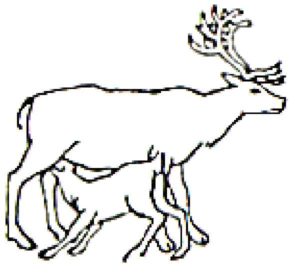

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A DECISION-TOOL FOR ADAPTATION OF REINDEER HERDS TO RANGELANDS: THE USER'S MANUAL

Final report from NOR-project
"Management of reindeer pastures under uncertainty"

Editor: Rolf Egil Haugerud

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PREFACE

This is the third report from a project dealing with the management of reindeer districts under uncertainty. The first report[1] dealt with optimal management strategies under uncertainty and measurement error. The second report[2] described in detail a practical tool to aid the learning about the relationships between reindeer and pastures and to aid decision making regarding herd sizes. The present report is a users' guide to this decision-tool. This guide which is a minor revision of SNF-report 19/03, will also be published in Finnish, Swedish, and Norwegian and is made available together with the decision-tool on the Internet.

While the decision-tool is the property of the authors, users can freely download copies of the decision-tool for personal use. The internet address is: http://www.ifi.uib.no/staff/erling/publications.htm (the publications are organized by year of publication). The more detailed technical report can be downloaded from http://www.snf.no/Meny/IndPubl.htm (locate the year 2002 and the report number 59/02).

The report is produced in co-operation between the Norwegian Institute for Nature Research in Trondheim, the Foundation for Research in Economics and Business Administration in Bergen, the Swedish University of Agricultural Sciences in Uppsala, and the Reindeer Research Station at the Finnish Game and Fisheries Research Institute in Kaamanen. Data for one of the cases is provided by Pall Hersteinsson in Iceland. The project has been financed by the Nordic Council of Ministers under the program "Nordic environmental strategies for agriculture and forestry 1996-1999". The project builds on a preceding project for the Nordic Council of Ministers[3]. Both projects were initiated and were managed by the Nordic Council for Reindeer Research (NOR). In this regard, the authors wish to thank Hans-Kolbein Dahle and Rolf E. Haugerud for co-ordinating the project and for valuable comments.

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[1] Moxnes, E., Danell, Ö., Gaare, E. & Kumpula, J. 2001. Optimal strategies for the use of reindeer rangelands. – *Ecological Modelling* 145(2-3): 225-241.

[2] Moxnes, E., Danell, Ö., Gaare, E., & Kumpula, J. 2002. Reindeer husbandry: a practical decision-tool for adaptation of herds to rangelands. – *SNF-report* 59/02. Bergen, Norway: SNF. 54pp.

[3] Dahle, H.K., Danell, Ö., Gaare, E., & Nieminen, M. 1999. Reindrift i Nordvest-Europa 1998 - biologiske muligheter og begrensninger. – *TemaNord* 1999(510). Nordisk Ministerråd, NMR. 116pp.

ABSTRACT

The management of reindeer ranges is a complicated task as indicated both by the complexity of the normative analyses required and the mismanagement observed in real and laboratory settings. The present report is a user's manual to a decision-tool that attempts to strike a balance between complex normative analyses and practical decision-making. A simulator is provided to give decision-makers experience with the tool and to build intuition for strategies. Several cases are used to illustrate the use of the decision-tool and to demonstrate how even scarce and imprecise data can yield important insights. The project has been financed by “Nordisk ministerråd” (“Nordic Council of Ministers”) under the program “Nordiska miljöstrategin för jord- och skogsbruk 1996-1999” (“Nordic Environmental Strategies for Agriculture and Forestry 1996-1999”). It was initiated and administered by “Nordisk organ for reinforskning” (NOR) (“Nordic Council for Reindeer Research”).

1. INTRODUCTION

The adaptation of reindeer herds to available food resources is complicated. In fact one can say the management of most renewable resources is complicated. There are numerous examples of renewable resources such as water reservoirs, fish stocks, endangered species, forests, and reindeer pastures that have been mismanaged. A frequent reason for this is the competition between the many users of each resource. For this reason there is a need for institutions and rules which regulate how much each user can extract from the resource. This is however not the challenge dealt with in this textbook. Here the focus is on the total use of a resource, assuming that there is private ownership or that institutions are in place to regulate the competition between individuals. More precisely, the focus is on the ideal number of reindeer for a district. For domestic reindeer that do not receive supplementary feeding, this number must reflect the availability and quality of winter and summer pastures. The question is how?

Deciding on how many animals is a challenging task that requires both data and analysis. The decision-tool presented here can be of help in this process. As the user, you must supply the raw data and feed them into the decision-tool. Then, with some help of you, the decision-tool produces information that can be very helpful when deciding on the number of animals.

In Chapter 2, focus is on the adaptation of the herd size to winter pastures which provide the reindeer with energy for maintenance during the winter. First you learn to use the decision-tool. Then we present several real-world cases that demonstrate the use of the tool and that teach some important lessons. In chapter 3 the focus is on the adaptation of the herd size to the quality and quantity of summer pastures. Again interesting real world examples are analysed.

Since different examples can teach different lessons, one version of the decision-tool is also equipped with a simulator that provides data for practise sessions. Using the simulator, you determine the herd size from year to year after having received information about the current situation. And, each simulated year, you can use the decision-tool to analyse the data from the simulator. Each time you restart the simulator, it represents a new reindeer district. Hence you get to practise in a new situation each time you use the simulator. Hopefully, some practice will make it easier to understand what the decision-tool is all about. Good luck!

2. WINTER PASTURES (LICHEN GROWTH)

First we present the most important part of the decision-tool and then some finer details. These finer details are not likely to be very important for management purposes and they typically require quite precise raw data. Finally, we present data and analyses for a few interesting cases.

2.1. Decision-tool, important part - winter

Reindeer migrate between summer and winter areas. In most winter ranges a handful of lichen species dominate the available parts of the pastures. Lichens are rich in digestible carbohydrates, energy rich maintenance food that the animals require this time of the year. The decision-tool focuses on the adaptation of the herd size to the productivity of the lichen pastures. If the winter pastures are large compared to the availability and quality of summer pastures, there is little need for a careful examination of the winter pasture, since the summer pastures will be limiting the herd size. Similarly, if the winter pasture contains large quantities of other sufficiently digestible food sources, there is little need for a detailed analysis of lichen. Then a depletion of the lichen mat may not be a direct concern for reindeer herders. However, experiences from many reindeer districts indicate that lichen is a vital source of winter food. The typical reason for this is the low digestibility of withering grass, herbs, mosses and bushes such that the animals are not able to digest large enough quantities to satisfy their energy needs.

The decision-tool does not explicitly deal with alternative winter food sources. If their quantity and quality is sufficiently high in your district, the summer pastures will be limiting and you should concentrate the analysis on summer pastures. Before doing so, however, you should be absolutely certain that the quality of the alternative winter food sources is sufficiently high. In this connection, note that a trial and error approach is dangerous. As long as there are small amounts of lichen left, the reindeer will prefer and eat lichen and thus be able to satisfy their energy needs. Only when the lichen is depleted to very low levels will the ability of the reindeer to satisfy their energy needs exclusively from alternative food sources be revealed. Since in many districts it has turned out that energy requirements are not met, we recommend that the quality of alternative food sources is thoroughly investigated before a depletion strategy is chosen for lichen. There may also be other reasons not to deplete lichen, reasons that are not dealt with in the decision-tool. Supplementary feeding has at times been used to counteract the effects of lichen deficiency; however, this mechanism is not available in the decision-tool.

Thus, regarding winter pastures, lichen is in focus in the decision-tool. The tool is designed to help adapt the herd size to the productivity of the lichen pastures. At the outset we say nothing about at what time during the winter lichen pastures represent a limiting resource. If lichen pastures used in the fall or the beginning of the winter are limiting, data for these pastures should be used in the tool etc. To the extent that the movements of herds from early to late pastures can be delayed or speeded up, it becomes more correct to use data for all lichen pastures. For instance if late autumn pastures are inadequate, the animals could be moved more quickly into mid-winter pastures. Thus, autumn pastures become less exploited while mid-winter pastures are grazed more heavily. This evens out the pressure on the different pastures and makes them look more alike.

The thickness of the lichen mat can be measured in millimetres lichen height or in grams of dry matter of lichen per square meter. One millimetre corresponds to about 20 g/m². However, this measure will typically vary with the composition of lichens and with locations. The height is easiest to observe. When measuring one should not include the uppermost part of the soil: the litter or loose humus. Ideally, one should also ignore the bottom rotten part and measure only the upper living part, however, different definitions are acceptable.

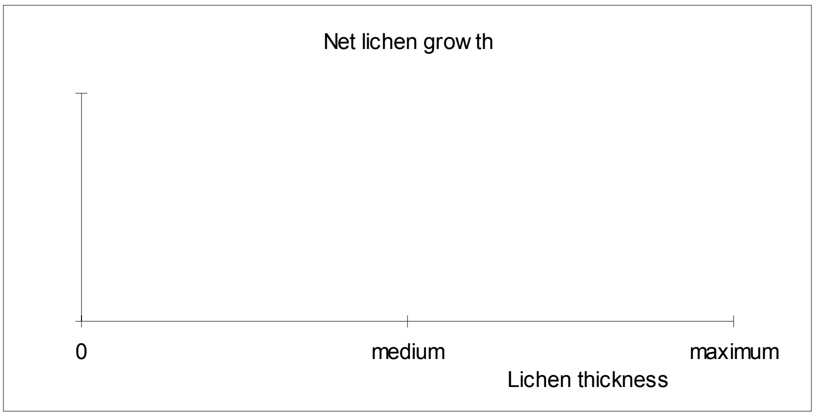


Fig. 1. Relationship between lichen thickness and lichen growth per year?

We start by considering the growth of lichen. Fig. 1 shows a diagram that is not yet finished. Along the x-axis is a measure of the thickness of the lichen mat. When there is no lichen, the thickness is of course zero millimetres. The maximum thickness typically ranges from 30 to 120 millimetres, depending on the type of lichen and on the growth conditions. Now, think about the net growth in lichen at different lichen thickness. What is the growth rate, in millimetres or grams per square meter, when there is no lichen? What is the net growth rate when the lichen thickness is at its maximum? Finally, what is the growth rate when lichen thickness is somewhere between zero and the maximum? Do not try to come up with precise estimates, just think about what you know and what you do not know at the moment.

The easiest point to establish is at zero lichen thickness. When there is no lichen, there can be no growth. Another point is similarly logical. When lichen has reached its maximum thickness, net growth must be zero otherwise the plant would continue to grow. However, this does not mean that the lichen plants die, it only means that what rots at the bottom of the plants is just as much as grows at the top. Hence it is the net growth that stagnates and not growth itself. By inspecting areas that have been protected from grazing one gets a rough idea about the maximum thickness of typical species of lichen in different areas.

