Chapter 12
What Drives the Number of Semi-domesticated Reindeer? Pasture Dynamics and Economic Incentives in Fennoscandian Reindeer Husbandry

Antti-Juhani Pekkarinen, Jouko Kumpula, and Olli Tahvonen

Abstract All Nordic countries regulate the maximum number of reindeer. However, long-term grazing pressure by reindeer together with the effects of forestry and other land uses raise concern regarding the possible overgrazing of the important winter lichen pastures. Understanding the dynamics between pastures and the reindeer population is imperative for determining the size of sustainable reindeer populations. Governmental regulation and subsidy systems additionally create economic incentives and set restrictions on reindeer management. Current herd sizes are, thus, based on both biological and economic factors. In this chapter, we provide an economic-ecological model of a reindeer herding system that can be used to analyze how the various forces drive reindeer numbers. We first show how ecological and economic factors affect model results. We then use Finland as an example to demonstrate how bioeconomic analysis can be used as a tool for understanding the reindeer herding system. Finally, we discuss how current restrictions on the maximum number of reindeer relate to economically and ecologically sustainable model solutions.

Keywords Economic-ecological model · Optimal harvesting · Overgrazing · Natural resource management · Herbivore-plant interactions

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12.1 Introduction

The reindeer (*Rangifer tarandus* L.) is one of the key species in the Arctic and subarctic. Reindeer herding is also an important income source for local people in these regions and an intrinsic part of the Sami culture in Fennoscandia (Forbes et al. 2006). However, long-term grazing pressure by reindeer together with the effects of forestry and other land use practices have led to a significant reduction and fragmentation of the most important natural ground and arboreal lichen pastures used in winter (Väre et al. 1996; Kumpula et al. 2009). Several reasons have been given for the loss, deterioration, and fragmentation of reindeer pastures (Kumpula et al. 2014; Sandström et al. 2016). However, questions concerning the sustainable size of reindeer populations and the possible overgrazing of ground lichen pastures have been at the center of this debate. The impact caused by reindeer numbers on pastures have therefore formed the main concern during the most recent decades (Kitti et al. 2006). In this chapter, we present an economic-ecological analysis of the drivers that affect reindeer numbers in Fennoscandian herding. We conclude with a case study estimating the current situation in Finland, where maximum reindeer numbers for the next 10-year period are decided by the Ministry of Agriculture and Forestry.

The existence of adequate winter pastures is critical for reindeer numbers in most parts of the Fennoscandian reindeer herding area (Pape and Löffler 2012). Lichen pastures, in particular, are essential for the productivity of the reindeer population in many areas. Thus, reindeer population and lichen pastures form a dynamic system, where reindeer numbers affect lichen biomass and lichen growth conditions and lichen pasture availabilities affect the number of reindeer that winter pastures can support. During recent decades, high reindeer numbers along with changes in lichen growth conditions have raised serious concerns about possible overgrazing of lichen pastures (Forbes et al. 2006).

National governments regulate reindeer numbers because of concern that reindeer herders operating under no restrictions may let reindeer populations levels rise too high. Ensuring pasture productivity and preventing overgrazing are the main reason for this regulation. As an example, according to Finnish law, the Ministry of Agriculture and Forestry has to evaluate and determine the maximum reindeer number for each reindeer herding cooperative during each 10-year period. This is done so that reindeer grazing does not exceed the sustainable production capacity of winter pastures (Finlex 1990). Thus, in addition to being of scientific interest, a clear understanding of the ecological dynamics between winter pastures and reindeer population is also necessary for policymakers, as they determine what will be reasonable sizes of reindeer populations in various areas within the country.

From the perspectives of the reindeer herding industry and many local people, the desired herd size and its economically sensible management should not be based solely on biological factors. They emphasize that social and economic factors should also be considered (Kitti et al. 2006). Also important in determining correct reindeer numbers are the impacts of forestry and other land use practices (Kumpula et al. 2014). Governmental regulation and the establishment of subsidy systems for herders may also influence reindeer numbers by producing economic incentives and setting certain management restrictions. Thus, we must consider all aspects of the reindeer husbandry system when determining what are sustainable and economically optimal herd sizes.

Reindeer husbandry within in Fennoscandia is a complex system of economic, ecological, and cultural interactions (Pape and Löffler 2012; Pekkarinen et al. 2018). The ecological importance of reindeer is evident in Arctic and sub-arctic areas, where reindeer are a keystone species and reindeer grazing shapes many plant communities. Indeed, nearly 40% of the total Fennoscandian land area is used as reindeer pasture (Pape and Löffler 2012). The importance of the reindeer for the northernmost cultures and economies is also undeniable. Reindeer herding forms a cornerstone of the Sami culture (Forbes et al. 2006). Furthermore, Sami culture is of special importance to the European Union (EU), as it is the only indigenous culture recognized within the EU as a whole and within the national constitutions of specific member states (Finlex 1990; European Union 2005). Sami culture and reindeer herding economics are tied together, and as noted in the EU constitution: "Traditional Sami culture depends on primary economic activities, such as reindeer husbandry" (European Union 2005).

