit loss (Section 2 above). The landowner 1 profit first increases and then decreases under the unified management scheme while the landowner 2 profit starts to increase when $\alpha$ becomes high.

## 6. The economic loss of neglecting dispersal

The unified management scheme is more or less in accordance with the actual management policy in Norway and in Scandinavia, although migration is currently not taken directly into account.[5] The theoretical reasoning and the numerical simulations imply that a management practice of neglecting dispersal has ambiguous stock as well as harvesting effects. However, as shown below, it is clear that there will be a total economic loss when harvesting quotas are implemented *as if* there was no dispersal. A management policy of neglecting dispersal will also redistribute profit among the landowners. In what follows, this is analysed under the unified management scheme by using the same specified functional forms as above, and we will find that this scheme then becomes more similar to the market solution.

Let $X_i^0 (i=1,2)$ be the optimal determined stocks if there had been no dispersal; that is, $X_i^0$ is the solution to the problem of maximising $[pF(X_1)-a_1X_1+pG(X_2)-a_2X_2]$. Accordingly, when dispersal is *not* taken into account, but the dispersal is governed by $\alpha$, the profit of the landowners reads $\pi_1^0=pF(X_1^0)-a_1(1-\alpha)X_1^0$ and $\pi_2^0=pG(X_2^0)-a_2(X_2^0+\alpha X_1^0)$. As above, $X_i^{\mathrm{u}}$ is the unified management optimal stock size subject to the *actual* dispersal rate $\alpha$. When the wildlife manager does not take dispersal into account, the gain, or loss, of landowner 1 under the unified management scheme will therefore be

$$\Delta\pi_1=(\pi_1^0-\pi_1^{\mathrm{u}})=p\left[F(X_1^0)-F(X_1^{\mathrm{u}})\right]-a_1(1-\alpha)(X_1^0-X_1^{\mathrm{u}}) \tag{11}$$

[5] 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, and where the size of the management area depends on institutional as well as ecological factors. In a next step, the total quota is distributed among 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 landowners, represent the management area. The management goal is usually to maximise the meat value in ecological equilibrium (Saether et al., 1992). Grazing damages are normally taken into account, however, often in ad hoc manner.

Table 3
Absolute profitability loss (1000 NOK) and relative profitability loss (in %) when neglecting dispersal

| | Migration rate ($\alpha$) | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
| Profit gain landowner 1, $\Delta\pi_1$ | 60 | 238 | 536 | 953 | 1489 |
| Profit loss landowner 2, $\Delta\pi_2$ | −75 | −298 | −670 | −1191 | −1862 |
| Total loss, $\Delta\pi$ | −15 | −60 | −134 | −238 | −372 |
| Gain landowner 1 (in %) $\Delta\pi_1/\pi_1^u$ | 5 | 18 | 38 | 71 | 130 |
| Loss landowner 2 (in%) $\Delta\pi_2/\pi_2^u$ | −17 | −37 | −67 | −112 | −192 |
| Total loss (in %) $\Delta\pi/\pi^u$ | −2 | −11 | −33 | −86 | −207 |

Unified management ($a_1=1500$ NOK per moose; $a_2=2500$ NOK per moose; $p=6500$ NOK per moose; $r=0.47$; $K_1=4550$ number of moose; $K_2=2540$ number of moose).

while

$$\Delta\pi_2 = (\pi_2^0 - \pi_2^u) = p\left[G(X_2^0) - G(X_2^u)\right] - a_2\left[(X_2^0 + \alpha X_1^0) - (X_2^u + \alpha X_1^u)\right]$$

is the loss, or gain, of landowner 2. As sub-population 2 is unaffected by the dispersal under the linear damage cost assumption (see above), this simplifies to:

$$\Delta\pi_2 = -a_2\alpha(X_1^0 - X_1^u). \quad (12)$$

Under the cost assumption of $a_1<a_2$, $X_1^u$ decreases with more dispersal and we hence have $X_1^0>X_1^u$ from the above Eq. (10). Eq. (12) therefore indicates that landowner 2 will experience an economic loss when the wildlife manager imposes harvesting quotas as if there was no dispersal, $\Delta\pi_2<0$. This loss will, to some extent, be counteracted by a gain of landowner 1, $\Delta\pi_1>0$.[6] However, there will always be an overall economic loss given by $\Delta\pi=(\Delta\pi_1+\Delta\pi_1)=p[F(X_1^0)-F(X_1^u)]-[a_1(1-\alpha)+a_2\,\alpha](X_1^0-X_1^u)\leq 0$.[7]

