SNF REPORT NO. 59/02

REINDEER HUSBANDRY: A PRACTICAL DECISION-TOOL FOR ADAPTATION OF HERDS TO RANGELANDS

by

Erling Moxnes
Öje Danell
Eldar Gaare
Jouko Kumpula

SNF-project No. 5461 :
“Forvaltning av reinbeiter under usikkerhet”

This project is financed by the Nordic Council of Ministers

Centre for Fisheries Economics
Report No. 83

INSTITUTE FOR RESEARCH IN ECONOMICS AND BUSINESS ADMINISTRATION
BERGEN, JANUARY 2003

ISBN 82-491-0251-7
ISSN 0803-4036

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PREFACE

This is the second report from a project dealing with the management of reindeer districts under uncertainty. The first report, Moxnes et al. (1998) also published as Moxnes et al. (2001), dealt with optimal management strategies under uncertainty. The focus in this report is on the design of a practical tool to aid the learning about reindeer and ranges and to aid decision making regarding herd sizes. A textbook for the decision-tool will be published separately.

The report is produced in co-operation between the Norwegian Institute for Nature Research in Trondheim, the Institute for Research in Economics and Business Administration in Bergen, Swedish University of Agricultural Sciences in Uppsala, and the Reindeer Research Station at the Finnish Game and Fisheries Research Institute in Kaamanen. Case studies are also provided by Christine Cuyler in Greenland and Pall Hersteinsson in Iceland. We also thank these two for valuable contributions at a project meeting held in Copenhagen. The project is financed by “Nordisk ministerråd” under the program “Nordiska miljöstrategin för jord- och skogsbruk 1996-1999”. The project builds on a preceding project for “Nordisk ministerråd", see Dahle et al. (1998). Thanks to “Nordisk organ for reinforskning”, NOR, for initiating the project and to Hans-Kolbein Dahle for co-ordinating the project and for valuable comments.

1. INTRODUCTION

In this report we focus on the adaptation of reindeer herds to available food resources in a district, i.e. to the availability and quality of winter and summer ranges. Previous studies have found that practical management is complicated by the dynamics involved and by a lack of precise information. Furthermore, formal analyses to find optimal herd sizes, to find optimal learning strategies, are both complicated to carry out and difficult to explain to decision-makers. Hence one is faced with an information problem.

The purpose of this report is to provide a decision-tool which can capture the essence of earlier normative studies, and be sufficiently simple that it can be used in practice. In short, the decision-tool helps organise time-series information such that it becomes directly useful for decision-making. The derivation of the decision-tool with its equations is not easy to popularise. However, to foster active and correct use, a training simulator goes along with the decision-tool. Hopefully, the simulator will help build the intuition needed without the explicit knowledge of underlying mathematics.

In section 2 we survey what can be learned from scientific approaches to the management problem. In section 3 we describe the decision-tool in detail, first the adaptation to winter lichen ranges and next to summer ranges. In section four a brief introduction to the use of the decision-tool and the simulator is provided. In section 4 we present case studies from numerous reindeer districts in all Nordic countries. These studies provide new insights into old problems and they clarify shortcomings of the decision-tool and provide guidelines to overcome these shortcomings. Section 5 concludes.

2. WHAT CAN BE LEARNED FROM SCIENTIFIC APPROACHES TO THE COMPLEX MANAGEMENT PROBLEM?

In this section we argue that the problem of adapting reindeer herd sizes to available rangelands is a complex one, referring to experimental investigations of decision making. Next we refer basic insights obtained by dynamic optimisation under uncertainty assuming a model with know parameters. Finally, we discuss the even more demanding task of finding the optimal strategy when model parameters are not know with high precision at the outset. In this case there is a trade-off between doing the best one can with existing knowledge and learning the most one can by varying the herd size. This is the so-called dual problem of adaptive management. In each section we draw conclusions with respect to important requirements of a practical decision-tool.

2.1. A complex problem

Reindeer rangeland management is primarily a question of adapting the size of the reindeer herd to the capacity of the rangeland. We focus on two classes of food for reindeer. In summer time a mix of grass, herbs and shrubs meet the requirements for growth and maintenance. In winter time a mix of lichens provides most of the required maintenance, the energy needed for survival. We also recognise that some other sources of energy are available during the winter season, White et al. (1981), Lenvik (1990), Danell et al. (1999), Danell and Gaare (1999), Gaare and Danell (1999).

The problem of optimal reindeer rangeland management is a very complex one. It involves dynamics (e.g. it takes time to build both the herd size and the lichen coverage), it involves uncertainty about the current conditions of nature (measurement error), it involves uncertainty about what will happen over the next year in terms of natural variations, and it involves uncertainty about the relationships in nature (learning). All these four factors are known to cause problems for practical decision-making and even for scientific treatment of these problems. Here we will concentrate on the problems of dynamics and learning.

Several experimental investigations of decision making in dynamic environments, e.g. Brehmer (1992), Diehl and Sterman (1995), Funke (1991), Sterman (1989b), and Sterman (1989a) show that even experienced people make systematic errors. They not only make imprecise decisions, which is a natural consequence of uncertainty, they also make decisions that are systematically biased. The main reason is that they tend to approximate dynamic systems by static mental models, and that they ignore relationships (feedback) that are not easily dealt with. Of particular relevance in this connection are three studies of decision making regarding the renewable resources fish, Moxnes (1998a) and reindeer, Moxnes (1998b) and Moxnes (2000). The participants failed to adapt respectively the fishing capacity and the number of reindeer to the underlying resources, respectively fish and lichen. Overinvestment and overutilisation of the natural resources resulted for nearly all participants. The reason was not the tragedy of the commons, since competition among fishermen and among reindeer herders was removed by the design of the experiments.

The core of the problem is illustrated by the growth curve for lichen in Figure 1. With very little lichen, growth is limited by the lack of lichen. At high lichen densities, growth is limited by competition between lichens (as much rots from the bottom as what grows at the top). Between these extremes, growth peaks at the maximum sustainable yield. Now assume that in year 1 the herd consumes more than the yearly growth of lichen (illustrated by a black square). Then in year 2 there will be less lichen available. Let us assume that at this point in time the level of lichen is either perceived as alarmingly low or that an ongoing reduction in the level of lichen is a cause of concern.

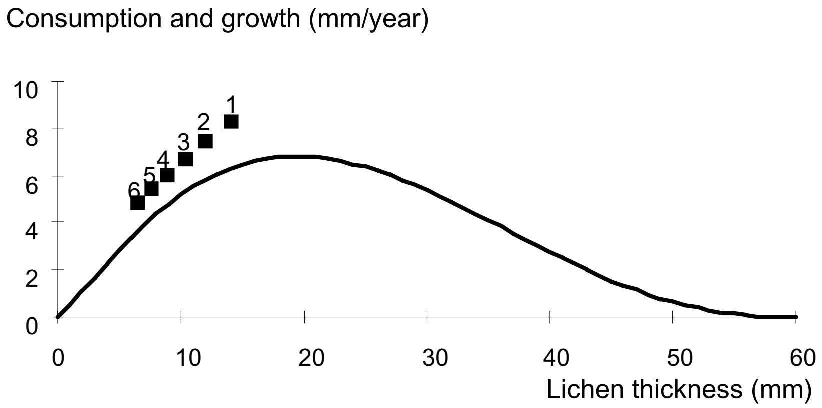

Figure 1: Illustration of consumption and growth of lichen as functions of the level of lichen.

Even for those that have not been presented with the growth curve in Figure 1, the obvious thing to do is to reduce the herd size. A static mental model for instance, predicts that fewer animals will lead to more lichen. However without the growth curve available, it is not obvious how much the herd should be reduced. This difficult quantitative question can be avoided by choosing a “careful” approach, relying on future corrective actions in case the adjustment turns out to be insufficient. Thus, the herd is reduced by a modest percentage. This is typically what is found in the experiments. The reductions are not sufficient to bring consumption below the growth rate. Hence, the lichen thickness continues to decline. In year 3 the same reasoning is repeated. However, since the growth rate declines as the level of lichen drops, a “careful” approach implies that overconsumption continues. Frustration increases among the participants as they fail to stop the decline in lichen, since they feel confident that they have chosen an appropriate strategy according to their more or less static mental model.

This failure to bring yearly consumption in line with yearly lichen growth might seem strange for a person who is presented with the illustration in Figure 1. However, in the experiment, as in reality, both the consumption and the growth rates shown in the figure, are unknown. Furthermore, the growth curve is not part of the normal repertoire of mental models for most people. Thus most participants were faced with the combined task of developing a new mental model and coming up with estimates for consumption and growth rates from the data available. This is a complicated problem, and most participants seem to have failed to develop a proper mental model. Learning was limited even when large amounts of data became available over time. This observation is also consistent with earlier investigations of dynamic decision making, e.g. Brehmer (1990), Paich and Sterman (1993), and Bakken (1993). For complicated dynamic problems, learning tends to be both slow and modest. Typically, only a small minority does fairly well and does learn.

The above implies that a decision-tool for reindeer management must focus the attention on rates of change in lichen, i.e. on growth and consumption of lichen. Relying on raw measurements of the amount of lichen is not likely to suffice.

While the adaptation to summer ranges should be easier than the adaptation to winter lichen, also this problem is complicated by dynamics and considerable uncertainty. The major difference between grass and lichen is that grass does not accumulate from year to year. What is not eaten in one season withers and disappears before the next season. Considerable natural variation in the quality of grass from year to year implies that observations over several years are needed to reveal for instance that the herd size has been increased above the optimal level.

2.2. Dynamic optimisation under uncertainty

Dynamic programming can be used to find optimal strategies for the adjustment of the herd size when a model with fixed parameters is established. In Moxnes et al. (1998) it is found that the optimal strategy for the herd size can be well approximated by a function of the current measurement of the amount of lichen. From a series of sensitivity tests, we note the following insights, which will be relied on in the decision-tool:

First consider the case when winter lichen ranges represent the limiting resources (i.e. abundant summer ranges). Then it is found that the aim for the policy should be to reach the maximum sustainable yield for lichen. I.e. the amount of lichen should be such that lichen growth is maximised, see Figure . This conclusion is hardly sensitive at all to variations in model assumptions with one exception. If reindeer consumption and wastage of lichen varies with the density of lichen, it is the equilibrium herd size (EHS) that should be maximised and not the lichen growth. The EHS denotes the number of reindeer that can be sustained exactly by the yearly growth in lichen, when the effects of lichen density on consumption and wastage are taken into consideration. Since consumption and wastage tend to increase with lichen density, the EHS is maximised for a lower lichen density than lichen growth.

Second, consider the case when summer ranges are limiting. In this case the optimal herd size is independent of the lichen ranges. The optimal herd size is characterised by a balance between the benefits of having more animals to slaughter and the consequent costs of more animals in terms of reduced weights, reduced calving fractions, reduced survival rates, and increased operating costs. The challenge is to find the herd size that maximises the net present value. It is found that the optimal herd size is not sensitive to variations in the discount rate in the range below 10 percent. Hence, instead of maximising the present value of profits, one could just as well aim for a maximisation of the sustainable yearly profits.

2.3. The problem of optimal learning

In the preceding section we referred to optimal strategies for a known model. For example, in case winter lichen is the limiting resource (and we disregard that consumption and wastage varies with lichen density), one should aim for the maximum sustainable yield for lichen growth. Applying this recommendation in reality, one needs to know at what lichen density the growth rate is maximised. Clearly one needs local data to answer this question for a particular reindeer district. The data available in turn depends on the history of reindeer lichen consumption. If small herds have been held before and while collecting data, there will only be observations of lichen growth for large amounts of lichen, i.e. in the right-hand portion of the curve in Figure . If there has been overgrazing going on before and during data collection, only data for the left-hand portion of the curve will be available. From this we understand that a truly optimal policy for the herd size should not only consider short-term profits. The effect of the herd size on the amount of lichen and consequently on the quality of our data is also important. In principle, it can be optimal both to under- and over utilise lichen ranges to get a good picture of where the yield is maximised. In the long term this information will lead to better policies for the herd size. Conversely, if one keeps the amount of lichen constant, one will only learn about one point on the curve. A piece of information that is of little use for future policies.

While the general idea of optimal learning is understandable, it is virtually impossible to find exact optimal policies[1]. Exact solutions have only been found for very simple systems, using complicated methods, e.g. Walters (1986). To guide an alternative, intuitive approach it is important to have a feeling for what information is needed, how valuable it is, and how costly it is to deviate from the policy that is currently thought to be optimal in terms of profits.

In some cases, records of data may be available from historical periods with large variations in both herd sizes and amounts of lichen. Then what is needed is only a proper method to estimate the position of the maximum sustainable yield in case lichen is limiting, or a method to estimate the herd size that maximises yearly profits in case summer ranges are limiting. Further data are only needed for fine tuning, or to detect possible longer-term fundamental changes in nature. Such long-term changes could be caused by climate change or by permanent changes in the mix of plant species due to new grazing patterns.

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[1] Optimal strategies which take learning into consideration are often referred to as “actively adaptive policies”, or as “dual control” since the method acknowledges that actions influence both current profits and the learning potential. Strategies which do not take into consideration the effects of actions on learning are referred to as “passively adaptive policies”. In this case the profit maximizing policy is always derived from the latest model based on the most recent data. This strategy is naturally followed whenever the effects on learning are overlooked. If natural variations are sufficiently large, this method could work reasonable well, since the natural variations would provide the necessary spread in data.