When lichen is between zero and its maximum thickness, there must be positive growth. If not, lichen would never grow to its maximum thickness. How much lichen grows at different lichen thickness is a more difficult question to answer. Careful investigations of individual plants (or small plots with continuous lichen mats) indicate that the net growth can be around 2 to 5 millimetres per year (or 40 to 100 grams per square meter per year) when lichen is at about half of its maximum thickness. Producing estimates for average growth of entire winter pastures is a more complicated task because growth conditions differ from spot to spot. The complexity may explain why there does not exist good estimates of lichen growth for any reindeer district.

It is the purpose of the decision-tool to provide rough estimates of net lichen growth at different lichen thickness for entire winter pastures. Fig. 2 illustrates what such a growth curve may look like. Net growth is zero at both ends and reaches a maximum somewhere between zero and the maximum lichen thickness.

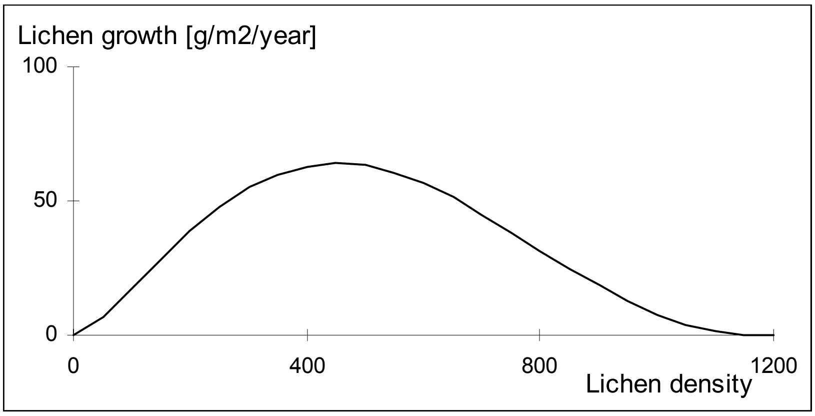


Fig. 2. Example of a lichen growth curve for a district.

Why is it important to know about net lichen growth in a district? Because in the long run reindeer grazing cannot exceed lichen growth without depleting the stock of lichen. To see this more clearly we consider the stock nature of lichen. In Fig. 3 the standing stock of lichen (measured by its thickness) is illustrated by a bathtub. Into this bathtub flows the net growth of lichen. Out of the bathtub goes what is removed by grazing reindeer. In this regard lichen is different from grass which withers in the autumn and starts growing from the roots each spring. Lichen is more like a forest, where only a small part is harvested each year and where yearly growth adds to the stock.

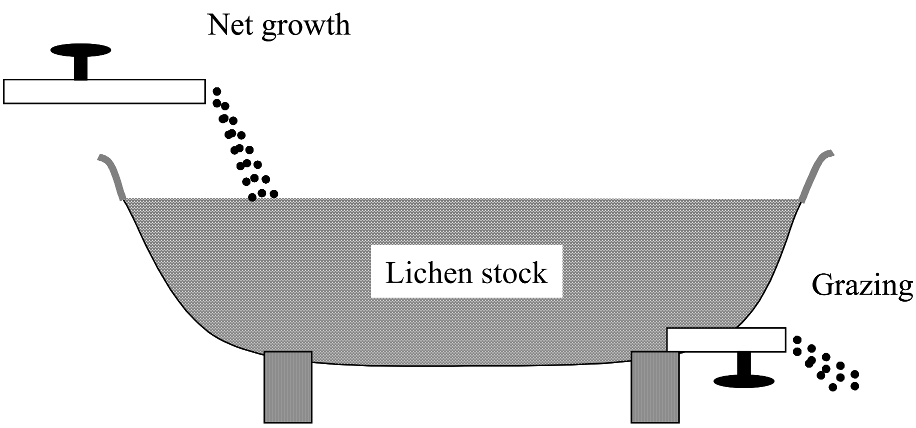


Fig. 3. Relation between growth, grazing and lichen stock.

Having the bathtub in mind we see more easily why it is important to have an idea about the net growth of lichen. Reindeer harvesting can exceed net growth for many years before the "bathtub" of lichen is emptied. In this period the reindeer will find sufficient amounts of lichen and there are no apparent problems for the animals. To stop the decline in the bathtub, reindeer grazing must be reduced such that it no longer exceeds the net growth rate. Only then will what goes in and out of the bathtub be the same and the level in the bathtub will no longer change. In order to adjust the reindeer grazing to the level that stabilises the lichen thickness, one needs to know what the net growth rate is.

Now we are ready to give a first introduction to how the decision-tool works. Again look at the bathtub figure. Think about a real bathtub for a while. Assume that the amount of water has decreased from 100 to 95 litres over the last minute and that 10 litres have flown out of the bathtub during that minute. In this case the inflow must have been 5 litres in the same period. Thus knowing the change in the amount of water and the outflow, we can calculate the inflow. Similarly, if we have information about how the average lichen thickness has changed over time, and we know the amount of grazing by reindeer over time, we can find out what the net growth of lichen has been in the same time period. This is basically what the decision-tool can help you do.

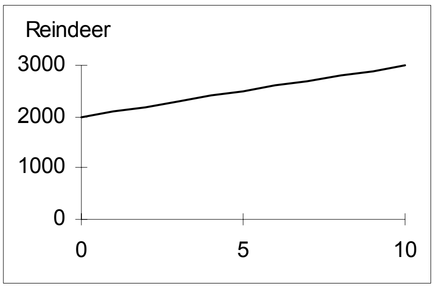
The only information you need about your reindeer district is the number of reindeer in the winter pastures each year, and the average thickness of lichen in the winter pastures. While the number of reindeer is usually known with quite good precision, the conditions of the lichen pastures are harder to assess. The quality of lichen data depends on what method is used. Large numbers of control plots are likely to give the best estimates, satellite images and systematic inspections from aeroplanes give good systematic data. However, it is also likely that less scientific methods such as visual inspections can give quite useful lichen data.

Note that if one switches between methods from year to year, this can give somewhat erroneous estimates of changes in lichen thickness. This happens if there are systematic differences between the different methods. Thus, if one switches from one method to another, the difference between the methods is interpreted by the tool as a real change in the lichen thickness.

Changing definitions can lead to similar errors. For instance if you at one time include lichen in areas that are not available to reindeer and at another time do not include these areas, the tool will interpret this as a real change in the average lichen thickness. The choice of definitions is normally not very important as long as you hold on to the same definition. For instance it is not likely to matter very much if one chooses to measure lichen density in millimetres thickness (height) or in grams of dry matter per square meter. Note, however, that using the decision-tool you must use grams of dry matter per square meter. Thus, if your data are in millimetres, you should multiply by a number around 20 to convert from millimetres to grams per square meter (you may perhaps obtain a more accurate conversion factor for the area of interest to you).

Then we are ready to perform a first demonstration of the decision-tool. To get a simple case we do not use real data, rather we use exact data produced by a simulator. The data for the number of reindeer and for lichen density are shown in the table in Fig. 4. This is the table you normally fill in with data from your own district. When using the tool, click on the tab DATA to find the table. Fig. 4 also shows two graphs of the time development for the number of reindeer and the thickness of lichen. These figures can be found by clicking on the tab EXTRA FIGURES. As can be seen, the number of reindeer increases steadily from 2000 to 3000 over a ten year period. In the same period, the lichen thickness declines from 789 to 169 g/m^2 of dry matter.

Year	Lichen density (summer) g/m2	Livestock in April [numbers]
0	789	2000
1	694	2100
2	615	2200
3	547	2300
4	486	2400
5	431	2500
6	378	2600
7	326	2700
8	275	2800
9	223	2900
10	169	3000



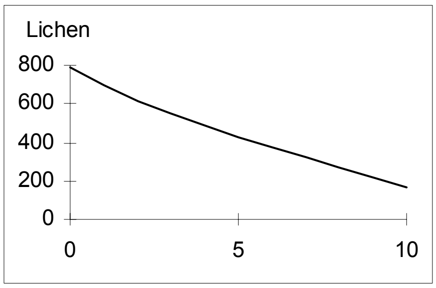


Fig. 4. Table with input data and graphs showing time development.

Knowing the bathtub figure, we immediately know that grazing must have exceeded net growth in all of the 10 years since lichen is steadily decreasing. However, it is not easily seen how large the net growth has been. To estimate lichen growth we use the decision-tool, which is presented in Fig. 5. To find the tool click on the tab named TOOL. To begin with, we concentrate on the left-hand side dealing with winter lichen pastures. More specifically we focus on the figure in the middle and at the bottom and the two entries for numbers called: *N-max* and *L-max* (We return to the other information later when discussing less important aspects of winter pastures and when discussion summer pastures).

The lower left-hand side figure shows lichen growth measured in grams dry matter per square meter, as in Fig. 2. In the middle left-hand side figure lichen growth is measured in winter season or annual "takeouts" of lichens (for an average reindeer). One annual lichen takeout is the sum of lichen that is eaten and lichen that is permanently removed by one trampling, digging and eating animal. Thus the solid line in the middle figure denotes the lichen growth measured in annual lichen takeouts. This is a practical measure because one can immediately see how many reindeer the yearly lichen growth could feed. This also means that we can compare directly the lichen growth with the herd size. The herd size is shown by plus-signs in the same figure. (A minor complication here is that the size of the annual takeout varies with the thickness of the lichen mat, however, this is something we will return to when discussing details.)

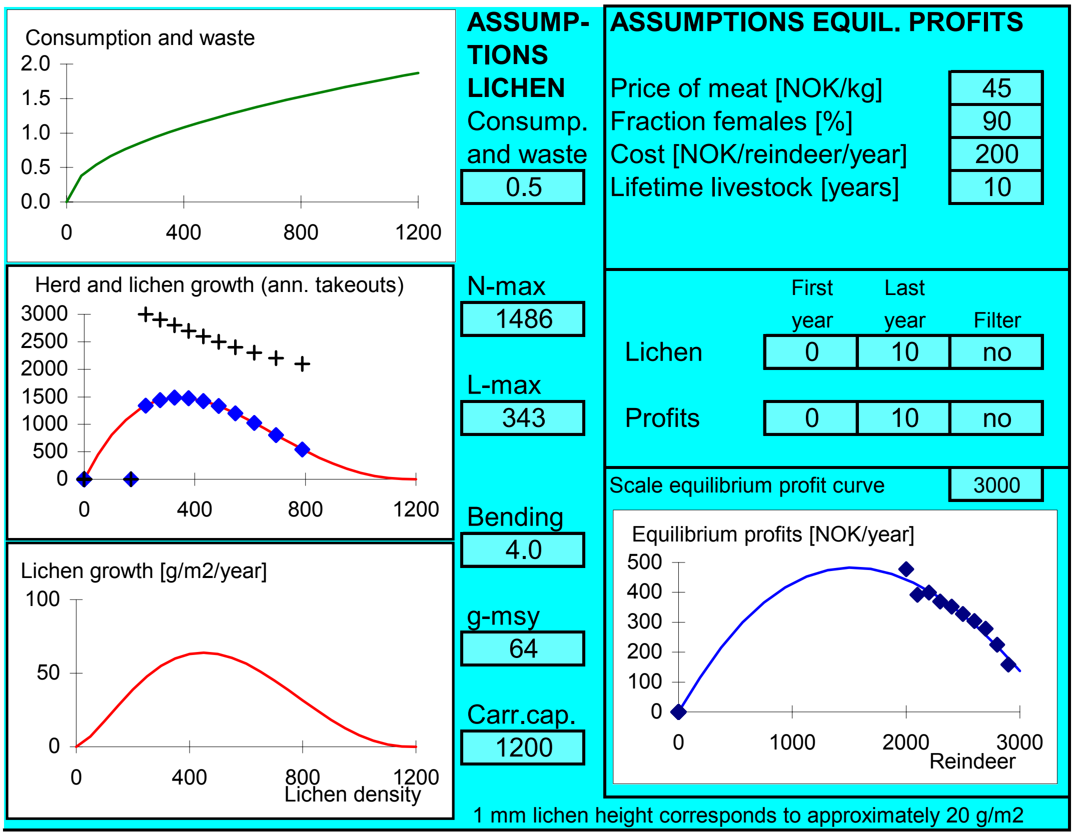


Fig. 5. Screen image of decision tool.