Reindeer herding is also greatly affected by other forms of land use in the Arctic. This has caused disputes between reindeer herders and other land users. Major disagreements, especially between foresters and reindeer herders, have been ongoing within Finland for decades (Jokinen 2019). However, the effects of forestry are typically not considered when decisions are made concerning maximum reindeer numbers. Although the final decision on this is, ultimately, a political question, this decision should be based on the best available understanding of the reindeer herding system and its needs. For this, we need a solid scientific understanding of all aspects of this complex system, together with useful practitioner knowledge. The interdisciplinary research approach carried out within the ReiGN project enables us to integrate perspectives from both the natural and social sciences. In addition, the wide network of people within the NCoE provides multiple opportunities for contact with both herders and policymakers. This helps us as researchers to produce practically relevant research and take part in ongoing policy discussions regarding reindeer husbandry in the Nordic region.

12.1.1 Understanding the Reindeer Herding System

The reindeer herding system is an economic, ecological, and cultural system. However, most research on reindeer herding has focused mainly on the biology and ecology of reindeer (Pape and Löffler 2012). In their review article, Pape and Löffler (2012) concluded that reindeer research needs to include more interdisciplinary approaches. This need for interdisciplinary system analysis is not limited to the reindeer herding system. According to Gordon et al. (2004), the future management of all wild large herbivores, in general, will require ecologists to cooperate with sociologists, economists, politicians, and the general public. ReiGN aims to contribute to interdisciplinary reindeer research by bringing scientist from various fields together and by cooperating with herders and policymakers.

Within the broad interdisciplinary framework of ReiGN, Work Package 5 aims, in particular, to develop mathematical system models that seek to combine economic and ecological knowledge of reindeer husbandry. Mathematical system models are an apt method for describing and analyzing complex system dynamics. Among others, Schmolke et al. (2010) concluded that they should be used more widely in the future for informing and supporting public policy decision-making. As such, it can be suggested that interdisciplinary mathematical system models may also prove valuable for studying the sustainable management of the reindeer husbandry system.

12.1.2 Model Development

Gaare and Skogland (1980) proposed one of the first system models for the reindeer-lichen system. They developed a simple reindeer-lichen population model that also accounted for lichen wastage caused by trampling. Danell and Petersson (1994) also constructed a detailed model of the reindeer herding system but did not include within it either pasture dynamics or the economics of reindeer husbandry. The first system model for the Fennoscandia reindeer-lichen system, that aimed at including both the ecological and economic dimensions of reindeer herding, was a two state-variable bioeconomic reindeer-lichen model provided by Virtala (1992). Moxnes et al. (2001) utilized a similar approach in their model and included a description of energy intake from various energy resources. They also included summer pastures and lichen wastage but no description of the population structure within their model. Coming a bit later, both Skonhoft et al. (2017) and Johannesen et al. (2019) developed a stage-structured reindeer population model to study the effects of predation. They found that predation may improve the economic output of reindeer herders in an unmanaged setting. However, the model only includes three stage classes (calves, adult males, and adult females) and no mating function or resource dynamics.

None of these models, however, described the reindeer population in necessary detail or took into account all the relevant ecological, economic, and management aspects required to describe the reindeer herding system as a whole. These deficiencies in modeling had to be addressed by others. Pekkarinen (2018) showed that the inclusion of pasture dynamics, the age and sex structure of a reindeer population, and the economic optimization framework are highly important features required for a model to be able to properly describe economically rational and sustainable reindeer herding. In Tahvonen et al. (2014) and Pekkarinen et al. (2015, 2017), we aimed to overcome the shortcomings of previous models by presenting an age- and sex-structured bioeconomic model of a reindeer-pasture system. In this essay, we aim to show how this complex interdisciplinary model may be used as a tool for understanding the current situation within Finnish reindeer husbandry.