3. A TOOL FOR PRACTICAL REINDEER RANGELAND MANAGEMENT

Here we suggest a practical management tool. The decision-tool should pay due respect to all the insights presented in the previous section, and it should be sufficiently simple that actors without knowledge of methods for optimisation and estimation could use it. Simplicity is important since it is often found that complexity hinders the diffusion of new ideas, Rogers (1995), and that user participation in the process of analysis promotes the transfer of knowledge, Morecroft (1992), Vennix et al. (1996), and Vennix (1996). This does not mean that we have been able to avoid somewhat complicated mathematics in the derivation of the tool. However, we hope that practice sessions, using a simulator, will help users build intuition and trust in the tool.

The decision-tool is not based on a package for formal parameter estimation and testing. A sufficient reason for this is that the task is complicated by nonlinearities and prior information requiring a Bayesian approach. Even scholarly articles tend to avoid such problems by reporting results based on limited sets of data (ignoring prior information). While that is acceptable and often preferable in science, it may lead to biased management decisions in a practical setting. Therefore guidelines will be developed, which seek to ensure a proper blending of data and prior information.

Nor will the decision-tool contain an optimisation package. Like the estimation problem, the optimisation problem (the dual problem of learning and management) is highly complex and is not properly solved in the optimisation literature. Hence, approximations cannot be avoided. The idea here is to provide information that by itself should lead to near-to-optimal decisions, with only a small amount of training. One reason to believe that this is possible, is that the transformation of information provided by the decision-tool helps define the problem and focus on the essentials.

The decision-tool addresses the two main situations discussed earlier: First, if winter lichen is the limiting resource, for what lichen density is the equilibrium herd size maximised? Second, if summer ranges are limiting, for what herd size are profits or total meat production maximised?

3.1. Adaptation to winter lichen ranges

The purpose of the decision-tool with regard to lichen is to help produce a reliable estimate of the curve for the equilibrium herd size (EHS). EHS is the number of reindeer that eats and wastes exactly the amount of lichen that grows up each year. The estimate will be based on measurements of the amount of lichen and of the herd size. In addition we will rely on prior information about lichen growth and reindeer consumption and wastage of lichen.

What sources of information do we have to estimate the growth curve for lichen? Early works of lichen growth were carried out in Norway by the lichenologist Bernt Lynge between 1910 and 1935. He measured growth of lichen thalli against fixed wooden sticks. Only the field journals are left. Igoshina (1939) studied growth by measuring thalli marked with India ink, Kärenlampi (1971) by repeated weighings of plastic trays with different species put back in natural environments between weighings, Yarranton (1975) repeated observations of fixed plots. Unpublished works by one of the authors, Eldar Gaare, combined the methods of Kärenlampi and Yarranton. All give consistent results: accumulation of ground lichens that reindeer use for food, follows a S-formed curve. In this work we have not adapted a symmetric logistic growth curve, instead we allow for a more flexible form of the curve.

Using the above methods, typical estimates of the maximum lichen growth range from 2.5 to 6.0 mm per year. Another method is to study lichen recovery after forest fires. Using this method Kumpula et al. (2000) find a maximum growth rate of around 1.5 mm per year. Some of the difference could be explained by the focus on average rather than individual growth in the latter study. This point is best illustrated at the point where the lichen density yields the maximum sustainable individual growth (confer Figure 1). If in a range, all individual plants have been grazed exactly the same, individual growth and average growth will be the same. However, reindeer grazing as well as forest fires are likely to cut back on individual plants to varying degrees. Hence when the average lichen density implies maximum individual growth, the average growth will be lower. This is because some areas will have a higher lichen density and some areas a lower density than the average, both areas having lower lichen growth than what the average implies. The observed differences could also to some extent be explained by uncontrolled grazing in the areas with forest fire and by different amounts of rainfall in the studied areas. The latter point should always be kept in mind since lichen growth is close to proportional to summer season precipitation, Karenlampi (1971).

Whichever of the methods one uses to estimate relative growth rates, it remains to estimate total growth rates for the reindeer district one is managing. One way to do this is to assess the entire district with respect to potential lichen coverage. One should adjust for the fact that some areas are not available during the winter season, and therefore are of marginal interest for the management problem. Using this method one should also distinguish areas with different growth potentials due to topology and weather conditions. The method is frequently used and the estimates provide useful prior information about a district. However, the remaining uncertainty is likely to be considerable, such that more information is desirable.

Here we will use information about the amount of lichen and the number of reindeer to estimate lichen growth. First consider the following equation for the rate of change in total lichen resources per year:

$$A(L_{t+1} - L_t) = Ag(L_t) - c'(L_t)N_t \qquad (1)$$

Here lichen L_t (g/m²) is defined as the average lichen biomass per square meter for the available range land. Thus, L_t is a measure of lichen density for ranges that are available for grazing and not excluded by snow cover or topography. The parameter; A, denotes the size of the area. Hence A times L_t is a measure of total lichen biomass in the available areas.

By definition, the change in lichen resources from one year to the next, $A(L_{t+1} - L_t)$, equals the difference between total lichen growth $Ag(L_t)$ and reindeer lichen consumption $c'(L_t)N_t$. Here average growth of lichen $g(L_t)$ is measured in lichen biomass per square meter per year, and this growth rate depends on the density of lichen. Reindeer consumption of lichen is given by the number of reindeer N_t times consumption per animal $c'(L_t)$. Consumption is here defined as the sum of intake and waste. Some of the wasted lichen will settle and continue growing, while some of it will be transported away by wind and water, or will settle in areas out of reach for the reindeer. We define waste as the amount of lichen that is removed permanently from the range that is actually grazed. Consumption per animal increases with the density of lichen.

Next, to focus on lichen growth, we reorganise Equation 1 by moving the growth term to the left-hand side.

$$(\text{EHS} =)\frac{A}{c'(L_t)}g(L_t) = \frac{A}{c'(L_t)}(L_{t+1} - L_t) + N_t \tag{2}$$

At the same time we divide by consumption per animal, $c'(L_t)$. Now the unit in Equation 2 becomes number of animals. On the left-hand side, total annual growth divided by consumption per animal expresses the equilibrium herd size, EHS, for the given level of lichen, L_t. Thus the equation now expresses what we are interested in, namely the number of animals that lichen growth can support.

From the right-hand side of the equation we see that the number of animals N_t is equal to the EHS if the lichen resource stays constant, $L_{t+1} = L_t$. Equation 2 can not be used to estimate both the size of the area and consumption per animal. We can only estimate a combined measure of "area per yearly food ration", . In the present version of the tool we do not allow for the use of prior information about the area, although estimates of A could be obtained by vegetation mapping, nor do we allow for prior information about consumption per animal.

To simplify and to focus on the essentials, we multiply the numerator and the denominator of the ratio $A / c'(L_t)$ by the ratio $g(L_{max}) / c'(L_{max})$, where L_{max} is the lichen density that maximises the EHS. After having multiplied, in the numerator we get the expression $Ag(L_{max}) / c'(L_{max})$, which by definition must be the maximum EHS, named N_{max}. In the denominator we get the expression $c'(L_t) / c'(L_{max})$, which denotes the relative consumption per animal, $c(L_t)$, which equals 1.0 when lichen density equals L_{max}. When we use this notation we can write Equation 2 in the following way

$$(\text{EHS} =)\frac{N_{max}}{c(L_t)}\frac{g(L_t)}{g(L_{max})} = \frac{N_{max}}{c(L_t)g(L_{max})}(L_{t+1} - L_t) + N_t \tag{3}$$

If L_t=L_{max} we see that the left-hand side becomes equal to N_{max}, recalling that $c(L_{max})$=1.0. The first term on the right-hand side has undergone the same transformation as the left hand side. Note that our new function for consumption $c(L_t)$ is a relative measure which only contains information about the curvature of the relationship. It does not carry information about absolute consumption per animal. All information about the maximum number of animals that can be supported by lichen growth is contained in our new key unknown parameter N_{max}. Together with L_{max}, N_{max} fully determines the location of the peak of the EHS curve.

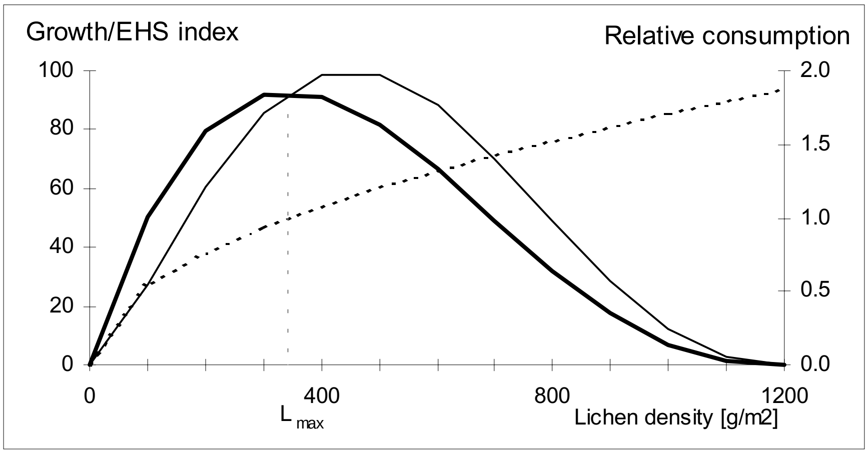

Figure 2: Relative consumption (intake and waste) (dashed line), growth of lichen (thin line), and EHS (thick line).

Figure 2 illustrates how the EHS is related to lichen growth $g(L_t)$ and relative consumption $c(L_t)$. The thin solid line shows lichen growth per square meter as a function of lichen density L_t. If it was not for the fact that relative consumption varies with the lichen density, see the thin dashed line, the curve for the EHS (thick line) would be identical to the growth curve, except for a difference in scale. To simplify the comparison of lichen growth and the EHS curves, we have rescaled them to a common index in Figure 2 .

When $c(L_t)$ is taken into consideration, the maximum of the EHS curve is shifted to the left of the maximum of the lichen growth curve. That this is so is most easily seen at the maximum of the growth curve. By moving slightly to the left of the maximum, growth is hardly reduced while consumption per animal is reduced more strongly. Thus one should move leftwards until the marginal reduction in lichen growth and the marginal reduction in the relative consumption is balanced. That is where the EHS is maximised. The steeper $c(L_t)$ is, the further to the left the maximum of the EHS moves.

Knowing the herd size and the lichen density, an estimate of the EHS can be produced by the right-hand-side (RHS) of Equation 3, given assumptions about the term $N_{max} / (c(L_t)g(L_{max}))$. With these assumptions in place, the RHS is used to produce “data points” needed to estimate the EHS curve.

Assuming for a while that both the functions $g(L_t)$ and $c(L_t)$ are known perfectly from prior data (including the location of L_{max}), Equation 3 can be solved for N_{max}, given observations of L_t and N_t. As long as N_t is greater than zero, there exists a solution to this problem. However, with numerous observations at different time points *t*, we can only obtain a statistical measure of N_{max}. Rather than using a statistical method however, we will use trial and error to get an acceptable fit between the EHS curve and the RHS data points. This is also the type of calibration the user should be doing to estimate the maximum number of reindeer.

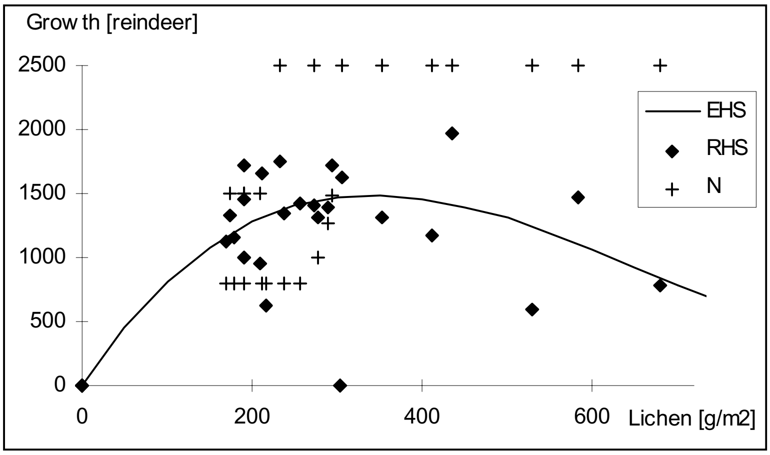

Figure 3: Example of combined learning and optimisation, EHS (solid line), RHS (filled squares), number of reindeer, *N* (+ signs).

The procedure is illustrated in Figure 3, where data is generated by a simulator. The simulator is based on the most advanced version of the model described in Moxnes et al. (1998). To keep things simple, for the moment we still assume that $g(L_t)$ and $c(L_t)$ are known perfectly and that it is only N_{max} that needs to be calibrated. In the simulator we assume that measurements of average lichen are corrupted by measurement error. Hence, we will not be able to achieve a perfect match between the left and the right-hand side of Equation 3 for all data points.

We start the simulator at an average lichen density of around 700 g/m^2 and we choose a herd size of N_t =2500 (+ signs). This herd size is kept for a few years while we collect data about the lichen density. With a few data points available, we adjust N_{max} such that the curve for the EHS starts to approximate the data points (shown by black squares) given by the RHS. The data points for the RHS will vary according to variations in lichen measurements and in herd sizes. In the example, the correct N_{max} equals 1486, however, it is not likely that one comes close to this value with only a few observations. However, what should be clear rather quickly is that the herd size is considerably above the EHS. The qualitative part of this conclusion follows directly from the mere fact that the lichen density is declining. In addition, Figure 3 indicates by what amount the herd size exceeds the EHS.

In the example we continue with a herd size of 2500 for 9 years. At this point in time we have a fairly good indication of where the EHS curve lies, and where the maximum is situated. The task is now to bring the herd size down below the EHS to ensure that lichen density increases towards the density L_{max} where N_{max} can be achieved sustainably. First however, three more observations are made with a herd size just above the estimated EHS curve. These provide more data with less risk of severe overgrazing. Finally, the herd size has to be kept below the EHS for some time before L_{max} is reached. Keep in mind that it also takes some time to increase the herd size towards N_{max}, such that the herd size should be gradually increased as L_{max} is approached.