When looking at the middle figure you can recognise the data from Fig. 4. The herd size in year zero, 2000 animals, shows up as the plus-sign to the far right where the lichen thickness is 789 g/m^2. As the herd size increases, the lichen thickness becomes smaller and smaller.

The "diamonds" denote data points that should be as close to the growth curve as possible. To improve the fit between data points and the growth curve, we adjust the numbers denoted *N-max* and *L-max*. *N-max* denotes the maximum lichen growth measured in number of annual takeouts. That is the maximum of the growth curve in the middle figure. *L-max* denotes the lichen thickness at which the maximum occurs. In Fig. 5 the fit is perfect, a situation that is quite unlikely using real data. *N-max* is 1486 animals and *L-max* is 343 g/m^2 (the last data point, just below 200 in the figure, always requires more raw data to be useful).

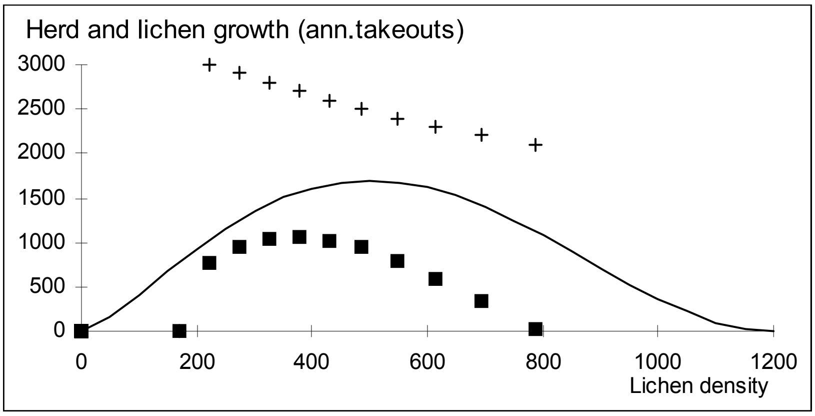


Fig. 6. Lack of fit between data and growth curve (*N-max*=1700 and *L-max*=500).

Fig. 6 shows the middle figure when we erroneously assume that *N-max* is equal to 1700 reindeer and *L-max* is equal to 500 g/m^2. Now the growth curve peaks too far to the right and the peak is too high. With a little practise you will be able to improve the fit by simply changing *N-max* and *L-max* in the directions indicated by the discrepancy between the diamonds and the curve.

The perfect fit between the data and the curve Fig. 5 is the goal for any adjustment of the numbers for *N-max* and *L-max*. However, in practise one will never get the perfect fit shown there. The data have errors (both for the data for the lichen mat and for the herd size) and the simple growth curve is not a perfect representation of an entire winter pasture. However, in spite of these weaknesses, the results that are obtained by adjusting *N-max* and *L-max* are likely to be very useful as will be seen later.

At this stage we suggest that you try out the tool yourself with the data from Table 1. Make adjustments in *N-max* and *L-max*. It may be a little confusing that the diamonds move around as you change the numbers for *N-max* and *L-max*. The detailed explanation for this is given in the technical report (see footnote 2). The technical report also explains why it takes two years of observations before the first useful diamond appears.

Does the middle figure make sense? From the very beginning the reindeer grazing (the plus sign to the utmost right) exceeds the growth of lichen, as indicated by the height of the growth curve just below the rightmost plus sign. The distance is large, which explains the rapid reduction in lichen density from the very beginning (Fig. 4). At around the sixth year (the fifth plus sign from the right) the distance is somewhat smaller and the reduction in lichen is a little slower. Then towards the end (plus sign at the very left) the gap widens again and lichen is depleted more rapidly.

The extremely important result that has been obtained through this exercise is to get an estimate of the growth of lichen, measured in reindeer winter takeouts. The maximum of the growth curve denotes the maximum number of reindeer the winter lichen pasture can accommodate. If one is afraid that lichen is being depleted, the growth curve shows how much the herd must be reduced to avoid further reductions in lichen density. Looking at Fig. 5, how many reindeer would you choose next year (in year 11, after the plus sign to the far left) to stop the reduction in lichen? Think carefully about this question before you look at the answer at the bottom of the page.[4] How would you have determined the size of the needed reduction with no knowledge of the growth curve? Look at the data in Fig. 4; do they give clear indications about how much to reduce the herd size in year 11? Probably not, since there is a widespread tendency to underestimate the need for reduction in the herd size in a situation like the one described here 11.[5]

In the above example we obtain data points for different lichen densities. This is important in order to get a good estimate of the net growth curve. If you have winter pasture data from a period with nearly constant lichen density, your data are only useful to find one point on the growth curve. Then you cannot find out where the peak of the curve is situated. In this case you may still have some use of your data if you use an estimate of *L-max* from similar winter pastures and only use the data to estimate *N-max*. However, the growth curve will be less reliable the less spread there is in your lichen density data.

It is our experience that even with poor data on lichen densities, for instance using only rough guesses about the development in lichen thickness over ten-year periods, the decision-tool gives interesting and useful results. In this regard, be aware that only a rough estimate of the growth curve can be good enough. Analysis shows that it does not matter very much for the economics of reindeer herding if the lichen thickness deviates somewhat from the density that produces the maximum lichen growth as long as one is successful in avoiding large and undesired reductions in the lichen density.

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4 The answer can be read from the growth curve, just below the plus sign to the far left. It is approximately 1200 reindeer.

5 See E. Moxnes. 2000. Not only the tragedy of the commons: misperceptions of feedback and policies for sustainable development. – *System Dynamics Review* 16(4).

Finally, note two other useful features of the decision-tool shown in Fig. 5. On the right-hand side, in the middle section, you can make selections of data points from your time-series data. By specifying the first and the last year of the data you want to consider, you can find estimates of the growth curve for different time periods. If you have long time-series this feature can be used to see if your estimates of the growth curve are stable over time. This feature has been used in the Snøhetta case which we analyse in Section 2.3.

In the same section of the screen for the decision-tool you can also choose to activate a filter which smoothes your data. Again the technical report explains the details. Write yes to activate the filter and no to deactivate it. This option is particularly useful if you have long time-series with measurements that vary quite a bit due to measurement errors. We recommend that you try to adjust *N-max* and *L-max* both with the filter on and off.

2.2. Decision-tool, less important parts - winter

The shape of the lichen growth curve is influenced by all the numbers shown under the heading *ASSUMPTIONS LICHEN* on the screen, see Fig. 5. It is normally sufficient to adjust the numbers for *N-max* and *L-max* to get an acceptable estimate of the growth curve for a reindeer district. The peak of the growth curve is after all the most important point on the curve. However, the decision-tool allows you to adjust four more parameters which influence the growth curve and also the data points around the growth curve. Consult the technical report for details on how the data points are calculated. The default values are based on established knowledge from other sources and should be applicable for a quite wide range of lichen pastures. You will need quite good raw data on herd sizes and lichen thicknesses to obtain reliable improvements of the numbers. Therefore you should be careful not to deviate too much from the recommended numbers.

The most important point on the growth curve, the peak, is fully determined by *N-max* and *L-max*. The four other parameters are only of importance for the fit between the curve and the data points to the sides of the peak. Note that some of the parameters can lead to quite similar changes in the fit. If this is the case, it may be difficult to know which parameter is the correct one to adjust. Also note that one of the parameters (*g-msy*) influence the data points such that an adjustment of this parameter implies that *N-*

max must be readjusted. Another parameter (*Consump. and waste*) has implications for *L-max*. Each of the parameters is discussed below and Table 1 summarises the discussion.

Table 1. Main effects of adjustments in the four less important parameters.

Parameter	Main effect on	Implications for L-max	Implications for N-max
Carr.cap.	Curve	-	-
Bending	Curve	-	-
g-msy	Data points	-	yes
Consump. and waste	Data points	yes	-

First consider the maximum density of lichen, referred to as *Carr.cap.* (carrying capacity). As a start we recommend that you use 1200 grams dry matter per square meter, corresponding to approximately 60 millimetre thickness. This refers to a pure lichen mat (near 100 per cent cover of the ground) with only negligible cover of plants like graminoids, herbs and dwarf bushes. The maximum density will depend on climate conditions and on what type of lichen is dominating in the winter pastures, see Table 2. It also varies with the type of vegetation the lichen mat is part of. Using the example in the previous section you will see that it is only the right-hand tail of the growth curve that changes if you use 900 or 1500 g/m^2 instead of 1200 g/m^2. Make similar tests yourself with this parameter and also with the parameters discussed below. *Carr.cap.* has no or very little effect on the choice of *N-max* and *L-max*.

Table 2. Maximum lichen density measured in millimetres and in grams of dry matter per square meter, assuming 100 per cent cover of the lichen mat. Unpubl. data from Norway. They correspond well with measurements in Sweden, Finland, Russia and Canada.

Dominating lichen species in the mat	Height of lichen mat mm	Weight of dry lichen mat g/m^2	For each mm height g/mm	Proportion of living part %	Weight of living part for each mm at 100% cover g/mm
In the alpine region					
Cetraria nivalis	50	1064	21.3	66	14.1
Cladonia stellaris	50	1193	23.9	66	15.7
In dry pine forest					
Cetraria nivalis	60	1277	21.3	60	12.8
Cladonia stellaris	80	1909	23.9	60	14.3

Second, the parameter called *Bending* influences the width of the curve. A low number gives a wide curve, while a high number gives a pointed curve which drops off quickly as one move away from the peak point. Different from *Carr.cap., Bending* influences both tails of the growth curve. *Bending* has no or very little effect on the choice of *N-max* and *L-max*.