Table 3 reports simulations when using the same parameter values as above. If, say, $\alpha=0.2$, but the management takes place as if there is no migration and $\alpha=0$, sub-population 1 becomes too high; 1158 animals instead of 1009, but sub-population 2 is unaffected (Table 2). Inserted into Eqs. (11) and (12), we find the landowner 1 gain as $\Delta\pi_1=60$ (1000 NOK) and the landowner 2 loss as $\Delta\pi_2=-75$. The overall profit loss is accordingly $\Delta\pi=-15$. The landowner 1 net gain is made up of an additional harvesting income of 238, outweighing the additional browsing damage loss of 178. The landowner 2 loss reflects the additional damage of the migratory individuals, as the sub-population 2 stays unchanged.

The consequence of neglecting migration therefore translates into a substantial profit transfer among the landowners while the overall loss is quite modest as it is just about 2% (−15/748, see Tables 2 and 3). With more dispersal, however, the total loss as well as the profit transfer increase, and for $\alpha=0.4$ and 0.6 the overall loss is 11 and 33%, respectively. Under the cost scenario of $a_1<a_2$ with $X_1^0>X_1^u$, the total browsing damage loss always outweighs the landowner 1 harvesting gain. Under an opposite damage cost difference with $a_1>a_2$ and hence $X_1^0<X_1^u$, however, we find that landowner 2 will gain while landowner 1 will experience an economic loss. The harvesting loss of landowner 1 then outweighs the benefit gained by a reduction in browsing damage. We also generally find that the total loss and profit transfer increase for higher forestry damage and more substantial cost differences either we have $a_2>a_1$, as in the numerical examples, or the opposite.

When neglecting dispersal, the unified management scheme becomes more like the market solution of individual profit maximisation (Tables 1 and 2), and hence the ‘Scandinavian model’ approaches the ‘North American model’. As the ecology is unaffected by the dispersal, it should be noted that no ecological mechanism reveals the allocation errors of neglecting dispersal suggested that the manager set quotas according to the population equations; that is, as long as $X_i^0$ ($i=1,2$) and the harvesting rates are in accordance with the ecological equilibrium conditions $X_1=(1-h_1)[X_1+F(X_1)]$ and $X_2=(1-h_2)[X_2+G(X_2)]$. Moreover, because the browsing damage often represents future loss of profit (Section 2), there is no clear economic signal indicating allocation errors either. These two features may explain today’s practice of ignoring migration when setting harvesting quotas. Saether et al. (1992) propose larger management areas due to the seasonal migration. Larger areas imply reduced cross border dispersal, but as long as the manager does not take it directly into account, the harvesting quotas and stock sizes will still generally be inefficient, accompanied by an overall profitability loss and profitability transfer among the landowners.

[6] This may be proved as follows. If we assume that landowner 1 gains, $\Delta\pi_1>0$ yields $[F(X10)-F(X1u)]/(X10-X1u)>a1(1-\alpha)/p$ after a slight reformulation of Eq. (11). Because $X10>X1u$ holds under the given cost assumptions and we also have $X1u<X1msy$ and logistic natural growth, $F\prime(X1u)>[F(X10)-F(X1u)]/(X10-X1u)$ holds. When comparing with the first order condition $F\prime(X1u)=[a1(1-\alpha)+a2\alpha]/p$ it is then seen that the assumption of $\Delta\pi_1>0$ is not contradicted.

[7] An overall loss follows per definition from the nature of the optimisation problem. It may also be proved in a same manner as the proof of the gain of landowner 1 (see footnote 6).

## 7. Concluding remarks

We have analysed the harvesting of a species—the moose (*Alces alces*)—that represents both a pest and value in a situation where dispersal causes an economic interdependency between different landowners exploiting it. The management is studied under a unified scheme where the wildlife manager (the planner) aims to find harvesting quotas maximising the difference between harvesting income and forestry damage. The management is also studied in a situation where the landowners follow their narrow self-interests and maximise their private profit. The harvesting scheme here is referred to as the market solution.