Actually, since we assumed that $g(L_t)$ and $c(L_t)$ were known perfectly, we could have done better than in Figure . From the initial starting point with 2500 animals, the herd size could have been gradually decreased towards N_{max} as lichen density approaches L_{max} from above. The approach taken in the example is more appropriate when $g(L_t)$ and $c(L_t)$ are not known perfectly. Then we would not know exactly where L_{max} is situated, and we would have to search for parameters in the functions for $g(L_t)$ and $c(L_t)$ that would determine the location of L_{max}. If we had aimed for what we believed was the correct estimate of L_{max} based on only a few early data points, a non-optimal situation could result.

To illustrate, assume that an early estimate of L_{max} was at a lichen density of 550 g/m^2, and that we brought the herd size down to the EHS at that point, i.e. to our current estimate of N_{max}. Further assume that this was a perfect estimate of the EHS at that point such that lichen density would stay constant in ensuing years. Further data generated at this point would serve to strengthen our belief in our estimate of the EHS at this point. However, they would not be helpful in determining whether the EHS would increase by moving towards lower of higher lichen densities. The rational for deviating from an early estimate of L_{max} and from an apparently profit maximising strategy, is potential learning. The approach in Figure 3 produces data that are much more useful to produce a reliable estimate of L_{max}.

To summarise: one cannot identify a curve by making repeated observations of only one point. A linear curve requires at least two points, a second order curve at least three points etc. With uncertain observations and an unknown order of the curve, it seems necessary to deviate from the true L_{max} by a considerable amount to be able to learn. Of course, the costs incurred in the process of learning should be weighted against the potential for increased profits in the future. For instance a more careful approach than the one chosen in Figure 3 could be more profitable. It is very difficult to determine the exact profit maximising learning strategy, see e.g. Walters (1986). We will not make any efforts in this direction. However, it is likely that training with the decision-tool using the simulator, will help develop some intuition on this problem.

Let us now turn to the search for parameters in the functions $g(L_t)$ and $c(L_t)$. First, however, we present mathematical descriptions of the two functions:

$$g(L_t) = \frac{g_{msy}}{(\frac{\alpha_1}{\alpha_1+\alpha_2})^{\alpha_1}(\frac{\alpha_2}{\alpha_1+\alpha_2})^{\alpha_2}} \left(\frac{L_t}{L_{cc}}\right)^{\alpha_1}\left(1-\frac{L_t}{L_{cc}}\right)^{\alpha_2} \tag{4}$$

Growth is given by a flexible function with four parameters. Growth is positive for lichen densities between zero and the carrying capacity L_{cc}. Maximum growth (the maximum sustainable yield) is given by g_{msy}, independent of the other parameters (the expression in the denominator ensures this independence). The sum b=α_1+α_2 influences the curvature or the bending of the curve. The lower the sum, the wider the curve for growth will be. Finally, the lichen density L_{msy} (not to be confused with L_{max}) for which lichen growth (not the EHS) is maximised, is found by setting the first derivative equal to zero:

$$L_{msy} = L_{cc}\alpha_1 / (\alpha_1 + \alpha_2) \tag{5}$$

Thus the skewness of the function is given by $\alpha_1 / (\alpha_1 + \alpha_2)$.The function for consumption (intake and waste) is given by

$$c(L_t) = \left(\frac{L_t}{L_{max}}\right)^{\alpha_c} \tag{6}$$

The function has the desired properties $c(0) = 0$ and $c(L_{max})$ =1. The parameter α_c determines the slope of the curve when $L_t = L_{max}$. Considering our limited prior knowledge about particularly the wastage of lichen, the simple relationship seems appropriate. For well managed reindeer ranges, L_t should not deviate too much from L_{max}, such that the slope at this point summarises what is of key importance.

When searching for parameters, we start by fixing the two key parameters L_{max} and N_{max}. All the remaining parameters determine the curvature and the skewness of the EHS curve. Note that when L_{max} is fixed, we are no longer free to set all remaining parameters. To find the relationship between L_{max} and the other parameters, we find the maximum of the left-hand side of Equation 3 (the EHS curve) by differentiation. The functions for $g(L_t)$ and $c(L_t)$ are entered from Equations 4 and 6. We find

$$L_{max} = L_{cc} \frac{\alpha_1 - \alpha_c}{b - \alpha_c} \qquad (7)$$

where, as mentioned above, $b=\alpha_1+\alpha_2$. We solve this equation for α_1 and find

$$\alpha_1 = L_{max}(b - \alpha_c) / L_{cc} + \alpha_c \qquad (8)$$

Knowing α_1, we find α_2

$$\alpha_2 = b - \alpha_1 \qquad (9)$$

Hence the two parameters α_1 and α_2 are determined by Equations 8 and 9[2] and are not set by the user of the tool. After having set values for L_{max} and N_{max}, one also has to set values for the remaining parameters: the curvature of the consumption relationship α_c, the parameter for the bending of the growth relationship *b*, and the carrying capacity L_{cc}. In addition the MSY for lichen growth g_{msy} needs to be set.

From the discussion of $g(L_t)$ we recall that the parameters *b* and L_{cc} influence the curvature of the growth curve for lichen and consequently the curvature of the EHS curve. It also turns out that α_c is primarily important for the curvature of the EHS curve. The curvature is independent of g_{msy} since this parameter enters both the nominator and the denominator of the expression for EHS, see the left-hand side of Equation 3. Hence, three of the remaining four parameters are basically important for the curvature of the EHS curve. Normally available data about L_t and N_t will not be sufficient to determine all three parameters. Hence, prior information must be used, as in a proper Bayesian approach.

When adjusting the parameters to improve the fit to the data, in light of prior information, one should try to follow the logic of Bayes theorem. Parameters that are known fairly well apriori, should not be adjusted at all or only by small amounts. Similarly, parameter values (or sets of parameters) which cannot be distinguished by the use of data (the likelihood does not vary much over the apriori likely ranges of parameters), should not be adjusted. Here we consider the carrying capacity L_{cc} to be established

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[2] Similarly, the lichen density for which the growth curve reaches its maximum can be found from the other parameters: $L_{msy} = \alpha_1 L_{cc} / b$.

fairly precisely from prior information (observing numerous cases of ungrazed areas). Hence L_{cc} is not a very likely candidate for calibration. This leaves us with *b* and α_c to determine the bending of the EHS curve. The prior information is probably most reliable for *b* since one can build on investigations of lichen growth. Note however that the average growth curve is wider than the growth curves that can be found from studies of individual plants (see the earlier discussion about the maximum sustainable growth from studies of individual plants and areas with forest fires). Upper limits for α_c are indicated by studies of reindeer consumption and wastage. The value of α_c is reduced by the reestablishment of wasted lichen in grazed areas. The two parameters are candidates for sensitivity tests where one asks the question: will different combinations of *b* and α_c lead to changes in estimates of the two key parameters L_{max} and N_{max}?

Until now we have discussed the effects of the parameters on the EHS curve. In addition, all parameters have an effect on the RHS of Equation 3. Thus, they all influence the fit between the RHS data points and the EHS curve. When $L_t = L_{max}$, $g(L_{max})$ is the only factor to adjust to reduce the spread around the EHS curve (recall that $c(L_{max})$ equals 1.0 and that N_{max} is a key determinant of the EHS curve). The value of $g(L_{max})$ is primarily determined by g_{msy}, a parameter which is of no importance for the EHS curve. Thus, g_{msy} seems a prime candidate to reduce the spread around the EHS curve once this curve is fixed. However, one should be careful not to deviate too much from prior information about this variable.

For values of L_t different from L_{max}, $c(L_t)$ is also a key determinator of the spread even though this factor also influences the shape of the EHS curve. Thus α_c can be used to reduce the spread around the EHS curve. The spread is not very sensitive to variations in the bending *b* of the lichen growth curve and the carrying capacity L_{cc}. While L_{max} and N_{max} have a certain effect on the spread, these two parameters are primarily set to position the EHS curve within the data points, not to adjust the spread of the data points.

To summarise the calibration process. The parameters of key importance L_{max} and N_{max} are set to position the maximum of the EHS curve correctly within the data points produced by the RHS of Equation 3. The parameter for the bending of the lichen growth curve *b* is set to adjust the shape of the curve. To minimise the spread of the data points produced by the RHS, g_{msy} and α_c are prime candidates for adjustment. Adjustments in α_c for this purpose can lead to the need for readjustments of *b*, since both α_c and *b* influence the curvature of the EHS curve (in theory, all parameters are candidates for iterations). When adjusting parameters, one should be careful not to adjust these outside the bounds given by prior information. Carrying capacity L_{cc} is a candidate for exclusive use of prior information. In cases with scarce time-series data, also *b*, g_{msy} and α_c may have to be given exclusively by prior data, with changes made only to study sensitivity.

For the case shown in Figure 3 a rough sensitivity test indicates the following. Variations in α_c (0.5 in the simulator) from 0.0 to 1.0 have no significant effect on the calibration of L_{max} and N_{max}. Taking α_c beyond 1.0, which is not totally ruled out by unreliable prior data about wastage, the variation in the data points produced by the RHS becomes sufficiently high to rule out this possibility (given that the data were produced by a value of 0.5 in the simulator, and given that other parameter estimates are sufficiently accurate). Variations in the bending *b* (4.0 in the simulator) has some effect on the calibration of N_{max}. For *b*=1 (probably wider than the limit indicated by prior data), N_{max} is reduced by approximately 15 percent. For *b*=20 (probably more narrow than the limit indicated by prior data), N_{max} increases by around 20 percent. Finally, we find that variations in g_{msy} (64 g/m^2 in the simulator) has a certain effect on the calibration of L_{max}. For g_{msy}=30, L_{max} is reduced by nearly 30 percent. For g_{msy}=100, L_{max} increases by about 15 percent (and N_{max} increases by about 10 percent). These values span the range in prior growth estimates referred to earlier from areas with forest fires and from studies of individual plants. The results of this rough sensitivity test indicates that g_{msy} is the parameter that it is most valuable to get more precise prior information about. Also note that the spread in the data points produced by the RHS does not seem to increase when g_{msy} increases from 64 to 100 g/m^2. Hence, our method does not guard against overestimations of g_{msy}. This is another reason to have good prior data about g_{msy}.

Finally, we comment on two ways to refine the above analysis. First, according to Karenlampi (1971), lichen growth is close to proportional to weakly precipitation (perhaps saturating at high precipitation rates). Thus lichen growth depends on the rainfall during the growth season, which typically ranges from May through September. This means that in Equation 3 we should correct for rainfall. Assuming a simple linear relationship, the left-hand side of the equation should be multiplied by the year’s summer rainfall divided by the normal rainfall for the area. Alternatively, the RHS could be divided by the same factor. The latter method is the most practical one, since it allows us to keep a clean curve for the EHS. The adjustment would only affect the data points for the RHS. Unless there are fairly large and autocorrelated variations in precipitation over the years under investigation, this correction factor is likely to be of little importance. Furthermore, if lichen densities are only measured years apart, yearly variations in rainfall tend to even out between measurements. This option is not included in the current version of the decision-tool.

Second, measurements of lichen density could be filtered somehow. In the simulator we have assumed that uncertain yearly measurements are available. In this case is makes sense to smooth the data for lichen densities over years before the data are used in Equation 3. The following smoothing function is implemented in the decision-tool:

$$L_t^S = \sum_{i=\max(-2,t_0-t)}^{\min(2,t_{max}-t)} w_i \, L_{t+i} \Big/ \sum_{i==\max(-2,t_0-t)}^{\min(2,t_{max}-t)} w_i \tag{10}$$

where the weights w_i from i=-2 to 2 are respectively: 0.15, 0.2, 0.3, 0.2, and 0.15. Upper and lower limits in the summations are such that weights are not given when data are not available (before the first year t_0 and after the last year t_{max}). Note one weakness with this smoothing routine: it will undervalue lichen density at upper turning points in long-term developments and overvalue lichen density at lower turning points. Figure 4 shows the example from Figure 3 when the above filter is used. The data points are closer to the EHS curve such that it is easier to do the calibrations.

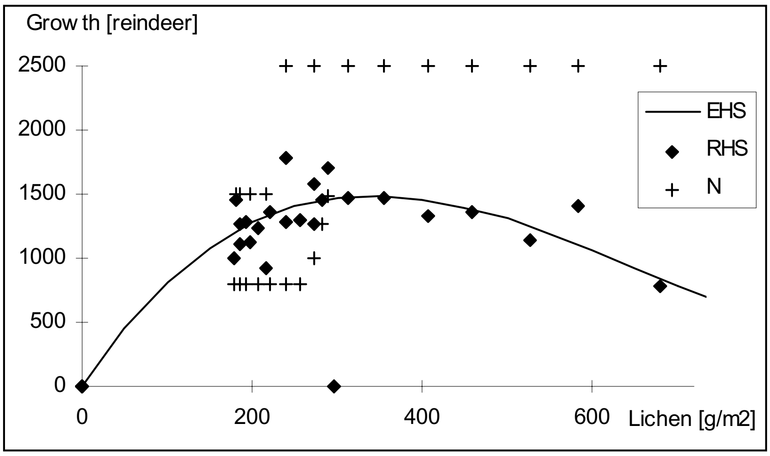

Figure 4: The example in Figure 3 with the described filter. EHS=equilibrium herd size, RHS=right-hand size of Equation 3, N=number of reindeer in different years.