Third, the parameter *g-msy* denotes the maximum growth (maximum sustainable yield) of lichen measured in grams per square meter per year, see the lower figure on the left-hand side of the decision-tool in Fig. 5. The number we recommend for *g-msy* is based on investigations of the growth of individual lichen plants, 64 grams dry matter per square meter per year. The size of this parameter will depend on what type of lichen is dominating the pastures and on the local climate, in particular summer precipitation, see Table 3. Lichens grow better with more precipitation. However, as precipitation increases, the competition from other plants also increases. Average lichen shares drop from about 80 per cent at less than 400 mm annual precipitation to 50 per cent at more than 1000 mm. Even stronger is the reduction in lichen dominated plant communities, from about 35 per cent of the landscape at less than 400 mm to less than 5 per cent at 1200 mm. The default value of 64 grams dry matter per square meter per year corresponds to 10 per cent annual growth at a lichen density of 640 g/m^2. We encourage users to use local data on *g-msy* if possible.

Table 3. Annual lichen growth in per cent at 60°N in two locations at Dovrefjell, Norway. Averages over the period 1979-1990; 5 parallels for each species. Results from an unpubl. experiment with lichen growing in trays (Eldar Gaare).

	Annual precipitation (mm)	*Cetraria nivalis* (%)	*Cladonia stellaris* (%)	*Cladonia mitis* (%)
Aursjø damsted	800	5.3	10.1	9.1
Grønnbakken gård	400	5.5	6.4	7.6

Your choice of *g-msy* has no effect on the growth curve measured in winter takeouts (middle figure), it only influences the location of the data points, both the height and to some extent the pattern formed by the data points. Also note that a change in *g-max* implies that your choice of *N-max* will change. An increase in *g-msy* leads to an increase in *N-max*, although the relative change in *N-max* is much smaller than the relative change in *g-msy*. If you are afraid of depleting lichen, you should perhaps safeguard against overly optimistic estimates of *N-max* by adjusting your estimate of *g-msy* downwards.

Fourth, there is a parameter called *Consump. and waste*. This parameter is included to capture the fact that yearly reindeer winter takeouts of lichen are not constant. If the density of lichen is high, the animals will both eat more and they will waste more lichen. While most of the wasted lichen will fasten and continue growing in new locations, some of it will be carried away by wind and water to places where the conditions are unsuitable for lichen growth. If the density of lichen is very low, the animals will eat less lichen and they will waste less. This effect is captured by the parameter *Consump. and waste*. The upper figure on the left-hand side of Fig. 5 shows how the yearly takeout changes when the parameter is changed. At the peak of the net growth curve *L-max*, the yearly takeout has the index value of 1.0. To the left the takeout is smaller than 1.0 and to the right it is higher than 1.0. Change the parameter and see the effect on the curve. There is only limited information about this entry such that our recommendation of a value of 0.5 may not be very accurate.

The variable size of a winter takeout explains why the growth curve measured in winter takeouts (middle figure in Fig. 5) has a different shape than the growth curve measured in grams per square meter per year (lower figure). Only when the parameter for *Consump. and waste* is set equal to zero, the two curves have the same shape. Test this yourself.

The effect of *Consump. and waste* on the growth curve is small, while there can be a quite large effect on the pattern formed by the data points. The effect is asymmetric meaning that the data points move upwards on one side of the peak and downwards on the other side. This asymmetric effect implies that your choice of *L-max* will be influenced by your choice of *Consump. and waste*. If you underestimate *Consump. and waste*, you will also underestimate *L-max*. Thus if you are afraid of depleting lichen, you should perhaps adjust your estimate of *Consump. and waste* upwards as a safeguard.

2.3. Interesting cases

In this section we use the decision-tool to investigate some interesting cases. For some cases we have good data, for others we have less reliable data. In all cases, however, we seem to obtain interesting and useful results. Further discussions of the cases and the data they build on can be found in the technical report.

SNØHETTA

We start by the Snøhetta district for which we have data from 1944 to 1997. From 1944 to 1961 the number of wild reindeer in the area increased from 6000 to 14 200 animals. The herd size was then reduced gradually to a low of 1400 in 1970. Thereafter the herd size has stayed 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 a reduction and a period with a build-up of lichen, we analyse the two periods separately. Fig. 7 shows herd sizes and lichen growth measured in winter takeouts for the period with lichen reductions. On the far right-hand side of the figure we find data for 1944, the plus signs denoting the number of animals, the diamonds denoting the data points and the line denoting the growth curve.

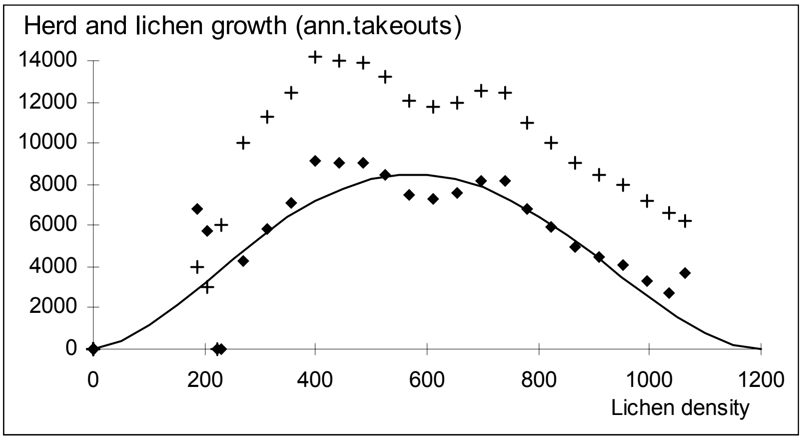

Fig. 7. Snøhetta – period with lichen reduction, 1944 to 1967.

The figure shows that the data points tend to fall along a typical growth curve, with the exception of the last two data points, those to the far left. However, also these two move close to the growth curve if the data are filtered. The herd size is above the growth curve for the entire period except in the final year 1967, consistent with the observed ongoing reductions in lichen density. In 1967 the herd is only 38 percent of the maximum growth of lichen winter takeouts *N-max*. Already when lichen density is reduced to about 600 g/m^2 it seems likely that overgrazing is taking place and that herd reductions are needed to maintain a lichen density which yields the maximum growth in lichen winter takeouts. Recalling the bathtub model, to stop the reduction of the water in a bathtub, the outflow must be reduced to the level of the inflow.

Looking at the actual management of the reindeer herd, we see that the number of reindeer was not quickly reduced as the lichen density was reduced below 600 g/m^2. Rather, the herd size, which already exceeded the maximum growth rate by a wide margin, was expanded for another 5 years, with a continued reduction in the lichen density as a result. Finally, the reduction in lichen became a reason for major concern. However, at this point, the herd was not reduced immediately below the growth curve. Rather, the reduction took place over a six year period. The reductions were all in the right direction, however they were gradual and insufficient to stop the decline in lichen density. It may seem as if the managers did not know exactly what herd size to aim for. However, they were determined to halt the depletion of lichen and finally they succeeded. Note however that by the time they succeeded, the lichen density had fallen to only 200 g/m^2. This is around one third of the level that seems to yield the maximum lichen growth.

The pattern of gradual and insufficient reductions in the herd size seen in Fig. 7 is not an exception, rather it seems to be a rather typical way of reacting. In this case it reflects a conflict between central and local authorities. There was a profound lack of understanding of the alpine ecosystem of which the reindeer is a part. As mentioned before, several laboratory experiments show the same type of reactions (see footnote 6). When depletion of lichen becomes evident, the laboratory participants start to reduce the herd size in a gradual and careful manner. Similar misperceptions of complex systems have for example been observed in fishery management, climate change policies, start-up firm management, and forest fire fighting. Thus there is no reason to speculate that the previous managers of the Snøhetta reindeer district were particularly poor managers or that they had some particular reason to favour a policy of overgrazing. The complexity and a lack of information about the growth curve seem to be a sufficient explanation. In a laboratory experiment where the participants received precise information about the growth curve, the results improved considerably.

The growth curve is described by the parameters shown in the first row in Table 4. Roughly similar fits can be obtained by somewhat different parameter sets: *Carr.cap.* can be increased above the levels which are thought to be correct from prior information, *Bending* can be varied between 3 and 7, *Consump. and waste* 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. Important though is the fact that the growth curve does not change much due to changes in parameters, partly because changes in one parameter are compensated for by changes in other parameters. Hence, the method seems to give a quite precise estimate of the growth curve itself, even though we do not know exactly why the curve has the shape it has.

Table 4. Parameters used in the different cases.

Case	*N-max*	*L-max* g/m^2	*Consump. and waste*	*Bending*	*g-msy* g/m^2/year	*Carr.cap.* g/m^2
Snøhetta, lichen down	8500	575	0.3	4	80	1200
Snøhetta, lichen up	4000	365	0.3	10	50	1200
West-Finnmark, lichen down	79500	250	0.3	10	60	1200
St. Paul, lichen down	500	575	0.3	4	80	1200

Before we go on to study the period after 1967 with lichen increase, it is worthwhile to recall the implications of the tool's lack of geographical distribution. A justification for this simplification is 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 the 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. Thus, the period with lichen reductions before 1967 could have left certain spots without lichen at all, and even eroded. For these spots new growth will at best be very slow even after a drastic reduction in the herd size. In practice the outgrowing area could therefore appear to be smaller than the original pasture. Since the tool operates with average lichen coverage for the original area, the growth curve for an outgrowing pasture could be lower than the original curve, permanently or for a very long time depending on ongoing grazing pressure, degree of erosion etc.

Fig. 8 shows the estimated growth curve for the years 1968 to 1997, in which period lichen increased again in the Snøhetta area. Even without filtering the fit is very good for the parameter values shown in the second row of Table 2. For the entire period the number of animals is lower than the net growth curve. Recalling the bathtub model, this is consistent with the observed increase in lichen density for the entire period.

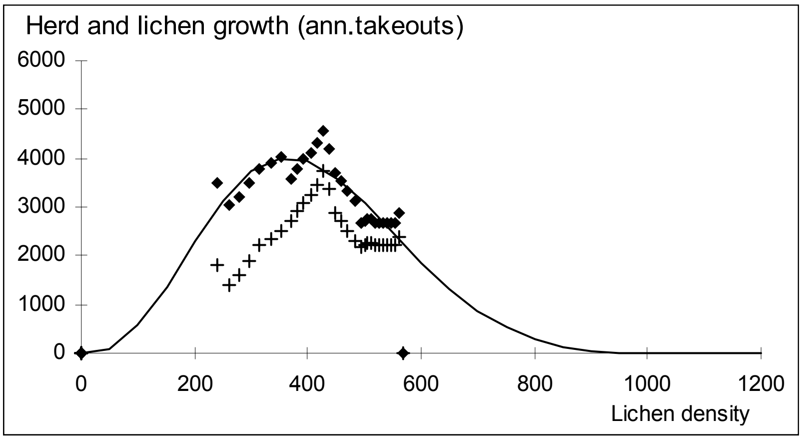

Fig. 8. Snøhetta – period with lichen increase, 1968 to 1997.