12.1.3 Aims of This Chapter: System Analysis with a Bioeconomic Model

In order to understand the current situation in reindeer husbandry and its prospects for sustainable development, we must account for economic factors in addition to ecological knowledge (Pape and Löffler 2012; Pekkarinen et al. 2018). Bioeconomic system models are an apt way to describe the complex economic-ecological interactions (Getz and Haight 1989). In this chapter, we use such bioeconomic modeling analyses to study the operation of various mechanisms and drivers in the reindeer herding system and how they direct economically sensible reindeer numbers in various situations. We use the economic-ecological model of the reindeer herding system first presented in Tahvonen et al. (2014) and Pekkarinen et al. (2015). It describes an age- and sex-structured reindeer population, the growth and consumption of lichen, and the economics of reindeer herding. The model includes the various natural winter energy resources of reindeer and incorporates supplementary feeding along with the effects of a seasonal pasture rotation system and government subsidies. Within the model we first examine how various ecological and economic factors affect economically sustainable solutions and reindeer numbers. We then use reindeer herding in Finland as an example to show how such bioeconomic analysis can be used as a tool to understand various reindeer herding systems and sustainable reindeer numbers in different areas of the country. Finally, in light of our research findings, we discuss what might be the maximum number of reindeer within different Finnish reindeer herding areas.

12.2 Models and Methods

12.2.1 A Bioeconomic Model of a Reindeer Herding System

The ecological-economic reindeer-lichen model we use in our research combines three widely utilized perspectives (age-structure, predator-prey dynamics, and bioeconomics) into an interdisciplinary description of the reindeer herding system. The ecological component of the model is based on a description of the development of the age- and sex-structured features of the reindeer population. Age-structured matrix models (Caswell 2001) have been used in ecology for decades, as models describing populations only as a biomass do not include the internal structure of the population or time delays associated in reproduction and other life history events. The description of the internal age and sex structure is especially important when studying the management of reindeer or other long-lived polygamous species (Gordon et al. 2004; Gerber and White 2014; Pekkarinen 2018).

The reindeer population model we utilize includes 17 female and 13 male age classes and a detailed description of winter energy resource utilization by the reindeer population. In the model, winter mortality increases as the winter weight of the reindeer decreases. The weight decrease of reindeer depends on energy intake during winter. This is determined by the availabilities of ground lichens, arboreal lichens, other cratered food resources (dwarf shrubs, mosses, and graminoids), and supplementary food. The number of calves born and their weights depend on the weight decrease of adult females during winter. In addition, the mating success during the previous autumn affects the number of calves born. Mating success is specified by a modified harmonic mean mating system (Bessa-Gomes et al. 2010), which gives the fraction of females mated as a function of population age and sex structure.

Additionally, our ecological model is rooted in analysis of predator-prey systems and plant-herbivore systems in our particular case. These systems are commonly studied using mathematical system models based on coupled difference or differential equations (Begon et al. 2005). These equations describe how predators affect prey populations (in our case lichen) and how prey density affects predator populations (in our case reindeer). We use this approach to study a reindeer-lichen system where reindeer population dynamics depend on winter food resources, mainly ground lichens (Kumpula 2001), and where the reindeer population is the main factor affecting lichen biomass (Kumpula et al. 2014). Within this model, reindeer population density is endogenously affected by lichen biomass. Thus, the model may be used for studying economically reasonable lichen biomass in addition to the optimal management of reindeer populations. This feature is necessary for studying how many reindeer current pasture conditions can support and what economically rational restrictions may exist for reindeer population size.

In addition to lichen, the model describes the use of other food resources by reindeer. The description of the diet choice between different energy resources (arboreal lichens, ground lichens, other cratered food, and supplementary food) follows the principles of the optimal foraging theory (e.g. Stephens 1986). See Pekkarinen et al. 2015 for a detailed description of energy intake and population models.

The model also describes the seasonal pasture rotation system used in many parts of the reindeer herding area in Fennoscandia. When a seasonal pasture rotation system is used, reindeer consume winter lichen pastures only during the winter season. However, without pasture rotation, lichen is also consumed during the spring, summer, and autumn. In the model, lichen growth depends on the areas of lichen-dominated habitat types and their lichen biomass after winter and spring consumption. Arboreal lichen consumption is affected by the availability of natural old-growth coniferous forests and their arboreal lichen biomass per hectare.

To account for the total lichen reduction coming from grazing reindeer, the model we have used also includes lichen wastage by reindeer in addition to what is ingested and converted to energy. Pekkarinen et al. (2017) estimated two wastage functions (constant and linear). By incorporating either one of these functions, the model is able to describe measured changes in lichen biomass with a high degree of accuracy. Of these two estimated wastage functions, we used the constant wastage function in this study, as it is simpler and reduces the computing time.

The economic component of our model follows the approach presented in the seminal book by Colin Clark (1976), entitled *Mathematical Bioeconomics: The*

Optimal Management of Renewable Resources. It describes bioeconomics as a study of the economically optimal utilization (also including other values besides monetary income) of biological resources. Bioeconomic models solved by dynamic optimization are at the center of bioeconomic research. Development of an economic model often begins by defining the resource user/owner and his/hers objective. In our case, we assume that a reindeer herding district is the decision maker concerning activities relating to reindeer herding in the district area. However, this is not always the case, as for example, maximum reindeer numbers in Finland are decided by the Ministry of Agriculture and Forestry despite being defined at a district level.