The built-in smoothing function is the most practical alternative when using the simulator. An alternative when using real data is to smooth the data by hand before they are entered into the decision-tool. If data are not collected each year, one has to interpolate between infrequent data points and thus perform some smoothing of the data. The interpolations could take account of changes in herd sizes. For instance, the lichen density should drop more quickly in a period with large herds than in a period with small herds. Be aware however that filtering may disguise weaknesses of the data, they may appear more accurate and representative than they really are. Also be aware that manual smoothing should not be used to get the answers one prefers. Hence one should smooth the data based on the best knowledge before the tool has been used, and not after the results of the calibration is observed.

3.2. Adaptation to summer ranges

While the adaptation to winter lichen ranges is complicated by the dynamics of lichen, the dynamics of summer ranges are thought to be more simple. As long as one stays away from extreme changes in the grazing pressure, the composition and the yearly growth of the vegetation are not likely to change much due to changes in the number of reindeer. It seems to be a good first approximation to assume that the availability and quality of summer ranges stay constant from year to year, with the exception of changes due to weather conditions.

With an assumption about constant availability and quality of summer ranges from year to year, the adaptation of the herd size is in principle simple. Use the following rule: Adjust the herd size from year to year and observe yearly profits (or meat production if that is the criterion). Change the herd size in the direction that yields higher profits. Stop the search when profits stagnate or start to decline. At the optimal point there is a balance between the benefits of having more animals to slaughter and the consequent costs of more animals in terms of reduced weights, reduced calving fractions, reduced survival rates, and increased operating costs. Due to the random factors, it will not be possible to move directly to the optimal point and stay there forever after. Observations away from the optimal point are needed to establish a reliable estimate of the profit curve (profits as a function of the herd size). Hence, one has to strike a balance between learning about the system and short-term optimisation given current knowledge, i.e. adaptive management is needed as in the case of winter lichen.

The profit curve that we are interested in represents the equilibrium profits that can be reaped sustainably. I.e. we want to learn about the equilibrium profit curve (EPC). Two types of dynamics imply that one cannot make a direct use of yearly observations of profits. First we note that whenever the herd size is adjusted downwards, profits rise due to the extra slaughtering of livestock. Similarly, profits decrease when the herd size is adjusted upwards. Clearly this represent transient and not sustainable profits.

Second, the full effect on profits of adjustments in the herd size is delayed. In the very autumn when the herd size is adjusted, there is no effect on underlying variables for profits. The next autumn, profits are affected for two reasons: the adjustment of the herd size has a direct effect on the number of calves, and the autumn weight of the adult animals (and to some extent the calves) is changed due to changes in the level of competition between the animals in the summer ranges. First after two years, will the effects on calving percentages and survival rates be felt. This is because these rates depend on the autumn weights in the preceding year. This is to a large extent also the case for calf weights, which depend on the weights of the mothers. Finally, if the herd size is adjusted upwards, the effect of the number of animals on the number of calves is also delayed because the fertility is lower for one year old females than for older ones. (This latter effect is not captured by the simulator and is not corrected for by the decision-tool).

To avoid that these dynamics distort our measure of profits, we produce estimates of equilibrium profits at time points *t*. The data points are used to construct the EPC. The following formulae is used:

$$\pi_{E,t}(N_t) = p_E(w_{A,t}S^E_{A,t} + w_{K,t+1}S^E_{K,t}) - c_0 N_t \tag{11}$$

In short the profits are made up of the incomes from sales of meat from slaughtered adults and calves minus the operating costs $c_0 N_t$. The incomes are made up by total slaughter weights times a price p_E. The total weight of slaughtered adults is the product of the average weight $w_{A,t}$ and the number of adults being slaughtered $S^E_{A,t}$. The total weight of slaughtered calves is the product of the average weight $w_{K,t+1}$ and the number of calves being slaughtered $S^E_{K,t}$. Related to the above discussion of delays note the following. The autumn herd size is assumed to be represented by herd countings taking place towards the end of the ensuing winter (in Norway this would be in April). Hence N_t is actually representing the autumn herd for the year before (*t*-1). Thus in the subscript for time denotes the year when observations are made. Slaughtering and adult weights are measured and belong to year *t*, while calf weights, survival rates, and calving rates are measured and belong to year *t*+1.

For the moment the tool does not include any effect of declining lichen. However, the tool can be used to display possible effects of varying lichen conditions. This is easily done by selecting time periods with low and high lichen levels and then compare the data points and the equilibrium profit curves.

Slaughtering of adults is given by the equation

$$S_{A,t}^{E} = v_{t+1} N_t / \tau_A \tag{12}$$

where v_{t+1} is the observed survival rate. This rate is calculated from measurements of the stock size and is directly related to loss estimates. The parameter τ_A is the desired average lifetime of adults. This is a parameter that can be chosen freely to see how it affects the EPC. If for instance τ_A=10 years, 10 percent of the surviving adults are slaughtered each year. The slaughtering of calves is given by

$$S_{K,t}^{E} = K_t^{E} - (S_{A,t}^{E} + N_t(1 - v_{t+1})) \tag{13}$$

where K_t^{E} is the reported number of calves. The number of calves available for slaughtering is reduced by the need for replacements of livestock. In equilibrium one needs to replace the slaughtered adults, $S_{A,t}^{E}$, as well as the adult animals that do not survive for other reasons, here given by the expression $N_t(1 - v_{t+1})$. The total number of calves is given by the expression

$$K_t^{E} = f_f k_{t+1} v_{t+1} N_t \tag{14}$$

where f_f is the desired fraction of females in the herd and k_{t+1} is the calving fraction for females. The desired fraction of females can be set freely. The calving fraction is calculated from measurements of the number of females and the number of calves surviving until the autumn.

Instead of using actual prices, which vary from year to year as a random variable, the "equilibrium price" p_E is entered as a parameter. Thus as for τ_A and f_f one can see if the profit maximising herd size is sensitive to the price level. The natural choice is the price which one expects to prevail in future years. Operating costs are assumed proportional to the number of reindeer, where c_0 is the cost per reindeer. The parameter c_0 is the fourth and the last parameter that can be varied freely. E.g. by setting c_0 equal to zero and p_E equal to 1.0, one will find the herd size that maximises meat production. Since the tool does not capture weight growth over age classes, the weight jumps from calf weight to adult weight once the animals are entered as livestock, thus predicted effects of adjusting τ_A becomes increasingly unrealistic as τ_A approaches 1.

The above calculation of the EPC is not quite correct. We have ignored that changes in calving fractions and survival rates in turn influence the number of animals in the summer ranges, which in turn influences weights, which influence calving fractions and survival rates and so on. However, the longer-term effects of these dynamics are small. To convince oneself of this, one can run the simulator and observe the long-term effects on π_E of a step change in the number of reindeer.

Another warning is also pertinent. The decision-tool is not strong on herd structuring. While one can change two major design parameters: the fraction of females f_f and the average lifetime of livestock τ_A, there are no mechanisms by which one can select particular animals for slaughtering. The prime example is that animals with low weights are selected for slaughtering. Such a policy will influence the average weight in the herd and possibly also the composition of the gene pool. Hence longer-term weights may also be affected. Such changes in weights over time will lead to a larger spread in the EPC data points, and if the effects are large enough, will make older observations incorrect and of less value. Weights, calving percentages, and survival rates can also change for other reasons, not included in the decision-tool, for instance due to climate change and changes in the composition of species in summer ranges due to grazing. Also such changes imply that older data points become obsolete and that ongoing variations in the herd size are needed to reestimate the curve for the EPC.

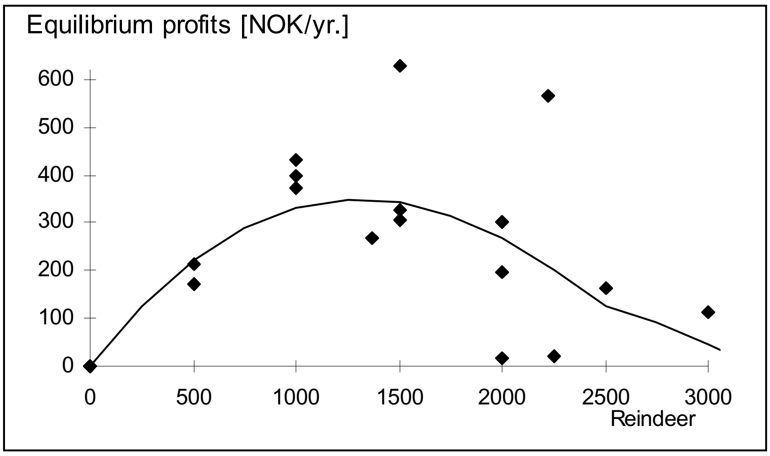

Figure 5: Calculated data points for equilibrium profits. Solid line: EPC based on estimated coefficients.

Figure 5 shows an example of how the decision-tool works, when using data from the simulator. We have started out with 3000 animals and have reduced the herd size in steps toward 500 (lichen ranges are abundant all the time). In each year we have calculated the equilibrium profits using Equations 11 to 14. The values of π_E are shown by black squares. The impression one gets is that natural random variations cause a considerable spread in the data. From the data points the optimum seems to lie somewhere between 1000 and 1500 animals, and the optimum seems to be rather flat (the optimum herd size in case of no natural random variation is near 1600). With such a spread in data, many observations are needed and one needs observations for widely differing herd sizes to get a sense of the EPC. Regarding learning, the figure indicates for which herd sizes new data points are needed the most.

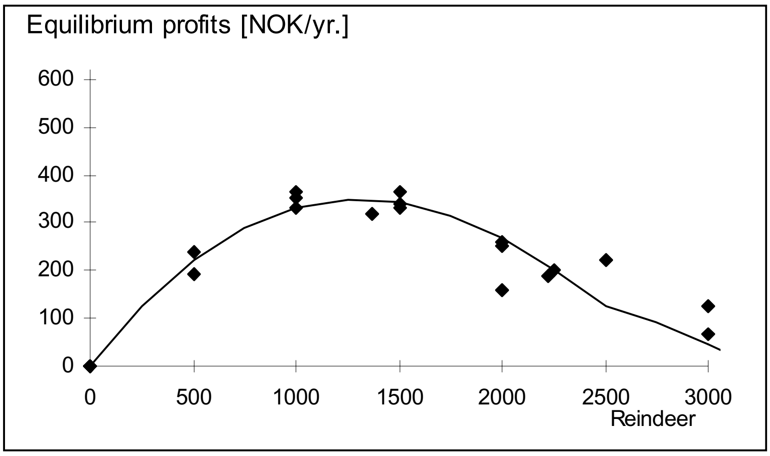

Figure 6: Same as Figure 5 except data points are filtered.

At least three methods can be used to help estimate the optimum herd size more precisely. First, to guide the eye-balling method just described, data points can be filtered. We use Equation 15 to filter the calculated equilibrium profits

$$\pi_t^S = \sum_{i=\max(-2,t_0-t)}^{\min(2,t_{max}-t)} w_i \; \pi_{t+i} \Big/ \sum_{i==\max(-2,t_0-t)}^{\min(2,t_{max}-t)} w_i \tag{15}$$

The procedure is the same as in Equation 10 where L_t is replace by π_E. Using the same example as in Figure 5, the effect of filtering is shown in Figure 6. The data points are less spread and it is easier to see that the optimum is likely to lie between 1000 and 1500 animals.

Second, it is possible to estimate the EPC more formally from the available data. Within the decision-tool there is a package which performs linear regressions between respectively calving fractions, survival rates, calf weights, and adult weights, and the independent variable, the herd size[3]. The estimated relationships are used in Equations 11 to 14 to find equilibrium profits as a function of the herd size, $\pi_{E,t}(N_t)$. In the above example, this function is shown in Figure 5 and Figure 6 by a solid line. The estimated curve is based on data that are not filtered. The optimum herd size is estimated close to the actual optimum, and the optimum is sufficiently flat that minor deviations have little economic consequences. When using the decision-tool, the curve

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[3] The data points used are shown in separate figures in the decision-tool. The data are appropriately lagged according to the earlier discussion about dynamics.

does not appear before a minimum of observations have been made. Also note that the curve will typically move about quite a lot as the first few data points are entered. One will also notice that observations for widely differing herd sizes helps stabilise the curve, in accordance with the earlier discussion about learning. Observations for only one and the same herd size will not lead to a stable curve.

Third, the effects of natural variation could be reduced if one had information about the underlying causes of variation, notably weather conditions[4]. Corrections would be parallel to the corrections for rainfall described in the section on lichen. However, this possibility is left out in this version of the decision-tool.

Finally we mention a little trick to get an indication of the importance of the different time-series used to calculated the EPC. If for instance the number of calves in the DATA-sheet is set equal to a constant fraction of the adult females (total number of animals times the fraction of females), the effect of historical variations in the calving fraction are removed for the data underlying the EPC. Comparisons reveal the effect of calving fractions. Similar manipulations can be performed with losses and weights in the DATA-sheet.