The estimated parameters are all consistent with the above argument about a more or less permanent reduction in the productive area of lichen pastures. The growth curve peaks at a lower lichen density (*L-max* equals 365 g/m^2), *Bending* is stronger (10), and most important, maximum growth of lichen winter takeouts is reduced by more than 50 percent (*N-max* is reduced from 8500 to 4000 animals).

This finding has important implications for the management of lichen pastures in general. Our investigation shows that severe overgrazing can have long-term consequences. After severe overgrazing has taken place, one can no longer be confident that previous estimates of the growth curve (or the productivity of the area) are representative for the medium-term future.

On the other hand, it is not obvious that all cases will show as strong an effect of overgrazing as found for the Snøhetta case. The Snøhetta area was a virgin area with very good lichen conditions before the number of reindeer increased to record levels. 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 already. Thus one may already be dealing with a lower growth curve. However, even in this case, a similarly severe relative reduction in lichen density could leave new areas depleted of lichen and possibly eroded. Hence, even for mature districts, one should be aware that drastic reductions in lichen density could lead to a long-lasting reduction in the growth curve.

WEST-FINNMARK

Then we go on to analyse the winter pastures of West-Finnmark in Norway. These pastures have been grazed for centuries. After 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 images.

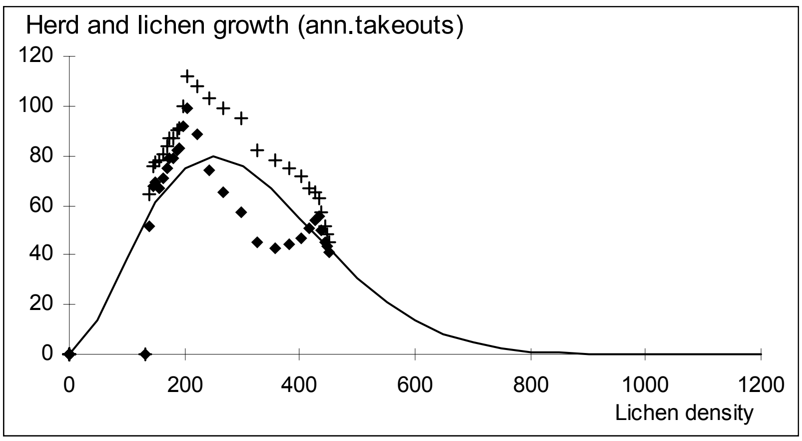

Fig. 9. West-Finnmark – period with lichen reduction, 1973 to 2000.

Fig. 9 shows our estimate of the growth curve for West-Finnmark. For the entire period since 1973, the grazing has been greater than the growth curve. Recalling the bathtub model, this is consistent with the observed reduction in lichen. The overall pattern is similar to what was found for Snøhetta during its period with declining lichen density. The fit between data and the growth curve is not as close as in the Snøhetta case. One reason for this may be the fact that lichen data are only available at five points in time. A measurement error at one of these points can produce a poor fit of the type shown in Fig. 9. Increasing the parameter *g-msy* improves the fit considerably, however we resisted the temptation to do this since other investigations indicate that *g-msy* is not much higher than what we have assumed, see Table 2.

The figure explains the cause of much frustration in West-Finnmark during the 1990s. While the herd size was steadily reduced, lichen continued to decline. Knowing the bathtub model and the growth curve, it is obvious why the density continued to decline. Reindeer grazing was all the time higher than net lichen growth. Knowing the growth curve, it is also obvious what is needed to stop the decline in lichen density and to begin rebuilding lichen. The herd size must be brought below the growth curve, just as it was in the Snøhetta area. Perhaps are 40 000 animals sufficient. In light of the long-lasting damage found for the case of Snøhetta, maybe a somewhat lower level is even better as an insurance policy. If a lasting damage is limited, the good news is that the herd size can be increased to nearly 80 000 animals again once lichen density has increased to around 300 g/ m^2.

The peak of the growth curve at around 80 000 animals is similar to earlier estimates of the upper limit for the total number of reindeer in West-Finnmark, ranging from 60 000 to 80 000 animals. However, it is important that this upper level is not confused with the much lower number of reindeer that is needed in the short run to rebuild lichen. In a publication from 2001, estimates for the upper limit in the short run ranges from 31 300 to 45 000 animals.[6] To rebuild lichen the number of animals must be lower than this upper limit. Thus, also in this regard our analysis seems to be roughly consistent with the analyses of others. This is reassuring since it may be perceived as a weakness of the present decision-tool that it only makes use of two aggregate time-series (the number of reindeer and the average lichen density). A clear strength of the decision-tool is that it provides explicit estimates of the growth curve measured in yearly reindeer winter takeouts. Previous studies do not provide this information.

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6 See A. Aa. Ims & A. J. Kosmo. 2001. *Høyeste reintall for distriktene i Vest-Finnmark*. Reindrifts-forvaltningen i Alta.

SAINT PAUL

Next we consider the case of St. Paul in Alaska. This case is perhaps the most severe case of overgrazing known from the literature[7]. Twenty-five animals were placed on the island in 1911. The herd grew rapidly towards a peak of 2046 in 1938, by which time lichens were reported to be fully depleted. The herd collapsed and by 1950 there were only 8 animals left. The reindeer herd was planned to be a sustainable meat source for the islanders, however, the slaughter rate increased far too little and far too late to save the lichen pastures. The remaining food plants were not sufficient in quantity or quality to carry the large herd through the winters.

While the historical records of herd numbers are thought to be very accurate, we only know the claim that lichen was gone by the end of the thirties. Hence this is a case with very poor lichen data. To estimate the growth curve we make some rough assumptions about lichen development from initial virgin conditions (1200 g/m^2) in 1911 to nearly full depletion in 1938 (10 g/m^2). A simple approach, which could be easily performed with the decision-tool, is to assume that lichen density is reduced with the same amount each and every year from start to end. However, here we have made a more elaborate assumption where lichen density is reduced more quickly in the years with many reindeer, see the technical report. With this approach, the fit between the data points and the growth curve becomes perfect, however, the conclusions are not very different from those obtained with the simple approach.

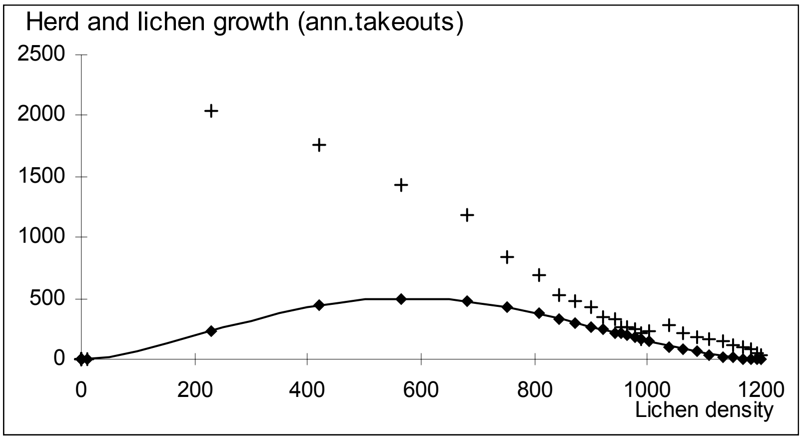

Fig. 10. St.Paul – period with lichen depletion, 1911 to 1938.

Since our data are only useful to estimate the peak of the growth curve, *N-max*, we set all the other parameters equal to the parameters estimate for the Snøhetta –lichen down case, see Table 4. *N-max* is set such that lichen is reduced to 10 g/m^2 in 1938. Fig. 10

7 See V. B. Scheffer. 1951. The Rise and Fall of a Reindeer Herd. – *Scientific Monthly* 73(6): 356-62.

shows the resulting growth curve. The amazing finding is that the number of reindeer exceeds the maximum growth rate by a factor of about 4. Again it is reassuring that our estimate of the maximum growth rate based on very crude assumptions about lichen development is similar to an estimate made by Scheffer (see footnote 7) who claims that "the reindeer population was at least three times the carrying capacity of the range".

The St. Paul experience is interesting for several reasons. There was only one herd on the island such that there was no commons problem present. Thus overgrazing did not take place because different owners were competing about a limited pasture resource. The tiny population on the island had high hopes that reindeer herding would provide a steady supply of fresh meat. To manage their resource they sought professional advice regarding the management of the herd. However, it seems highly unlikely that they had an estimate of the growth curve for lichen or that they had a bathtub model of lichen in mind when managing the herd. Most likely, lack of these types of information can explain the severe mismanagement, which was clearly contrary to the stated goals for reindeer herding in St. Paul.

The behaviour of lichen in laboratory experiments is typically surprising to the participants and lead to considerable frustration. The same type of frustration can be sensed in the following quote by the American Society of Mammalogists in 1950: "(The Society) urges that the Canadian Government not undertake the introduction of reindeer into Ungava. Before any introduction is seriously considered, those persons involved in any planning are urged to make a thorough study beforehand of the problems of integrating lichen ecology, reindeer biology, and native culture - serious problems that have not been solved to date on any workable scale on the North American continent." [8]

Once one focuses on growth and grazing, and has a rough growth curve available, it is quite easy to see what an appropriate herd size should be. However, be aware that if you talk to people that do not have the same perspective, you are easily misunderstood. In a situation with low and declining lichen density, they may all agree that the herd size should be reduced. However, a quick reduction of the grazing pressure below the growth curve, may be viewed as unnecessarily drastic and risky, compared to a more careful reduction. Note in this connect that the more careful approach makes perfect sense for all those who think that the reindeer herd can be managed by trial and error, a strategy which typically works well for other systems we have daily experience with.

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8 Complete reference is lacking.

3. SUMMER PASTURES (PROFITS)

First, we present the decision-tool. Focus is on finding the herd size that gives the highest sustainable meat production or profits. The analysis is performed as if summer pastures represent the limiting resource for meat production. However, if summer pastures suggest a herd size above what winter pastures can sustain, winter pastures must be seen as the limiting resource. Second, we use the decision-tool to investigate interesting real-world cases.

3.1. The decision-tool

While the adaptation of the herd size to winter lichen pastures is complicated by the "bathtub-nature" of lichen, summer pastures are thought to be easier to manage. As long as one stays away from extreme changes in herd sizes and 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. When using the decision-tool it is acceptable to assume that the availability and quality of summer pastures stay constant from year to year. This is not to say that there are no changes going on in summer pastures. Weather conditions influence pasture quality, the availability of pastures may change due to variations in insect populations and to for example new roads and power lines, and survival may change due to changes in predator populations. Later we indicate how you can use the decision-tool to investigate long-term effects of such changes.

With an assumption about constant availability and quality of summer pastures 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 goal). Change the herd size in the direction that yields higher profits. Stop the search when profits stagnate or start to decline. This procedure is illustrated in Fig. 11. For example going from 200 to 300 animals, profits increase a lot. Going from 500 to 600 animals, there is hardly any increase in profits. At 700 animals the profits will be lower again. At the optimal point there is a balance between the benefits of having more animals to slaughter and the consequent costs of having more animals in terms of reduced weights, reduced calving fractions, reduced survival rates, and increased operating costs. All these factors are included in the profit curve in the illustration.