In the first part of the paper, we show how dispersal influences stock levels, harvesting quotas and profitability. We also show how profitability differs among the two management schemes. The unified management scheme (the 'Scandinavian model') yields a higher total profit than the market solution (the 'North American model') and it is demonstrated that this difference may be quite substantial in an ecological and institutional setting (small areas) with high dispersal. It is also shown that the market solution generally yields a wider gap between harvesting income and forestry damage among the landowners than the unified management scheme. In the second part of the paper, it is demonstrated how the present practice of neglecting migration either leads to too many or too few migratory individuals within the unified management scheme. By not taking migration into account when setting the harvesting quotas, a larger gap between the actual harvesting income and browsing damage of the landowners is therefore attained. In addition, the total economic viability of the moose populations decreases. All these results can be related to the standard economic theory of having a unidirectional externality.

Models are only approximations of how we conceive reality, and they are only as good as the assumptions they are based on. Environmental and biological stochastic variations are neglected, and the present analysis is carried out at ecological equilibrium where current profit is maximised. Maximising present-value profit is an obvious alternative management goal. The analysis of the long-term equilibrium (steady-state) of such a problem, either under the market solution or the unified management scheme, however, does not add much compared to the present analysis as the equilibrium solutions coincide when the rate of discount is equal to zero (see, e.g. Munro and Scott (1985)). It should also be noted that a dynamic approach implies no dynamic game situation under the market solution because of the unidirectional nature of the externality among the landowners. On the other hand, there is a fundamental difference between static and dynamic approaches as the present exposition of maximising 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 among males, females and calves, and there are variations in browsing pressure and damage among the different sex and age groups. The migration pattern may clearly also be more complex than just seasonal migration. However, by doing all these simplifications, it is possible to reveal some important driving forces that we will also find in more complex, and hence, realistic, settings.

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## Appendix. Convex damage cost functions under unified management

Strictly convex grazing damage costs are introduced by specifying the cost functions as $D_i = a_i Z_i + (b_i/2)Z_i^2$ with $a_i > 0$ and $b_i > 0$ $(i = 1,2)$. Solving for the unified

Table A1
Strictly convex grazing costs

| | Migration rate ($\alpha$) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
| Stock, area 1 $X_1^u$ | 664 | 688 | 653 | 542 | 373 | 197 |
| Stock, area 2 $X_2^u$ | 188 | 134 | 84 | 59 | 69 | 110 |
| Total stock $X^u$ | 852 | 822 | 737 | 601 | 442 | 307 |
| Harvest rate area 1 $h_1^u$ | 0.29 | 0.29 | 0.29 | 0.29 | 0.30 | 0.31 |
| Harvest rate area 2 $h_2^u$ | 0.30 | 0.31 | 0.31 | 0.32 | 0.31 | 0.31 |
| Profit, landowner 1 $\pi_1^u$ | 1002 | 1178 | 1277 | 1220 | 964 | 576 |
| Profit, landowner 2 $\pi_2^u$ | 71 | −266 | −606 | −795 | −715 | −425 |
| Total profit $\pi^u$ | 1073 | 912 | 671 | 425 | 249 | 150 |

Unified management. Stock sizes (number of moose), harvesting rates and profit (1000 NOK) for different migration rates ($a_1 = 1100$ NOK per moose; $a_2 = 2300$ NOK per moose; $b_1 = b_2 = 1.6$ NOK per moose$^2$; $p = 6500$ NOK per moosel; $r = 0.47$; $K_1 = 4550$ number of moose; $K_2 = 2540$ number of moose).

management scheme, we find that the first order conditions (10) and (9) are replaced by

$$X_1^u = \frac{1}{\left[\frac{2r}{K_1} + \frac{b_1(1-\alpha)^2 + b_2\alpha^2}{p}\right]}\left[r - \frac{1}{p}\left((1-\alpha)a_1 + \alpha a_2 + \alpha b_2 X_2^u\right)\right] \tag{A1}$$

and

$$X_2^u = \frac{1}{\left[\frac{2r}{K_2} + \frac{b_2}{p}\right]}\left[r - \frac{a_2 + b_2\alpha X_1^u}{p}\right] \tag{A2}$$

respectively. In contrast to the linear cost case, these equations therefore represent an interdependent system, and 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 1500 (NOK per moose) in area 1 and 2500 (NOK per moose) in area 2 when $X_1^u = 614$ and $X_2^u = 139$.

It is also seen 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. It is also seen that the area 2 stock now is affected by the migration rate. The profitability distribution between the two areas, however, follows much of the same pattern as in the linear case.

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