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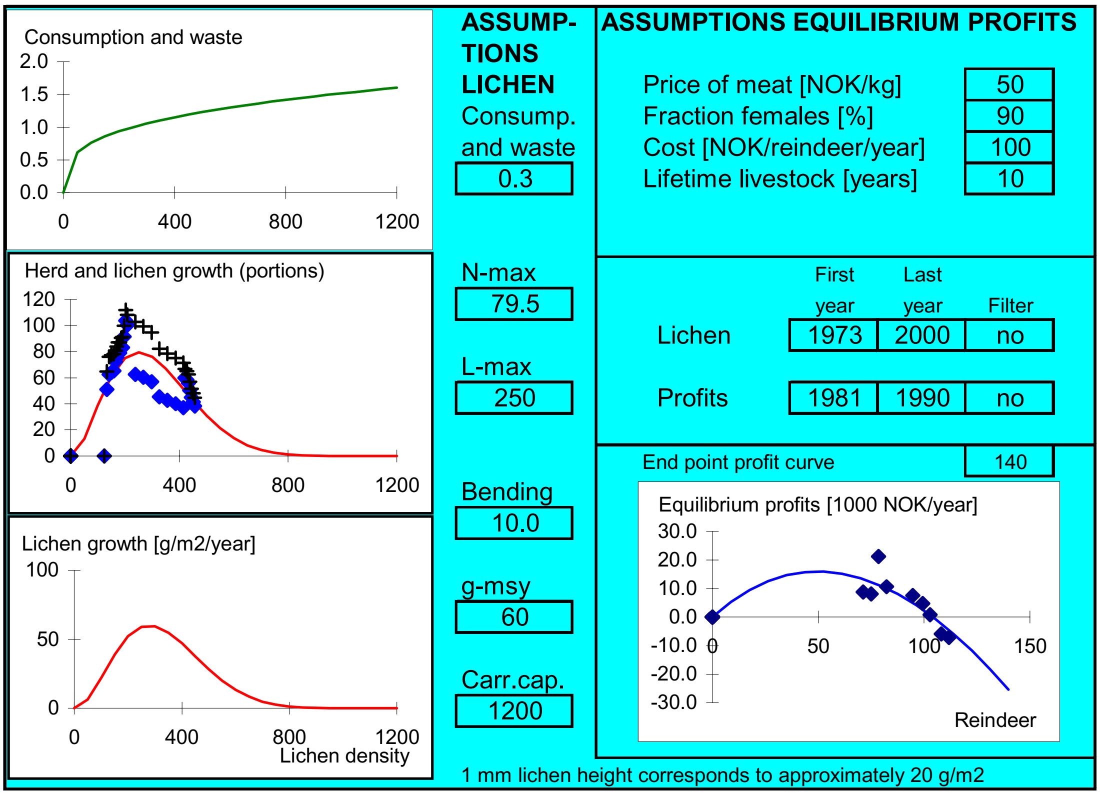
[4] E.g. Tyler (1998) finds that reindeer weight-gains during summers are related to temperatures in different periods of the summer, influencing both vegetation and insect problems.

4. HOW TO USE THE DECISION-TOOL AND THE SIMULATOR

The decision-tool and the simulator are both programmed in Excel. Figure 7 shows the screen for the case when the decision-tool is used without a simulator. The tool is on a sheet called TOOL. Data are entered in a separate sheet called DATA, and yet another sheet called EXTRA FIGURES shows some extra figures.



ASSUMPTIONS LICHEN

Consump. and waste: 0.3

N-max: 79.5

L-max: 250

Bending: 10.0

g-msy: 60

Carr.cap.: 1200

ASSUMPTIONS EQUILIBRIUM PROFITS

Price of meat [NOK/kg]: 50

Fraction females [%]: 90

Cost [NOK/reindeer/year]: 100

Lifetime livestock [years]: 10

	First year	Last year	Filter
Lichen	1973	2000	no
Profits	1981	1990	no

End point profit curve: 140

1 mm lichen height corresponds to approximately 20 g/m2

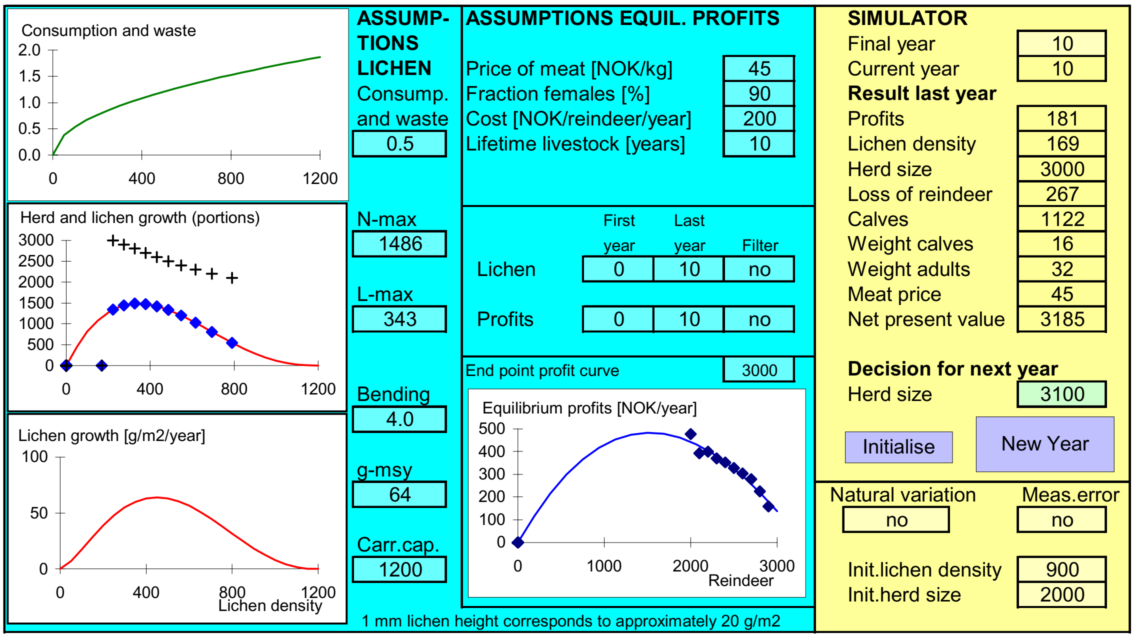
Figure 7: Computer screen for decision-tool.

The left-hand-side of the screen is for winter lichen and the right-hand-side for summer ranges. One is free to adjust all the parameters shown in rectangles. For lichen three graphs are shown: the upper graph shows the consumption and wastage function $c(L_t)$, the lower graph shows the lichen growth curve $g(L_t)$, and the middle graph shows the EHS curve, the data points from the RHS, and the historical herd sizes (similar to Figures 3 and 4). Recall from the previous discussion that L_{max} and N_{max} are set to position the maximum of the EHS curve. The “Bending”, b, is used to adjust the shape of the EHS curve, while “g-msy”, g_{msy}, and the “consumption exponent”, α_c, are primarily used to reduce the spread of the data point around the EHS curve.

The right-hand-side of the screen indicates the optimal herd size as determined by the quality of summer ranges (similar to Figures 5 and 6). The four upper parameters are set to see how the optimal herd size varies with basic assumptions about meat price p_E, fraction of females in livestock f_f, operating costs per animal c_0, and the average lifetime of livestock τ_A.

The filters for lichen and profits can be turned on and off by writing “yes” and “no”. The scales of the figures are adjusted automatically, while one has to adjust the end point of the estimated equilibrium profit curve (EPC). Time periods selected for analysis (including first and last year) must be specified.

Figure 8 shows the screen when the simulator is included. In this case there are two main sheets one called TOOL AND SIMULATOR the other is the EXTRA FIGURES. In addition there is a sheet called Macro1 which contains the simulator equations and a sheet called Time-series. The latter two are not available to the user. Macro1 performs the calculations and Time-series is automatically updated by data from the simulator, and deleted when initialising the simulator.



ASSUMPTIONS LICHEN

Consump. and waste 0.5
N-max 1486
L-max 343
Bending 4.0
g-msy 64
Carr.cap. 1200

ASSUMPTIONS EQUIL. PROFITS

Price of meat [NOK/kg]	45
Fraction females [%]	90
Cost [NOK/reindeer/year]	200
Lifetime livestock [years]	10

	First year	Last year	Filter
Lichen	0	10	no
Profits	0	10	no

End point profit curve 3000

1 mm lichen height corresponds to approximately 20 g/m2

SIMULATOR

Final year	10
Current year	10
Result last year	
Profits	181
Lichen density	169
Herd size	3000
Loss of reindeer	267
Calves	1122
Weight calves	16
Weight adults	32
Meat price	45
Net present value	3185
Decision for next year	
Herd size	3100

Natural variation	Meas.error
no	no

Init.lichen density	900
Init.herd size	2000

Figure 8: Computer screen for decision-tool with simulator.

Except for the simulator, the computer screen is nearly identical to the one for the pure decision-tool. The only exception is that after a practice session is over, the true underlying parameter values used in the simulator are revealed (under the respective input rectangles). Thus, one can see how well one did in revealing the true parameters, and one can enter the revealed parameters in the respective rectangles to see if the errors made are important for decisions about the herd size.

Before a practice session, the simulator has to be initialised. The five rectangles marked with light yellow on the colour screen, have to be set before one pushes the button marked “Initialise”. This is the final year, the initial herd size, the initial lichen density, and one has to determine whether there should be natural variation in the simulator and whether there should be errors in the measurements of average lichen density (“yes” or “no”). None of these settings can be changed after the simulator has been started (initialised). After the simulator is initialised, fill in the decision about the herd size (only green rectangle in the simulator) and push the button marked “New year” to advance one year. All the other rectangles are filled with new information each year, except the one for net present value, which only shows a value in the final year.

The sequencing is as follows. One considers the data available in the decision-tool and tests different parameters. Next one decides on the herd size for the next year and advances the simulator one year by pushing the button “New year”. New data are considered in the decision-tool, parameters are adjusted, a new desired herd size is set, another year is simulated, and so on. (Remember that the herd size in the simulator is set in the green rectangle named “Herd size” and not in the decision-tool rectangle named “N-max”.)

5. CASE STUDIES FROM THE NORDIC COUNTRIES

First we present case studies of winter ranges. A typical problem is lack of precise data concerning lichen and at times even of herd sizes. For this reason we start out with the cases with the best data, and then we use what is learned from these cases as prior information in the cases with lacking data. Tests are performed to see how sensitive conclusions regarding proper management are to various assumptions. In a second section we present case studies of summer ranges. Data are shown in an Appendix.

5.1. Winter range cases

We start by the case of Snøhetta, Jordhøy et al. (1996) From 1944 to 1961 the wild reindeer in the area increased from 6000 to 14200 animals. Then the herd size was reduced gradually to a low of 1400 in 1970. Thereafter the herd has been in the interval from 2200 to 3700. The high reindeer levels in the early period lead to a decrease in lichen from 1064 g/m^2 in 1944 to a lowest point of 186 g/m^2 in 1965. Thereafter lichen grew steadily to 567 g/m^2 in 1997. Since we have both a period with reduction and build-up of lichen we split the period in two, from 1944 to 1967 and from 1968 to 1997. Figure 9 shows the diagram for the equilibrium herd size (EHS) (as in Figure 3) for the period with lichen reduction.

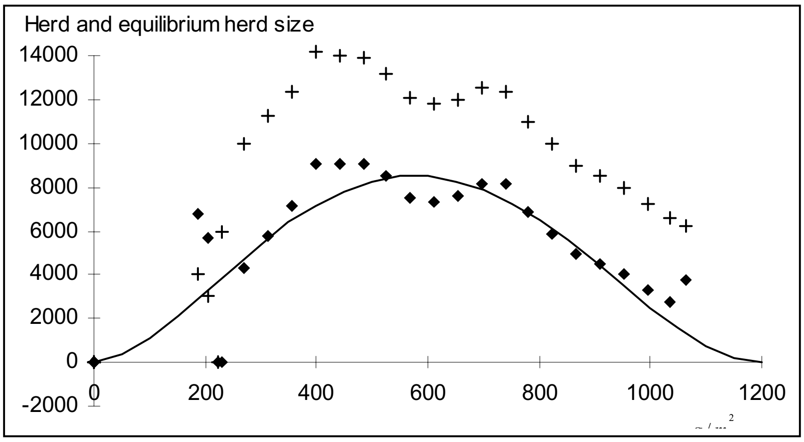


Figure 9: Snøhetta - lichen down, 1944 to 1967.

The figure shows that the data points (RHS) do describe a growth curve with quite good accuracy with the exception of the last two data points to the left, which move close to the EHS-curve if the data are filtered. The herd size is above the EHS for the entire period except the final year 1967, when the herd is nearly in equilibrium. At this point the EHS is only 38 percent of the estimated maximum herd size N_{max} of 8000 animals.

Already from data received for lichen densities above 4-600 g/m^2 it seems rather obvious that overgrazing is taking place and that herd reductions are needed to stay around the maximum EHS.

The EHS curve is described by the parameters shown in the first row in Table 1. We note that the EHS reaches its maximum at 575 g/m^2 (the MSY is at g_{msy}=620 g/m^2). Roughly similar fits can be obtained by somewhat different parameter sets: carrying capacity L_{CC} can be increased above the levels which are thought to be correct from prior information, the bending parameter b can be varied between 3 and 7, the coefficient for consumption α_c can be varied between 0.0 and 0.7, and maximum lichen growth g_{msy} can be varied from 40 g/m^2/year to levels above those believed to be correct from prior information.

Table 1: Parameters used in the different cases.

Case	Consumption α_c	N-max N_{max}	L-max L_{max} g/m^2	Bending $b=\alpha_1+\alpha_2$	g-msy g_{msy} g/m^2/year	Carr.cap. L_{CC} g/m^2
Snøhetta, lichen down	0.3	8500	575	4.0	80	1200
Snøhetta, lichen up	0.3	4000	365	10.0	50	1200
Vest-Finnmark, lichen down	0.3	79500	250	10.0	60	1200
St. Paul, par: Snøhetta down	0.3	500	575	4.0	80	1200
Itivnera, par: Snøhetta down	0.3	4560	575	4.0	80	1200
Isortoq, par: Snøhetta down	0.3	2550	575	4.0	80	1200

Before we go on to study the period with lichen recovery, it is worthwhile to recall the implications of the tool's lack of geographical distribution. A justification for this simplification was the assumption that reindeer are opportunistic feeders and seek lichen where it is most easily available. This implies that lichen should be evenly grazed if it is only density of lichen that matters. However, if availability is also influenced by topography, wind, snow cover etc., the most easily available spots could be grazed more than the less available ones. All experience confirms this. Thus, the period with lichen reductions before 1967 could have left certain spots without lichen at all and even eroded. For these spots recovery will at best be very slow after a severe reduction in the herd size. In practice the recovering area could therefore appear to be smaller than the original range. Since the tool operates with an average lichen coverage for the original area, the EHS for a recovering range could be lower than the original

EHS, permanently or for a very long time depending on grazing pressure, degree of erosion etc.