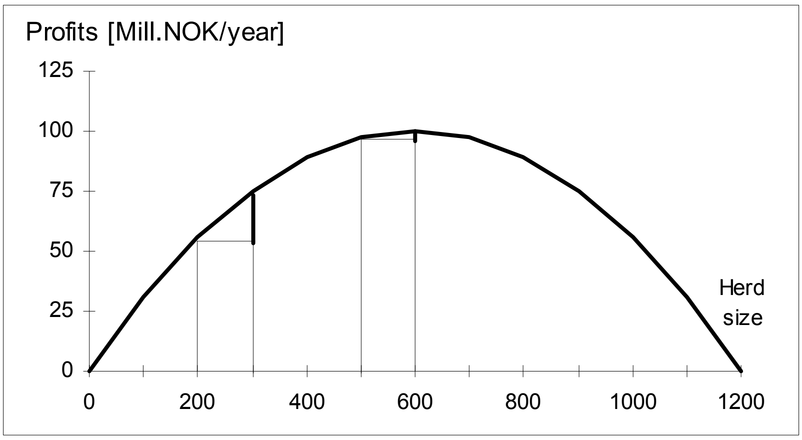

Fig. 11. Illustration of simple decision rule to find the maximum yearly profits.

However, there are three factors that complicate this procedure. First, whenever one changes the herd size, one has to increase of decrease the slaughter rate. If one wants to reduce the herd size, the slaughter rate must be increased leading to higher profits in the year of extra slaughtering. However, this increase in profits is not a signal that profits will increase permanently if the herd size is reduced; it is only a short-term effect. Thus, to use the simple rule, one has to remove the effect of changing herd sizes. Second, changes in meat prices, costs and climate from year to year can have quite strong impacts on profits. Unless these effects are removed, these variations will confuse the use of the simple rule. Third, to use the simple rule one must collect and keep track of data about yearly profits or meat production for all the reindeer in the summer pasture. This is a demanding task if the district is large with many reindeer herders. The task becomes even more demanding if profits or meat production in a common summer pasture are considered sensitive information that the individual herders will not release.

For these reasons we construct a measure that reflects long-term profitability and that does not depend on sensitive information about individual profits or meat production. What we are after is an expression which relates long-term profits to the number of reindeer on the summer pastures. Central in this expression is a regular profit calculation

Profits=MeatPrice*(AdultWeight*AdultSlaughter+CalfWeight*CalfSlaughter)-
UnitCost*HerdSize

Yearly meat production is the sum of meat from adults and calves. Meat production from adults is given by the slaughter weight of adults, AdultWeigth, times the number of adults being slaughtered, AdultSlaughter. Meat production from calves is given by

CalfWeight times CalfSlaughter. Income is given by the price of meat, MeatPrice, times the total meat production. Total yearly costs are given by UnitCosts[9] times the number of reindeer, HerdSize. Finally, profits are the difference between incomes and costs. Note that if MeatPrice is set equal to 1.0 and UnitCost is set equal to zero, the expression for Profits will measure meat production rather than profits. Hence by making this choice, the user can choose which of these two goals to guide management. This choice is made in the upper right-hand corner of the screen, see Fig. 12.

In the sheet called DATA, see Table 5, you enter your raw data for different years. The tool produces a profit curve similar to the one in Fig. 11. Such a curve is shown in the lower right-hand corner of the screen, see Fig. 12. The better estimate one has of this curve, the closer one should be able to position the herd size to the level that gives the maximum profits (or meat production). To calculate the profit data for the profit curve, the decision-tool uses actual measurements of average slaughter weights for adults and calves from year to year. The data for the slaughter weights represents estimates based on measurements from for example slaughter houses. The number of adults and calves being slaughtered on the other hand are not based on actual measurements. Rather the decision-tool calculates long-term slaughter numbers based on current measurements of the number of animals, HerdSize. The idea is that in the long run a given herd size will lead to a new equilibrium with given slaughter rates. The details are given in the technical report; the basic ideas are presented in the next paragraph.

The long-term slaughtering of adults is directly related to the herd size. First note that only animals that survive can be slaughtered. Therefore you have to provide data about the number of reindeer that are lost each year. Next you have to specify a desired lifetime of adult animals (largely dominated by the lifetime of female livestock). This number is one of two numbers that are used to characterise your desired herd structure. This number does not have to reflect current lifetimes; it is a number of your choice. This number is entered in the upper right-hand corner of the screen image in Fig. 12. If you for example choose a short lifetime, a rather high fraction of the livestock will be slaughtered each year. To maintain the current herd size, this of course implies that fewer calves can be slaughtered.

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9 UnitCosts should 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. Investments, for instance snow-scooters, 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.

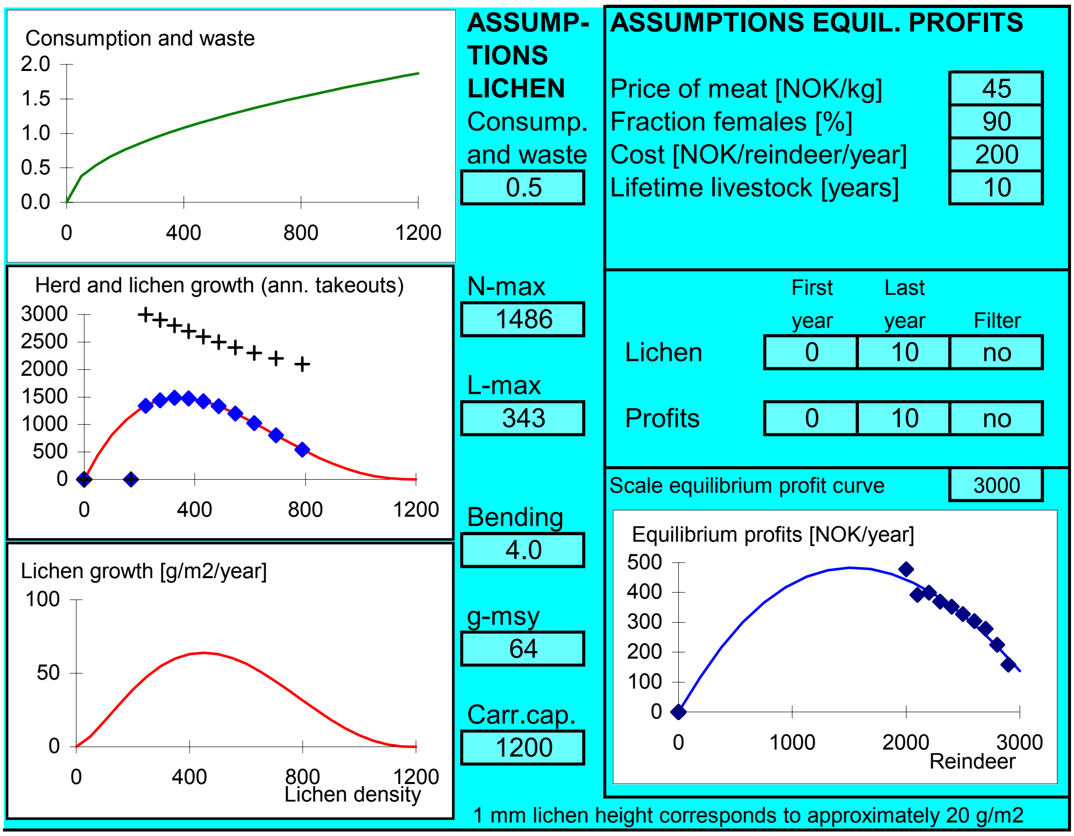

Fig. 12. Screen image of decision tool (replicate of Fig. 5).

Table 5. Table seen in the DATA sheet used to estimate the profit curve and the capacity of summer pastures (here data from the simulator).

Year	Livestock in April [numbers]	Female ratio in livestock %	Calves in fall [numbers]	Slaughter weight calf kg	Slaughter weight adult kg	Loss livestock [numbers]
0	2000	90	896	16	33	141
1	2100	90	1158	17	35	104
2	2200	90	1093	17	34	132
3	2300	90	1141	17	34	139
4	2400	90	1142	17	33	155
5	2500	90	1160	17	33	168
6	2600	90	1168	16	33	183
7	2700	90	1178	16	33	198
8	2800	90	1184	16	32	214
9	2900	90	1160	16	32	238
10	3000	90	1122	16	32	267

The calculation of the number of calves to be slaughtered is somewhat more complicated. First the decision-tool calculates the total number of calves that the current herd size is likely to produce. The total number of calves depends on the total number of adults that survive; it depends on the calving fraction and on the fraction of females in the herd. The calving fraction is based on yearly data for the number of calves (calves surviving towards the counting in the autumn) and the ratio of females in the livestock, again raw data you have to provide. The desired fraction of females in the herd is another choice you make freely in the upper right-hand corner of the screen. This is the second parameter that characterises the structure of the desired equilibrium herd. Having a number for the total number of calves and the slaughtering of adults, the decision-tool calculates the slaughtering of calves that is needed to maintain the current herd size.

To summarise the need for data: First you have to provide yearly data for the following variables: herd size, calves, average slaughter weight adults (for example 3 year old), average slaughter weight calves, and losses measured in numbers of animals, see Table 5. Then you choose assumptions about the meat price, unit costs per reindeer, the desired fraction of females in the herd, and the desired lifetime of the livestock. These numbers can be freely changed to see the effects on the shape of the profit curve.

As in the case of winter pastures, you have to specify what time period you will use for your analysis, that is you specify the first and the last year. In addition you have to enter a number to the right of the text "Curve extends to:" This number determines how much of the estimated profit curve you get to see in the figure just below. If you choose zero you will not see the curve at all, and you are not influenced by the estimated curve when you form your own opinion from the data points. Normally you should choose the same value as the maximum value on the x-axis.

Different from the winter pasture analysis you do not have to engage in a trial and error calibration of parameters. The four choices you have in the upper right-hand corner do not serve to produce more or less correct estimates of the profit curve. They are mainly there for you to find out whether the maximising herd size depends on your herd structure (desired average lifetime of livestock and desired fraction females in the herd), or whether it depends on prices and costs. Recall that if you set the price equal to one and costs equal to zero, the profit curve will be a meat production curve.

As for the winter pasture analysis, you can choose to filter the data points. This will normally remove some of the spread in the data points, and it will be easier to see where the profit curve may lay. Note that the estimated profit curve is not influenced by filtering. Exactly how the estimated curve is produced is explained in the technical report. When using the decision-tool, be aware that the estimated curve will typically move about quite a lot to begin with. You should also note that as long as you keep the herd size nearly constant at one level, the curve will vary quite a lot. To get a more stable estimate of the curve, you need data for different herd sizes. If the herd size is not varied, you will not learn anything about the profit curve.

3.2. Interesting cases

We consider three cases that teach different lessons.