Figure 10 shows the estimated EHS-curve for the years with increasing lichen in the Snøhetta area. Even without filtering the fit is very good for the parameter values shown in the second row of Table 1. For the entire period the grazing pressure is lower than the EHS, consistent with the observed lichen growth in the period. The current average lichen thickness, to the very right, is about where the EHS for the reduction phase reached a maximum. However, if the goal for management is maximisation of meat production, it seems that the current herd is smaller than what it needs to be and that the average lichen thickness is higher than what is optimal. From the figure it looks as if the managers were not satisfied with the recovery of lichen around 1981 when the number of reindeer peaked. Consequently the grazing pressure was reduced again. While this reduction succeeded in terms of continued lichen growth, it lead to a situation with lower lichen growth.

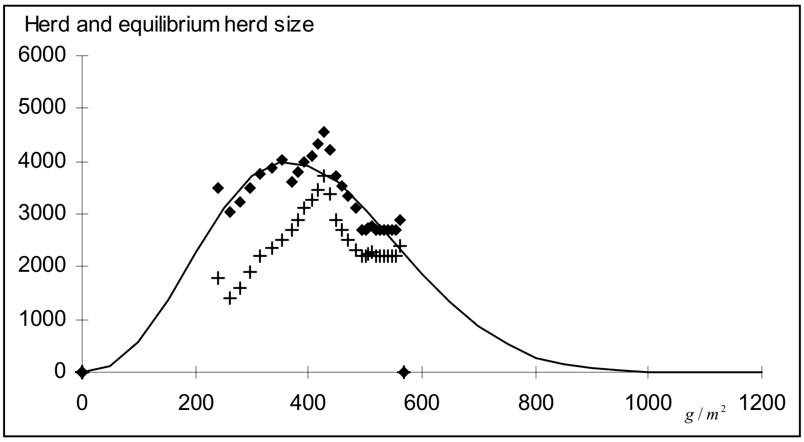


Figure 10: Snøhetta - lichen up, 1968 to 1997.

The estimated parameters are all consistent with the above argument about a more or less permanent reduction in the productive area of lichen ranges. The EHS peaks at a lower (average) lichen level (365 g/m^2), and so does the growth curve for lichen (390 g/m^2), the bending of the curve is stronger (10.0), and most important, the maximum EHS is reduced by about 50 percent (4000 animals). This finding has important implications for the management of the Snøhetta ranges after the incidence of severe lichen depletion, and it has potentially important implications for other areas that are currently heavily grazed. However, one should be careful not to extrapolate without further consideration. The Snøhetta area was a rather virgin area before reindeer started to graze there. This means that the most available spots were filled with lichen. This is not likely to be the case in areas where reindeer grazing has been going on for decades or centuries. There the starting point for the analysis can be characterised by a considerable fraction of the area being depleted or eroded. Then it is not obvious that the EHS for a period with recovery will differ that much from the EHS for a preceding period with depletion. The extent to which new spots have been fully depleted or eroded seems to be important for the difference.

Before we go on to compare the results for other ranges to the above ones, we also note that the distribution of sampling points for lichen measurements will matter for calibrated parameters. For instance, if one is observing only the spots that are most easily available, lichen will appear to decay faster than what eating and wastage implies. Then we are likely to underestimate the EHS at high lichen densities and overestimate it at low densities, the curve will be skewed to the left. If one observes only areas that are hardly available at all for the reindeer during the winter season, the EHS curve will be skewed to the right. For these reasons, estimated differences between ranges do not necessarily reflect biological differences, but could reflect other factors as well, factors which we do not have full control over. For the individual ranges these considerations are of little importance when it comes to policy conclusions. However, we note that proper conclusions depend on a certain constancy in sampling strategies over time.

Then we go on to analyse the winter ranges of Vest-Finnmark in Norway. These ranges have been grazed for centuries. Since 1973 the number of reindeer increased from 51,000 to a peak of 112,000 in 1989. Since then the number has been steadily reduced to 65,000 in 2000. Lichen has decreased from a density of 456 g/m^2 in 1973 to 124 g/m^2 in 2000. While we have yearly data for the herd size, lichen data are interpolated between five data points based largely on satellite photographs, Johansen and Karlsen (1998).[5]

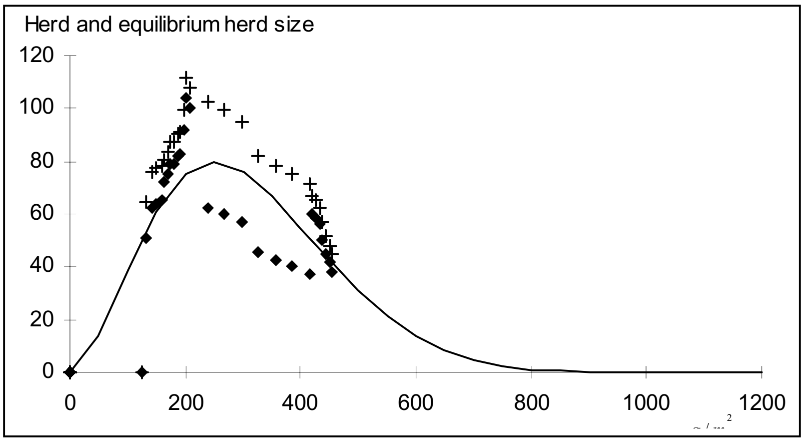


Figure 11: Vest-Finnmark - lichen down, 1973 to 2000.

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[5] Also personal communication with B. Johansen, 2001.

Figure 11 shows our estimate of the EHS-curve for Vest-Finnmark, row three in Table 1 shows the accompanying parameters. For the entire period since 1973, grazing has been greater than the EHS, consistent with the observed reduction in lichen. The figure explains the cause of much frustration in Vest-Finnmark over the last decade. While the herd size has been steadily reduced, lichen has continued to decline. A further policy of modest reductions could lead to a situation where the herd size is reduced in parallel to the EHS-curve, leading to a continued and frustrating decline in lichen, see experimental evidence of this possibility in Moxnes (1998b) and Moxnes (2000). On the other hand, a policy which succeeds in bringing the grazing pressure below the EHS in one jump, will denote the beginning of a period with recovery. The maximum EHS is at 79,500 animals, which is not very different from earlier estimates of the upper limit for the reindeer herd in Vest-Finnmark, ranging from 60,000 to 80,000, see Prestbakmo (1984) and Ims and Kosmo (2001). However, even though the ranges in Vest-Finnmark have been used for centuries, the current overgrazing of lichen could have left certain spots fully depleted and eroded such that the appropriate EHS-curve for the recovery period could be lower than the estimated one. This implies increased downward uncertainty about our results and calls for stronger measures to ensure recovery.

Compared to the Snøhetta case for lichen recovery, we have assumed the same parameters for consumption and wastage (0.3), bending (10.0), and carrying capacity (1200 g/m^2). The lichen level for which the EHS is maximised is lower (250 versus 365 g/m^2). We have assumed a slightly higher MSY for lichen growth (60 g/m^2/year) partly because that gives a somewhat better fit and because we suspect that spots eroded in earlier times are no longer considered potential lichen ground in Vest-Finnmark. The fit is not very sensitive to the following parameter variations. L_{CC} and b can be changed together within the limits of prior information, α_c can be increased to around 1.5 if at the same time g_{msy} is increased to around 80 g/m^2/year. The fit becomes progressively worse as g_{msy} is reduced below 80 g/m^2/year in spite of compensating changes in other parameters. For some parameter combinations the current herd size is even slightly below the EHS-curve, for others it is well above. Thus while our analysis clearly indicates that a further reduction in the herd is appropriate, we cannot produce a precise estimate of how much. On the other hand, from an economic point of view great precision is not really needed, the important thing is to hinder a further decline in lichen and to ensure a certain recovery.

The lacking fit between the EHS and RHS observations in Figure 11 could be due to measurement errors. To get an impression of what measurement errors are needed to explain the lack of fit, we simulate lichen development using the parameters shown in row three of Table 1. Figure 12 shows both simulated development and original observations. The maximum deviation is seen in year 1987 when simulated lichen is 33 percent above the observed level. Recalling that the herd size peaked in 1989, the simulated curve seems most logical with its steepest decline at that point in time. Observed lichen has its strongest decline before 1987 when on average there were reported to be 30,000 fewer animals than at the peak (1980 to 1986). This does not prove that the measurements were wrong, the test only justifies that one questions measurement accuracy. Other factors may also explain the deviation.

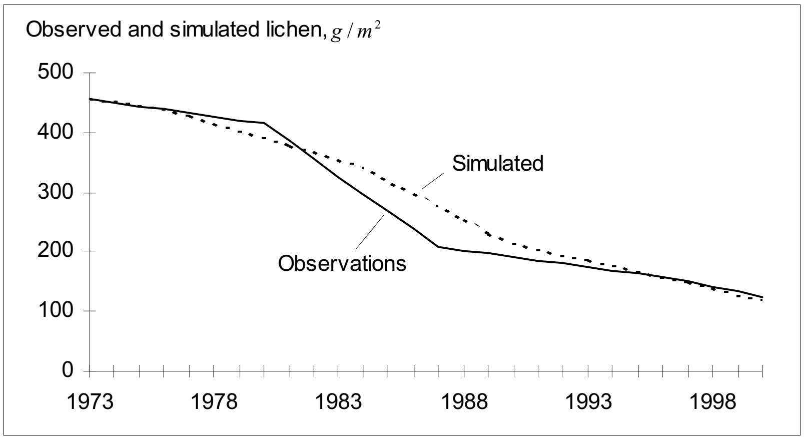

Figure 12: Vest-Finnmark, observed and simulated development in lichen.

Next we consider the case of St. Paul in Alaska which is perhaps the most severe case of overgrazing known from the literature, Scheffer (1951). Twenty-five animals were placed on the island in 1911, the herd grew rapidly towards a peak of 2046 in 1938, by which time lichen was reported to be fully depleted. The herd collapsed and by 1950 there were only 8 animals left. The reindeer herd was planed to be a sustainable meat source for the islanders, however, the slaughter rate increased far too little and far too late to save the range. While the herd numbers are thought to be very accurate, we only know the claim that lichen was gone by the end of the thirties. To estimate the EHS-curve we simulate lichen development from initial virgin conditions (1200 g/m^2) to nearly full depletion in 1938 (10 g/m^2). When simulating, all parameters are chosen similar to the Snøhetta - lichen down case, except N_{max} which is calibrated to get to the guessed at lichen state in 1938, see Table 1.

Figure 13 shows the resulting EHS-curve. (Since the RHS data points are generated by a perfect model, they fall along the EHS-curve). According to the figure, enormous damage was done to the lichen ranges the last years before depletion. N_{max} is found to be 500 animals, which is only one fourth of the maximum herd size. Again it is reassuring that our estimate of N_{max}, based on very crude assumptions about lichen development, is similar to an estimate made by Scheffer who claims that “the reindeer population was at least three times the carrying capacity of the range”.

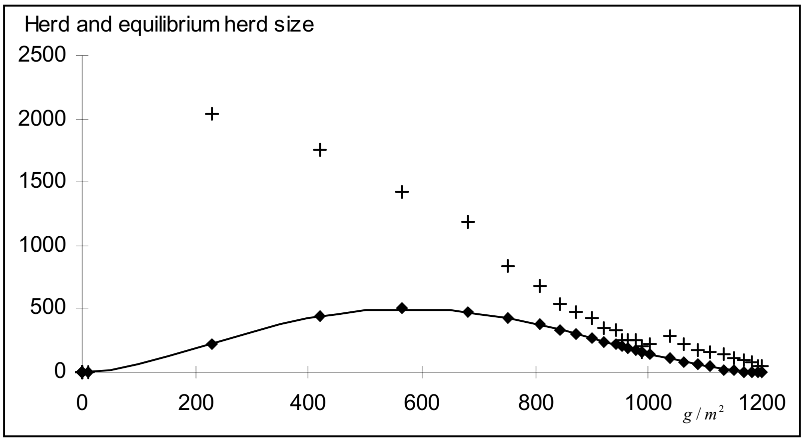

Figure 13: St.Paul - lichen down (parameters: Snøhetta down), 1973 to 2000.

This conclusion about severe overgrazing, at an early stage, is not very sensitive to parameter changes. When we choose parameters given by the Snøhetta - lichen up case, N_{max} is found to be slightly lower, 475 animals. If we increase α_c from 0.3 to 1.5, N_{max} is reduced to 100, if g_{msy} is reduced from 80 to 40 g/m^2/year, N_{max} is reduced to 307. Probably these tests do not span the entire range of uncertainty in N_{max}, however, they indicate that a dramatic overexpansion of the herd took place. Still the managers did not realise how severe it was. As mentioned above, while the slaughtering rate was increased, the reaction was far from adequate.

Then we turn to a case from Itivnera in Greenland. Here we have were little data about both the herd size and about the lichen conditions[6]. However, it is possible to use the tool to reason about the little and uncertain information we have. Before 1979 the lichen range was nearly in a virgin state. By 1999 there were roughly 15,000 animals, and the lichen mat was severely depleted to roughly 100 g/m^2. Now we assume that the herd size grew at a steady rate of 16 percent per year, implying that the initial stock in 1979 was 770 animals. Having made this rough assumption about the herd size development, we use the parameters for the Snøhetta - lichen down case to simulate lichen development. As in the St. Paul case we calibrate N_{max} to get to the likely state for lichen in 1999.

Figure 14 shows the resulting EHS-curve with a N_{max} of 4560 animals. The current herd size seems to be more than three times the size of N_{max}. The impression is the same that we got from Figure 13 for the case of St. Paul. Unless there are sufficiently nutritious

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[6] Speculations offered by Christine Cuyler in Greenland.

alternatives to lichen as a winter food source, or unless there are alternative winter ranges where the animals can emigrate, a collapse in the herd seems inevitable. One can only speculate to what extent a rapid and drastic reduction in the herd size will help in the current situation.

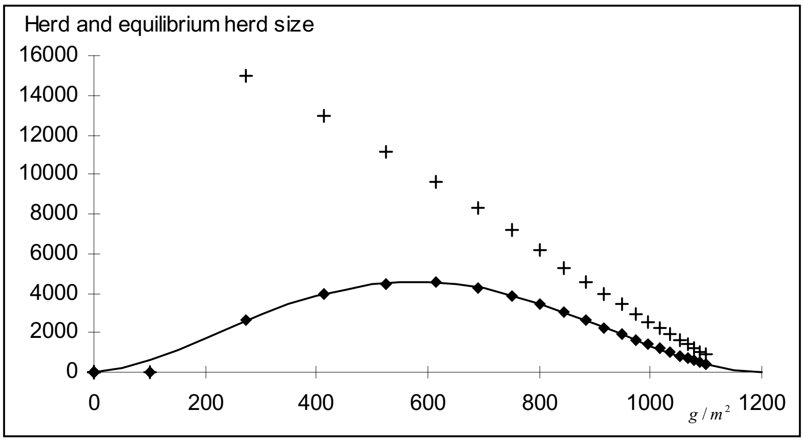

Figure 14: Itivnera - lichen down (parameters: Snøhetta down), 1973 to 2000.

The current state of lichen is uncertain, if we assume 400 g/m^2 rather than 100, we find N_{max} equal to 6000. In this case the current herd is 2.5 times as high as N_{max}, and an adequate reduction in the herd size could help save the range. Thus we see that in this case we get a clear indication of overgrazing for widely differing assumptions about the current lichen state, 100 to 400 g/m^2.

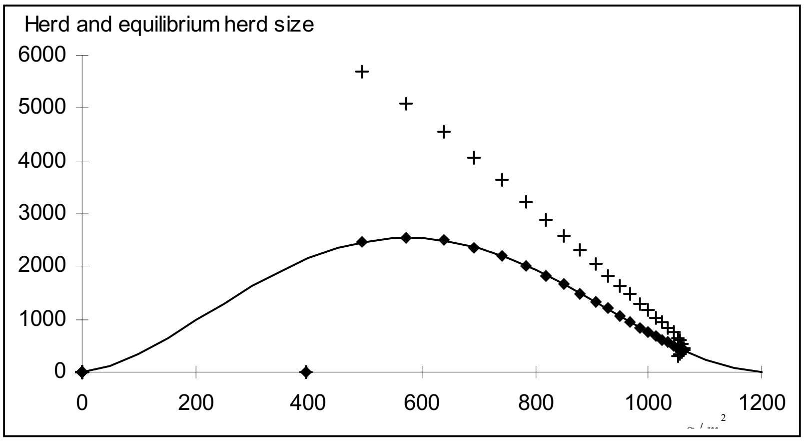

Figure 15: Isortoq - lichen down (parameters: Snøhetta down), 1973 to 2000.

Finally, we consider the case of Isortoq in Greenland. As for the case of Itivnera, both the time-series for herd and lichen are constructed over the period 1973 to 2000. The assumption is that lichen was nearly ungrazed in 1973 and that it has been reduced to

400 g/m^2 by 2000[7]. The current herd size is believed to be around 5700 and we assume that the average growth rate has been a steady 12 percent per year, consistent with a stock size of 268 animals in 1973.

Figure 15 shows the EHS-curve. The current herd size is found to be 2.2 times N_{max}. Hence a quick and considerable reduction in the herd seems needed to get the range in equilibrium.

5.2. Summer range cases

We start with the case of Vest-Finnmark. Data for the livestock numbers in April, the female ratio in the livestock, the number of calves surviving until the fall, the slaughter weights for calves and for adults, and the number of livestock being lost over the year are obtained for the period 1981 to 1999.[8] We start by estimating the equilibrium meat production curve (EMPC), that is a version of the equilibrium profit curve (EPC) where the price p_E is set equal to 1.0 and the unit cost c_0 is set equal to 0.0. For a desired fraction of females of 90 percent and for a desired lifetime of livestock of 10 years we get the result shown in Figure 16.

The general impression is that the spread in data points is quite wide. The estimated curve suggests that maximum meat production occurs when the herd size is around 65,000 animals. The maximum meat production is 0.19 million kg per year. If only the data points from a first period from 1981 to 1990 are included (black squares), the maximum increases to 0.43 million kg per year, while the maximising herd is reduced to just below 60,000 animals. The estimates are uncertain. We also note a lack of observations for lower herd sizes. From the point of view of learning, observations in this range are needed. Thus a positive side effect of the need to reduce the herd size to get a recovery of lichen ranges, is that one can obtain more certain estimates of the EMPC and the EPC. The estimate is not far from estimates of the capacity of the summer ranges made with other methods, for instance a recent estimate of a desirable highest number of reindeer is 63,700.[9] The estimates of the maximising herd size is not very sensitive to changes in the desired fraction of females or the desired lifetime of livestock, 30 percent changes in these parameters move the maximising herd size by less than around 5,000 animals.

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[7] Speculations offered by Christine Cuyler in Greenland.

[8] Data come from “Melding om reindrift” 1981-1994, and from “Resursregnskap for reindriften” 1995-1999, both published by Reindriftsadministrasjonen i Alta.

[9] Highest number of reindeer on summer ranges in Vest-Finnmark, decided by Reindriftsstyret January 30, 2002.

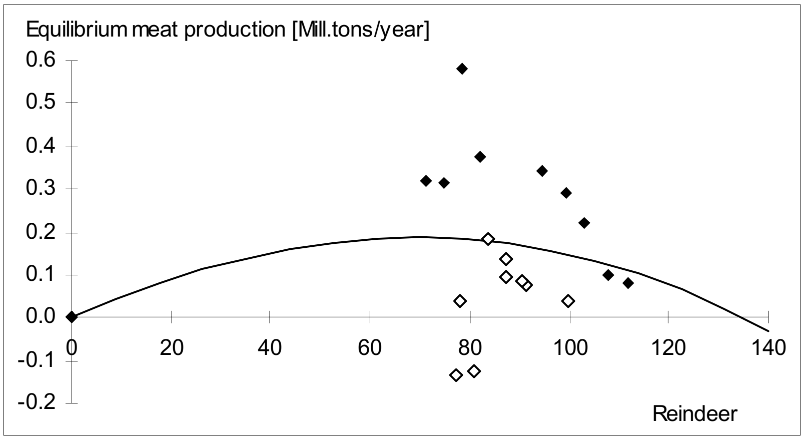

Figure 16: Vest-Finnmark equilibrium meat production, 1981 to 1999, data point from 1981 to 1990 in black.

An interesting observation is that practically all the data points from the first period (1981 to 1990) fall above the estimated curve, and all the points from the second period (1991 to 1999) fall below. The reason could be natural variability or measurement errors, however that is not very likely since the pattern is systematic (which could be caused by autocorrelation). Several other explanations are possible however. First we note that the second period is characterised by lower lichen levels than the first period. During the first period the lichen level is reduced from 390 to 190 g/m^2 while in the second period it is reduced from 190 to 130 g/m^2. If lichen is the cause, it means that a reduction below 190 g/m^2 is detrimental to potential meat production from the summer ranges and detrimental to the economics of the reindeer business.

To get a statistical measure of the effect of lichen we go beyond the capabilities of the tool and perform four regressions between respectively the calving fraction, loss fraction, weight adults, and weight calves and the explanatory variables lichen and herd size. We use the same subscripts with respect to time as described in section 3.2. Table 2 shows the results.

Table 2: Regression results for Vest-Finnmark, 1981 to 1999.

		Lichen	Herd size	Constant	R^2
Calving fraction	Param.	0.09	-0.28	37.56	0.68
	St.dev.	0.02	0.14	14.52	
	p-value	0.0006	0.06	0.02	
Loss fraction	Param.	-0.06	-0.20	50.39	0.64
	St.dev.	0.01	0.08	8.30	
	p-value	0.0001	0.02	0.0000	
Weight adults	Param.	0.02	0.04	20.94	0.51
	St.dev.	0.00	0.03	2.73	
	p-value	0.001	0.10	0.0000	
Weight calves	Param.	-0.01	-0.01	18.79	0.09
	St.dev.	0.00	0.03	3.20	
	p-value	0.23	0.66	0.0000	

We see that the most important variable, the calving fraction, is positively influenced by the lichen level at a very low level of significance (p-value). The calving fraction is influenced negatively by the herd size, although that is a borderline case with respect to significance. The loss fraction is negatively influenced by lichen at a very low level of significance, and it is also negatively influenced by the herd size at a higher level of significance, however, the latter effect does not have the expected sign. The weight of adults is positively affected by lichen at a low level of significance. The weight of calves is not significantly influence by neither lichen nor herd size. Since the calving fraction, the loss fraction and the adult weights all seem to be influenced by lichen, it also seems likely that lichen development is one cause of the diverging data points in Figure 16. However, limited data and a possible correlation between lichen and not tested explanatory variables implies that one should be open to other explanations. In the following we consider some alternatives.

First we cannot rule out that the estimated effect of lichen is actually caused by a decay in summer ranges. In the late 1980s, summer ranges may have been utilised to such an extent that their production potential was reduced for an extended period by overgrazing, trampling, erosion and altered species composition. If this is the cause rather than declining lichen, the decline in summer ranges must coincide with the decline in lichen, i.e. be correlated. In this case the formal statistical test is of limited value; other sources of information are needed to settle the issue. Explicit time-series data on summer range quality would be helpful.

A second possible explanation is that losses have increased due an increasing amount of predators. This factor could explain increasing losses of adults and also increasing losses of calves. This factor is not likely to explain lowered weights. From earlier studies it is known that weight is good predictor of calving fractions and losses.

A third possible explanation of diverging data points is that it takes longer before the reindeer recover after an overexpansion of the herd than what is assumed by the one year delay used in the tool. For instance, adult animals never recapture fully the weight they do not gain in early years, White et al. (1981) and Lenvik (1990). Since the total number of reindeer peaked in the late 1980s, this should not be an explanation in the late 1990s when most of the livestock has been replaced, unless the herd size is still overexpanded relative to summer or winter ranges.

Then we focus on equilibrium profits by assuming a meat price of NOK 50 per kg and a unit operating cost of NOK 100 per reindeer. For a herd of 500 animals the yearly operating costs will be NOK 50,000. This cost is supposed to cover all operating costs or elements of operating costs that vary with the size of the herd, for instance transportation to slaughterhouses, veterinary expenses, some of the snow-scooter expenses, and some of the expenses for hired labour, and some of the opportunity cost of the owners labour. The majority of the cost items, for instance snowscooters, 4-wheel motorcycles, mountain cabins, fences, and own labour should be considered fixed costs. These fixed costs are not part of the definition of the equilibrium profits. Thus, for investment decisions one must consider whether the yearly equilibrium profits are large enough to justify rental payments for fixed investments and own labour.

Figure 17 shows the data points for the first and the second time period. The equilibrium profit curve is based on all data points. The same pattern as in Figure 16 can be seen. As expected the frequency of negative observations is greater, and the second period only produce one data point with a slight positive value. Clearly the second period draws down the EPC.

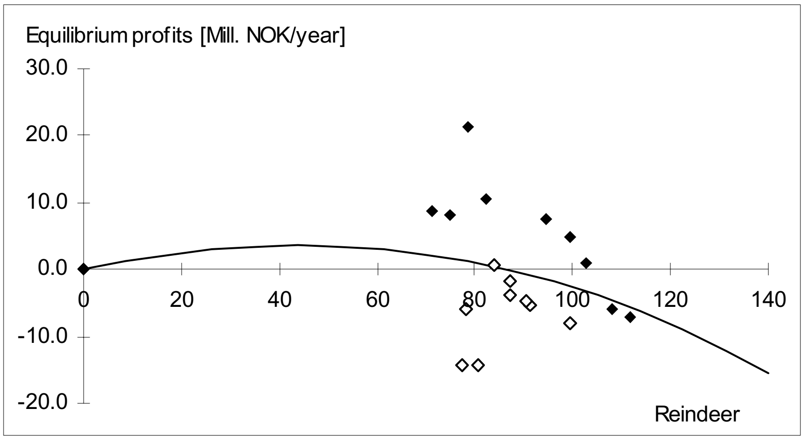

Figure 17: Vest-Finnmark equilibrium profits, EPC, 1981 to 1999.
Data points from 1981 to 1990 in black.

Based on data only for the first period we find a maximum equilibrium profit of NOK 16 million for a herd size of around 50,000 reindeer. If the meat price is increased from NOK 50 to NOK 80 per kg, maximum profits increase to NOK 29 million and the corresponding herd size increases to around 53,000. Keeping the price at NOK 50 per kg we find that maximum profits are reduced to NOK 11.5 million if unit operating costs are increased to NOK 200 per reindeer for a herd size of around 40,000. If the unit costs are reduced to zero, the maximum occurs for a herd size just below 60,000 as we found when studying equilibrium meat production.