WEST-FINNMARK

We start with the case of West-Finnmark. Time-series data of the type shown in Table 5 are obtained for the period from 1981 to 1999. The following choices are made in the upper right-hand corner. Price of meat is NOK 50/kg, operating costs is NOK 100/animal/year, the desired fraction of females is 90 per cent, and the desired lifetime of livestock is 10 years. Fig. 13 shows the estimated equilibrium profit curve based on data from 1981 to 1990, that is the data points in black. The data points in white, from 1991 to 1999, do not influence the shown profit curve. (Note that the figure in the lower right-hand corner of the decision-tool can only show profit curves that are based on all the chosen data points; Fig. 13 is produced outside of the decision-tool).

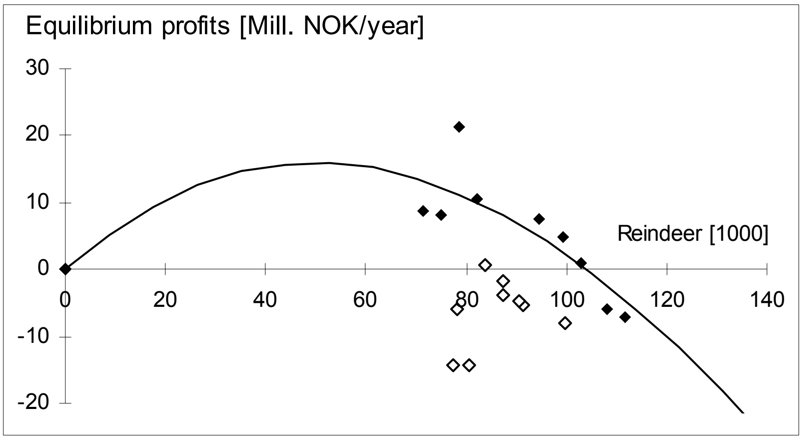

Fig. 13. West-Finnmark equilibrium meat production, 1981 to 1999, data points from 1981 to 1990 in black.

Based on data for the first period, the filled diamonds, we find a maximum equilibrium profit of NOK 16 million for a herd size just above 50 000 reindeer. The data points do not deviate much from the curve, and the fit looks even better if the data are filtered. However, it is important to be aware that the estimates are uncertain. In particular, the lack of observations for low herd sizes means that the curve is more uncertain in that range. The estimate seems quite similar to previous estimates, maybe somewhat lower.

Fig. 14. Time-series data for West-Finnmark.

A puzzling observation is the data points (open diamonds) for the last 9 years, they all fall below the curve. Given the good fit between the curve and the black data points, it is quite unlikely that the white data points reflect the same profit curve. A lasting change in the underlying conditions seems to have taken place. Thus this case illustrates the usefulness of splitting the time-series into segments to see if the different time periods produce approximately the same profit curve. There are several possible explanations for the observed deviation. The figures shown in the sheet called EXTRA FIGURES can be of some help when discussing explanations. Fig. 14 shows the key variables for this discussion.

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 profits. Consistent with this explanation, calving fractions are systematically low during the second period and losses are high. The weight of adults may have a downward trend while the calf weights do not seem to have a declining tendency (these observations are uncertain since the true tendencies may be hidden behind variations due to weather conditions). Given the observed decline in the number of animals, and a reduced competition about summer pastures, one should perhaps have expected slaughter weights to have increased.

A second possibility is that the composition of species and the quality of summer pastures changed due to the strong grazing pressure in the last half of the 1980s when the number of animals peaked. We have no direct data on the quality of summer pastures to support this explanation or to rule it out. The stronger effects on the calving fractions and the losses than on weights suggest that declining lichen is a stronger influence than reduced quality of summer pastures.

A third possibility is that low calf weights in the second half of the 1980s, has carried over to the adults in the 1990s. The data do not support this idea since higher calf weights in the early 1990s do not lead to higher adult weights towards the end of the 1990s.

A fourth possibility is that increasing predator populations have lead to increased loss rates and to reduced calving rates. We do not have data on predator population numbers to support or rule out this explanation. Perhaps, inconsistent with this explanation is the declining weight of adults.

We will not conclude anything from the above discussion. The main purpose of this example is to demonstrate how data for different time periods can reveal long-term trends and raise interesting questions. The above discussion also points to the need for more data about for instance the quality of summer pastures and the size of predator populations and possibly the number of animals they kill each year.

By varying the assumptions made in the upper right-hand corner, one can find the sensitivity to these assumptions. For instance if the meat price is set equal to 1.0 and the costs per animal is set equal to zero, we find the equilibrium meat production curve. Such a test suggests that maximum meat production occurs when the herd size is just below 60 000 animals, when using data for the first period (1981 to 1990). The maximum meat production is 430 tons per year. Thus whether one is searching for maximum meat production or maximum profits, the decision-tool suggest nearly the same herd size, between 50 000 and 60 000.

Similarly, the estimate of the maximising herd size is not very sensitive to changes in the desired fraction of females or the desired lifetime of livestock, 30 per cent changes in these parameters move the maximising herd size by less than 5000 animals.

Comparing our analysis of summer pastures to the earlier analysis of winter lichen pastures in West-Finnmark, it seems that in the long run summer pastures represent the limiting resource. The maximising herd size seems to be below 60 000 reindeer, while the maximum equilibrium herd size based on lichen pastures is nearly 80 000 animals. Thus if summer pastures had been allowed to determine the herd size historically, the current situation of overgrazed lichen would probably not have occurred. For the medium term future, the estimate of 80 000 reindeer may be too high if parts of the lichen pastures have been more or less permanently damaged. In the short run, with overgrazed lichen, lichen pastures represent the limiting resource.

SNÆFELL

Next we turn to the case of Snæfell in Iceland where we have data for the period 1991 to 2000. Data on losses is lacking and losses are set equal to zero. The number of animals was 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 per cent which is representative of historical data. The desired 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 West-Finnmark.

Fig. 15 shows that equilibrium profits seem to 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 is 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.

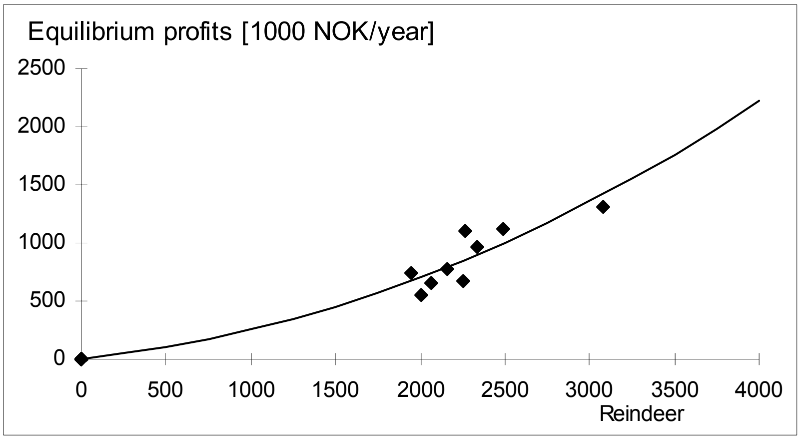

Fig. 15. Snæfell equilibrium profits, 1991 to 2000.

However, even with this goal in mind, it seems from the profit curve as if the herd size could be increased. There are two main reasons for this that can be explored by the decision-tool. First, if we set the price equal to 1.0 and costs equal to zero, the meat production curve shows the same upward tendency. And since meat production is strongly related to the condition of the animals it seems safe to increase the number of reindeer. Second, the upward tendency is not very sensitive to the herd structure data. In particular the female fraction could be reduced to have more bucks. While these tests demonstrate the capabilities of the decision-tool, the conclusions must be taken with a grain of salt. We lack data on losses, implying that the upward tendency of the curve could be overestimated, and we have not considered the adequacy of the winter pastures.

PAISTUNTURI

Finally we turn to the case of Paistunturi in Finland where we have data for the period 1990 to 1997. During this period the herd was reduced from around 9700 before 1991 to around 7700 after 1993. We use a meat price of NOK 50/kg, a cost of NOK 100/animal/year, 90 per cent females and 10 years lifetime of livestock. Fig. 16 shows the equilibrium profits.

In this case there are very few data and the spread is large. This implies that one should be very careful in concluding about the profit maximising herd size. The curve produced by the decision-tool suggests that profits will increase with an increasing herd size. However, when judging this curve you must look at the data. If they suggest uncertainty about the slope of the curve; than the curve should be considered unreliable.

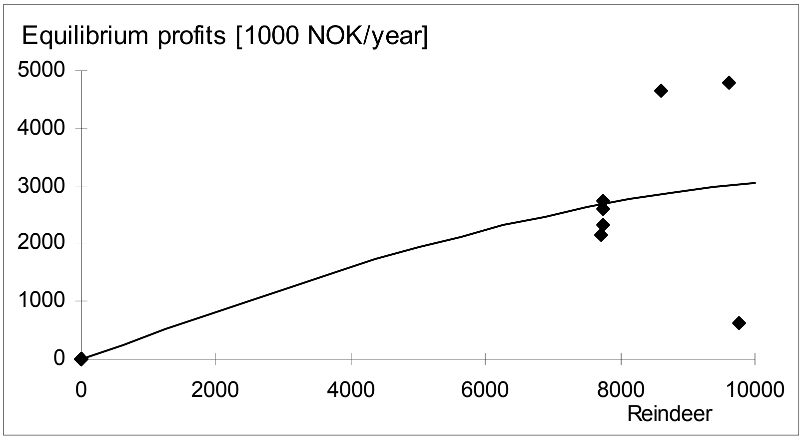

Fig. 16. Paistunturi equilibrium profits, 1990 to 1997.

There are however ways to reduce uncertainty. One way is to correct for variations in weather conditions, variations that one is fairly confident will have given effects on calving fractions (surviving to the fall), weight growth, and losses. Currently you cannot enter information about weather conditions in the decision-tool. However, you may try to correct your data for weather effects manually. For instance if bad weather during calving one year lead to large losses of calves, you may adjust the number of calves for this year upwards to make the number look more like a normal year.

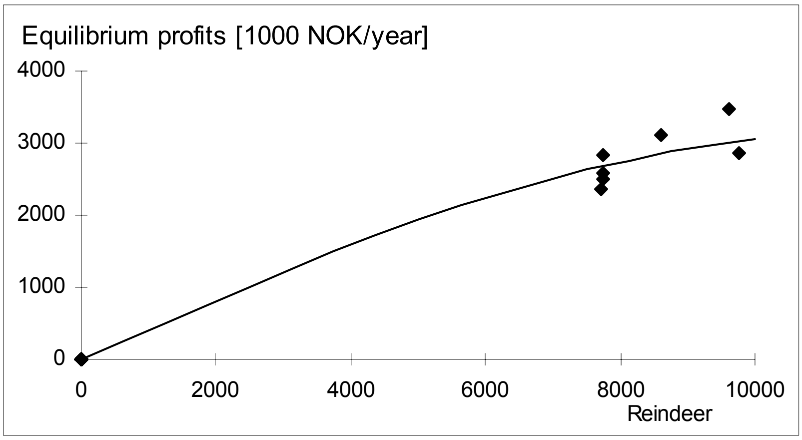

Fig. 17. Paistunturi equilibrium profits, 1990 to 1997, filter on.

A second way to reduce uncertainties is to use the filter in the decision-tool. The filter does not change long-term tendencies in the data. However, large variations from year to year are evened out. The reasoning is as follows. If for instance in a long period with a rather constant herd size and high profits, there is one year with much lower profits than the others, this incidence is likely to have been caused by unfortunate weather conditions, some infrequent disease or some other random factor. It does not seem correct to explain the profits of a particular year by the herd size. By writing “yes” for the filter option, a smoothing over time is carried out automatically. Fig. 17 shows the result. Clearly much of the variation in the data points in Fig. 16 were caused by variations from year to year, and not related to variations in the herd size. Thus, the filtered data gives some support to the idea that larger herd sizes could lead to higher profits. However, still it is important to remember that there are few data points. Small adjustments in the data could easily lead to the different conclusion. Probably the herd size is not too far away from the optimum. Again, winter pastures must also be considered before deciding on the herd size.

Finally, we make a quick comparison of the three cases. To compare we make a rough calculation of the maximum profit per animal at the profit maximising herd size. For both West-Finnmark and Paistunturi we get approximately NOK 300 per animal. For Snæfell the corresponding estimate is only slightly higher if we assume that the maximum is at 2500 animals. It is somewhat reassuring that the estimates are not widely apart.

4. THE SIMULATOR

In order to practise with the decision-tool, one version of the tool is equipped with a simulator. This simulator produces data from year to year, and each new year the data are automatically transferred to the decision-tool. Thus each new year you get new raw data to help you improve the calibration of the growth curve for lichen and to help you learn about for what herd size profits (or meat production) are likely to be maximised. The decision-tool and the attached simulator are shown in Fig. 18. First, we summarise quickly how to use the decision-tool, and then we explain how to use the simulator.

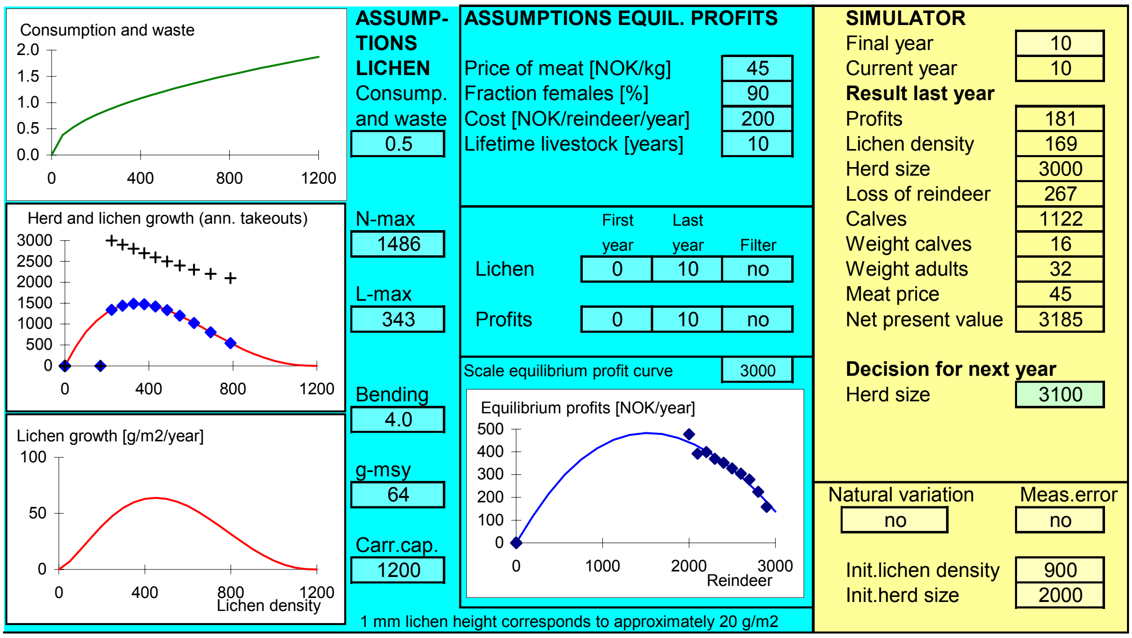

Fig. 18. Decision-tool with simulator.

4.1. A quick summary of how to use the decision-tool

Normally, when using the decision-tool, the data are entered in the sheet called DATA. Using the simulator this happens automatically. Thus the DATA sheet is only for inspection of the time-series data produced by the simulator. Do not try to enter your own data when using the decision-tool with the simulator. From the data in the DATA sheet you may select the data you want to use in the decision-tool.

First year denotes the first year from which you want to use data

Last year denotes the last year from which you want to use data

You can select different periods of data to analyse to lichen growth and to analyse profits. In both cases you may choose to filter the data over time. This removes short-term variations, most likely caused by random and not lasting changes in climate, while the long-term variations remain intact.

Filter is activated by writing *yes* and deactivated by writing *no*. Filtering does not by itself influence any of the curves shown in the figures of the decision-tool.

WINTER PASTURE (LICHEN GROWTH)

N-max and *L-max* are the two key parameters to manipulate in order to get an estimate of the lichen growth curve measured in yearly reindeer winter takeouts, see the middle curve on the left-hand side. These two parameters determine the location of the peak of the curve. If you only have a few data points, and/or if these points are of low quality, you should focus on adjusting *N-max* and *L-max* and keep the other parameters constant. Either use the parameter values suggested in the decision-tool or use information from other sources.

Consump. and waste influences the relationship between the size of a yearly reindeer takeout and the lichen density. The higher the density, the more lichen the reindeer eat and the more they waste. The upper left-hand side graph shows the direct effect of this parameter.

Bending influences the width of the lichen growth curve.

g-msy determines the peak of the lichen growth curve measured in grams dry matter per square meter, that is the peak of the curve shown in the graph in the lower left-hand side corner.

Carr.cap. determines the carrying capacity for lichen. This is the lichen density for which the net lichen growth equals zero. At this point the lichen is so dense that as much rots from the bottom as what grows at the top.

SUMMER PASTURE (PROFITS)

The data points and the suggested equilibrium profits curve show up automatically once data are entered and a suitable time-period is selected. To see the equilibrium profit curve correctly you have to specify

End point profit curve ensures that the profit curve is drawn through and beyond all the data points. Thus, a typical value is somewhat higher than the highest observed herd size.

Then there are four parameters you can choose freely to see how they influence the location of the equilibrium profits curve.

Price of meat is simply the price of meat measured in NOK per kg slaughter weight.

Fraction females is the desired percentage of females in the livestock.

Cost is the operating costs measured in NOK/animal/year.

Lifetime livestock is the desired average lifetime of livestock measured in years.

These four parameters are typically used to investigate sensitivity. By setting *Price of meat* equal to 1.0 and *Cost* equal to zero, the profit curve represents meat production.

4.2. How to use the simulator

When the simulator is initialised, it chooses some parameters itself. These parameters are not revealed to you. Thus each time you use the simulator, it is as if you deal with a new reindeer district for which you have limited data. This way you are forced to learn insights that are useful in general. You will not only learn about the specifics of one single district. Before you start using the simulator you also have to make certain choices.

Final year denotes the year when the simulation is over. When this year is reached, the true parameters used in the simulator are revealed to you. They appear below the parameters you have suggested when calibrating the lichen growth curve to the data points.

Init. lichen density denotes the lichen density in year zero, when you start the simulator. Thus you can choose to manage for example a virgin district or a district that has been overgrazed.

Init. herd size is the herd size in year zero. By choosing a small herd size, it will take time before you have a much larger herd since the growth in the herd size depends on yearly recruitment. If you start out with a very large herd size, it can be quickly reduced by slaughtering. You are not allowed to buy reindeer from other districts.

Natural variation is activated by writing *yes* and deactivated by writing *no*. Natural variation means that both winter and summer pastures vary randomly from year to year and that the herd size varies randomly from year to year. The variations are supposed to be of the same type that has been observed in real reindeer districts.

Meas. error is activated by writing *yes* and deactivated by writing *no*. Measurement error means that yearly assessments of lichen density vary from year to year. This complicates your calibration of the lichen growth curve. The same types of error are also likely in reality. In addition, in reality, measurements of lichen density are typically not as frequent as every year. However, since lichen density is not likely to change much from one year to the next anyway, this difference is not very important.

Initialise is a button you should click on with the mouse when you have finished setting the initial parameters for the simulator. This activates a program that clears all the data and that gives you information about the initial year. (Fig. 18 shows data for the tenth and last year for the case used in Section 2).

Herd size is your choice of next year's herd size in the simulator. When you have decided on this number you click on the button *New Year*.

New Year activates the simulator and makes it simulate one year ahead. You will see that the data under the heading "Result last year" update, and you are ready for a new decision. However, first you should make use the decision-tool.

First you should calibrate the lichen growth curve in the decision-tool. Next you should consider the equilibrium profits curve. Having information about the adequacy of summer and winter pastures you have four main choices:

1a. You may move towards the herd size that maximises you profits by looking at the profits curve you have established thus far, given that this does not lead to a depletion of lichen.

1b. If the lichen growth curve you have established thus far suggests that lichen is the limiting resource, you may move in the direction of the lichen density which yields the maximum growth of lichen measured in yearly winter takeouts.

2a. You may change the herd size in order to get a better estimate of the profits curve. This typically implies that you change the herd towards a range where you have little data thus far. This could be a range in which you expect profits to increase; however, it could also be in a range where you are highly uncertain about the profits. These attempts to learn must be seen in light of the adequacy of lichen.

2b. You may change the herd size to get a better estimate of the lichen growth curve. This requires that you change the herd size to actively bring the lichen density into a range where you currently have little data. Recall from Section 2 that an increase in the density requires that grazing is brought below the growth rate, and vice versa.

Also recall from the Snøhetta case in Section 2 that in reality an exploration of the range with low lichen densities may cause long-lasting damage to parts of the winter pasture. This is not captured by the simulator! Thus be more sceptical to drastic reductions in lichen density than what a combined use of the simulator and the decision-tool suggests.

Finally note that the simulator and the decision-tool are not designed to find out if reindeer can do well without lichen during the winter. Using the simulator, you will see that the herd survives for many years after lichen has been depleted, however, eventually it will die out due to low calving fractions and high loss rates. This may not be the case in real pastures, if the digestibility and availability of alternative winter fodder is adequate. Our recommendation in this case is to perform small scale experiments in enclosed areas where lichen is already depleted or is allowed to be depleted. If the longer-term outcome of the small scale experiment is promising, then it seems more appropriate to follow the same policy for a larger area. If a policy of lichen depletion fails, studies show that it may take fifty and even hundred years before lichen is restored. Using the simulator, it takes around 50 years to build the lichen density from 3 to 150 g/m^2, when there is no reindeer present. In reality this number will probably vary quite a lot from area to area.