From our analysis of both lichen s and summer ranges for Vest-Finnmark it seems that in the long run summer ranges represent the limiting resource independent of whether meat production or profits is maximised. The maximising herd size seems to be below 60,000 reindeer, while we found the maximum equilibrium herd size based on lichen ranges to be close to 80,000 animals. Thus if summer ranges had been allowed to determine the herd size historically, the current situation of overgrazed lichen resources would probably not have occurred. For the medium term future, the latter estimate of 80,000 reindeer may be too high if parts of the lichen ranges have been more or less permanently damaged. In the short run, with overgrazed lichen, lichen ranges represent the limiting resource.

Next we turn to the case of Snæfell in Island where we have data for the period 1991 to 2000.[10] Data on losses is lacking and is set equal to zero. The number of animals were reduced from 3080 in 1991 to just below 2000 in 1995. Thereafter the herd has grown slowly to nearly 2300 by 2000. When investigating equilibrium profits we assume a female fraction of 70 percent which should be representative of historical data. The lifetime of the livestock is set equal to 10 years, the price of meat is NOK 50 per kg and the unit operating cost is NOK 100 per reindeer. Thus the latter three assumptions are the same as for Vest-Finnmark.

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[10] Data provided by Pall Hersteinsson, Iceland.

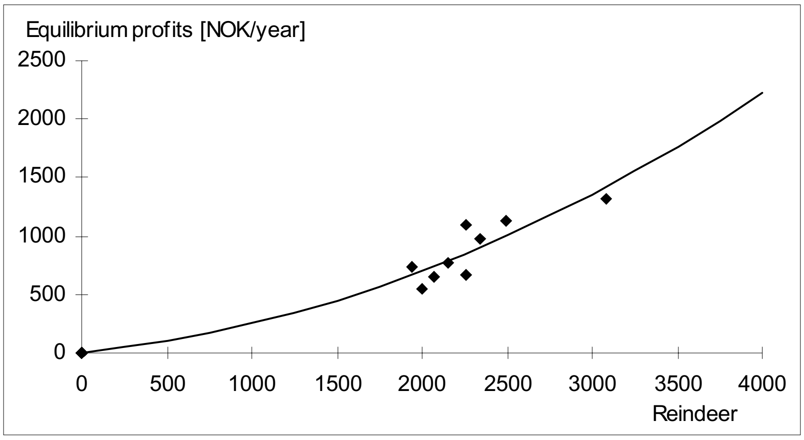

Figure 18: Snæfell equilibrium profits, 1991 to 2000.

Figure 18 shows that equilibrium profits increase with an increasing herd size. This is perhaps not very surprising because the Snæfell reindeer district is not managed to maximise meat production or profits from meat production. Rather the major source of income if from sales of hunting licences. To obtain high prices of licences it is important to have a considerable fraction of large males with impressive antlers.

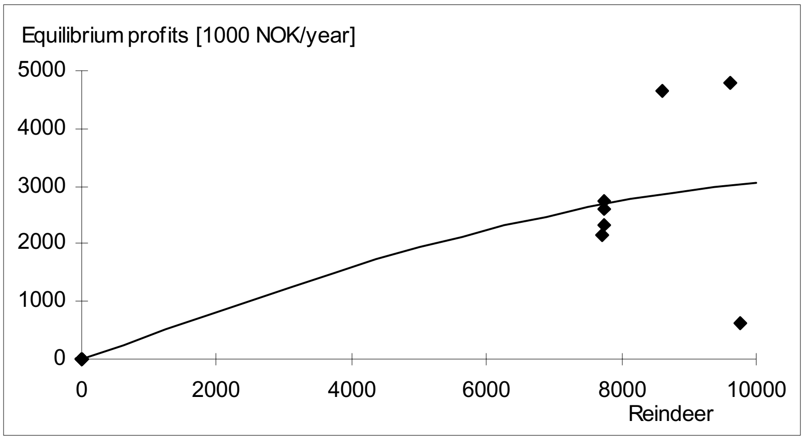

Figure 19: Paistunturi equilibrium profits, 1990 to 1997.

Finally we consider the case of Paistunturi in Finland. We have data for the period 1990 to 1997.[11] Figure 19 shows data points for the equilibrium profits which vary quite a lot. Thus from these data it is difficult to draw a firm conclusion about what the profit maximising herd size is. When looking at the underlying data, there is no clear time trend in the data, rather strong year to year variations. Therefore the filter has a strong effect on the data points, see Figure 20. From these data it seems that the herd size could be increased somewhat, given that winter ranges are adequate. We also note from the figures that there is not much variation in the herd size data, such that more vari-

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[11] Data provided by Jouko Kumpula.

ation would be useful to promote further learning. Similar results to those shown in Figures 19 and 20 are also found from data for the case of Vatsari in Finland.

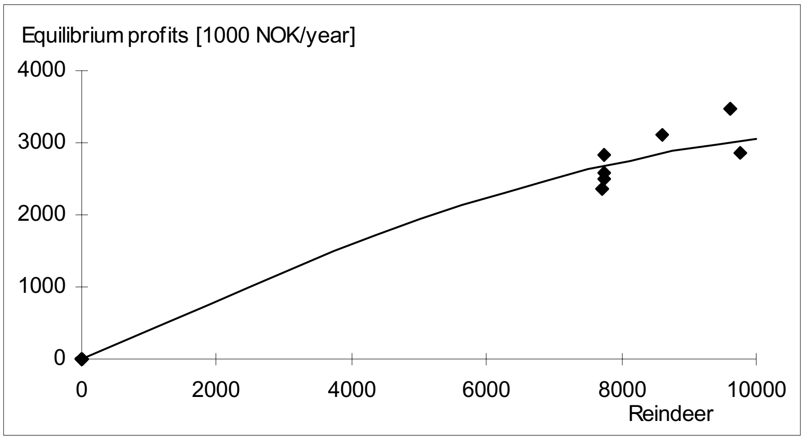

Figure 20: Paistunturi equilibrium profits, 1990 to 1997, filter on.

6. CONCLUSIONS

The management of reindeer ranges is a complicated task as indicated both by the complexity of the normative analysis required and the mismanagement observed in real and laboratory settings. The decision-tool proposed in this report attempts to strike a balance between complex normative analysis and practical decision-making. A simulator is provided to give decision-makers experience with the tool and to build intuition for strategies.

In earlier studies it has been found that decision-maker involvement in model building is important for the implementation of policy recommendations, so-called “group model-building”, Morecroft (1992), Vennix (1996), and Vennix et al. (1996). Our approach is meant to contribute to “group parameter-estimation” and “group policy-formation”, with no active modelling involved. With the growth curve model in place and the way information is organised by the tool, it is our belief that decision-makers will reach appropriate policies using simple heuristics. The fact that simple heuristics can be used is likely to contribute to the usefulness of the tool. The literature on decision-making shows that people typically resort to simple heuristics when dealing with complicated problems. Far too often, however, the simple heuristics turn out to be misleading, with poor management as a result. We believe that the decision-tool will guide the users towards a heuristic that is appropriate for the problem of reindeer management. At the same time it guards against the heuristics that follow naturally when decision makers have access to only raw data.

The tool has been used to study several cases from the Nordic countries. Concerning winter lichen ranges, we find that the tool can provide considerable guidance even when data are scarce and speculative. In such cases the insights follow from prior biological information about parameters and the dynamics of lichen. In cases where better data are available, acceptable fits are found between the proposed model for lichen growth (the equilibrium herd size) and the data. The case of Snøhetta indicates that heavy grazing by reindeer can lead to a more or less permanent reduction in the equilibrium herd size curve. Although we have only obtained limited amounts of data to study summer ranges, the tool does seem to provide reliable results. For both winter and summer ranges we have obtained estimates of optimal herd sizes that are consistent with results from studies that require more resources for data gathering. Most of the ranges that we have studied show tendencies towards excessively large herd sizes and overgrazing. This is the same tendency towards overutilisation that is seen in the management of many kinds of renewable resources, even those that are regulated by public agencies. Hence, there seems to be a need for the type of tool that we have developed.

APPENDIX - DATA FOR CASE STUDIES

The numerical data, entered in the sheet called DATA in the decision-tool, are shown here for all the case studies. References are presented when discussing the cases.

Table A1: Data for the Snøhetta case

Year	Lichen density in summer g/m2	Livestock in April [numbers]	Year	Lichen density in summer g/m2	Livestock in April [numbers
	LICHEN-DOWN			LICHEN-UP	
1944	1063.8	6000	1968	241.5	2500
1945	1036.0	6200	1969	260.0	1800
1946	993.5	6600	1970	278.5	1400
1947	951.0	7200	1971	297.0	1600
1948	908.5	8000	1972	315.5	1900
1949	866.0	8500	1973	334.0	2200
1950	823.5	9000	1974	352.5	2350
1951	781.0	10000	1975	371.0	2500
1952	738.5	11000	1976	382.1	2700
1953	696.0	12400	1977	393.2	2900
1954	653.5	12500	1978	404.3	3100
1955	611.0	12000	1979	415.4	3250
1956	568.5	11800	1980	426.5	3450
1957	526.0	12100	1981	437.5	3720
1958	483.5	13200	1982	448.6	3362
1959	441.0	13900	1983	459.7	2870
1960	398.5	14000	1984	470.8	2700
1961	356.0	14200	1985	481.9	2500
1962	313.5	12400	1986	493.0	2300
1963	271.0	11300	1987	499.7	2187
1964	228.5	10000	1988	506.5	2220
1965	186.0	6000	1989	513.2	2250
1966	204.5	4000	1990	519.9	2275
1967	223.0	3000	1991	526.6	2200
			1992	533.4	2200
			1993	540.1	2200
			1994	546.8	2200
			1995	553.5	2200
			1996	560.3	2200
			1997	567.0	2400

Table A2: Data for the Vest-Finnmark case

Year	Lichen density in summer g/m2	Livestock in April [numbers]	Female ratio in livestock %	Calves in fall [numbers]	Slaughter weight calves kg	Slaughter weight adults kg	Loss livestock [numbers]
1973	456	51					
1974	450	45					
1975	444	48					
1976	438	52					
1977	433	57					
1978	427	63					
1979	421	65					
1980	415	67	73	24			
1981	386	71	78	24	16.0	32.0	12
1982	356	75	77	26	15.5	29.0	13
1983	326	78	78	28	15.5	28.6	14
1984	297	82	78	41	17.4	29.9	12
1985	267	95	79	32	15.2	28.3	13
1986	238	99	80	30	14.8	28.5	15
1987	208	103	80	28	14.5	28.8	17
1988	203	108	81	26	15.1	28.7	20
1989	197	112	86	24	15.8	28.6	26
1990	192	100	92	24	16.1	30.1	25
1991	186	91	93	21	17.8	27.9	24
1992	181	90	90	23	17.5	28.4	23
1993	175	87	94	20	17.0	27.8	19
1994	169	87	92	21	18.2	30.0	19
1995	164	84	85	22	19.4	27.8	19
1996	158	81	74	23	17.1	25.7	20
1997	150	78	85	17	15.5	26.8	35
1998	141	77	79	21	15.4	25.2	26
1999	133	76	82	17	15.3	25.1	36
2000	124	65					

Table A3 Data for the Snæfell case

Year	Lichen density in summer g/m2	Livestock in April [numbers]	Female ratio in livestock %	Calves in fall [numbers]	Slaughter weight calves kg	Slaughter weight adults kg	Loss livestock [numbers]
1991	960	3080	70	1076	23	54	
1992	924	2488	67	780	23	54	
1993	888	2340	67	784	23	57	
1994	852	2255	68	753	19	51	
1995	816	1947	73	500	19	42	
1996	780	2002	68	676	22	59	
1997	744	2069	70	350	23	58	
1998	708	2156	58	384	23	59	
1999	672	2264	61	493	22	63	
2000	636	2256	69	771	22	64	

Table A4: Data for the St.Paul case (Lichen calculated)

Year	Lichen density in summer g/m2	Livestock in April [numbers]	Year	Lichen density in summer g/m2	Livestock in April [numbers
1911	1200	25	1931	843	472
1912	1192	40	1932	808	532
1913	1182	52	1933	753	684
1914	1168	75	1934	683	834
1915	1151	92	1935	564	1185
1916	1132	111	1936	418	1425
1917	1108	144	1937	229	1753
1918	1086	157	1938	11	2046
1919	1063	178	1939	0	1905
1920	1037	214	1940	0	1227
1921	1004	284	1941	0	1176
1922	988	228	1942	0	n.a.
1923	988	164	1943	0	2nd
1924	978	213	1944	0	world
1925	964	250	1945	0	war
1926	952	260	1946	0	240
1927	942	259	1947	0	250
1928	920	337	1948	0	120
1929	901	349	1949	0	60
1930	873	421	1950	0	8

Table A5: Data for the Paistunturi case

Year	Lichen density in summer g/m2	Livestock in April [numbers]	Female ratio in livestock %	Calves in fall [numbers]	Slaughter weight calves kg	Slaughter weight adults kg	Loss livestock [numbers]
1990		9619	95.7	3383	16.6	26.3	770
1991		9765	96.1	6722	17.1	27.1	0
1992		8617	96.5	2199	17.9	28.4	776
1993		7737	94.6	5106	18.8	29.8	0
1994		7756	92.9	4018	16.3	25.8	473
1995		7726	97.8	4014	17.1	27.2	0
1996		7740	97.8	3932	16.7	26.5	418
1997		7721	97.5	3808	17.1	27.1	0

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