Thus, we assume that a reindeer herding district makes the slaughter and feeding decisions and aims to maximize the present value of net revenues as suggested in the following equation:

$$\max_{\left\{b_t, h^i_{s,t}, s=0,\ldots n_i, i=f,m,t=0,1,\ldots\right\}} \sum_{\infty}^{t=0} \left(R_t - C_t\right)^{\alpha} \left(\frac{1}{1+r}\right)^t .$$

In this equation, decision variables are the number of animals chosen for slaughter ($h^i_{s,t}$) from the age (s) and sex (i) classes and the quantity of supplementary food given (b_t). R_t are the annual revenues from slaughtering, r is the annual interest rate, and C_t the total annual costs for year t. Total costs include constant and variable management costs, slaughtering costs, and feeding costs.

For our basic analysis of economically optimal reindeer husbandry, we used the costs and prices for years 2015–2016. For our case study examining the current situation of reindeer herding in Finland, we define costs, prices, pasture conditions, lichen biomasses, and reindeer numbers from new data developed for years 2015–2018 in conjunction with the ReiGN project. See Tahvonen et al. (2014) and Pekkarinen et al. (2015) for the complete description of the optimization procedure. All optimizations are computed using the AMPL programing language and Knitro (versions 7.0.0 and 10.3) optimization software (Byrd et al. 2006). The optimization codes are available as a supplementary data for Tahvonen et al. (2014) and Pekkarinen et al. (2015), on the website of the Economic-Ecological Optimization Group (www.helsinki.fi/en/researchgroups/economic-ecological-optimization-group/codes), and upon request.

12.3 Results and Discussion

12.3.1 Dynamic Solutions and Steady States

Lichen pastures are the most important winter energy resource for reindeer in many areas of Fennoscandia. The long-term balance between reindeer numbers and pastures may be studied by analyzing the steady states in the reindeer-lichen system model. However, Tahvonen et al. (2014) and Pekkarinen et al. (2015) showed that without harvesting by humans, predation, or significant alternative energy resources a reindeer-lichen system does not seem to stabilize. This result is based on dynamic model solutions, but it has also been empirically observed on predator-free islands when reindeer were introduced (Klein 1968).

However, although natural stable steady states are not typically found in reindeer-lichen systems, human influence often leads to a more stable situation. Thus, our analysis of economically optimal steady states considerably increases our understanding of the reindeer husbandry system. However, in addition to steady-state analysis, dynamic model solutions are needed for solving transitions from various initial states to these steady states. This is especially important in a reindeer herding system, where the transitions to a steady state may take a long time because of the slow recovery of lichen pastures and the fairly long-life span of reindeer. Figure 12.1, below, helps to explain the meaning of the initial state (= initial biomass of lichen and size and structure of the reindeer population), steady state (= long-term stable biomass of lichen and size and structure of the reindeer population), and the dynamic transition to the steady state from the initial state. Dynamic solutions are also necessary because it is not possible to compute optimal steady-state solutions with a positive interest rate without solving the transition to a steady state. Thus, to fully understand the reindeer herding system with bioeconomic model analysis, we need to study both steady states and dynamic transition solutions.

In Fig. 12.1 the initial states of the system are chosen so that they represent high and low reindeer densities as well as high and low lichen biomasses. The dynamic solutions show the economically optimal transitions from these four initial states to the two optimal steady states. Steady State 1 represents an economically sustainable state where it is optimal to base reindeer population management on natural pastures. In this given example, a 0% interest rate, the use of a pasture rotation system, and a high abundance of old forests with high-quality lichen pastures are all factors causing this steady state to produce the highest possible net revenues over a long-time horizon. In solutions leading to Steady State 2, the interest rate is 5%, no system of pasture rotation is used, and lichen pastures are located in lower-productivity commercial young forests. Using supplementary feeding as a main energy resource for reindeer and letting lichen biomass fall to a very low level is optimal under these conditions. The reindeer numbers in Steady State 2 are also much lower than in Steady State 1 because lichen pasture productivity is also lower.

It should be noted, however, that both the optimal slaughtering strategy and population structure of the herds are similar in both steady states. Tahvonen et al. (2014) has showed that it is economically beneficial to rely on intensive calf slaughtering and on a minimum number of adult males needed for efficient reproduction. Therefore, more than 60% of female calves and more than 95% of male calves are slaughtered during their first autumn. Many adult females are kept alive until 9.5 years of age while remaining adult males live only until they are 5.5 years old. The number of adult males is kept as low as possible without significantly lowering the fertilization rate of females and the reproduction rate of the population.

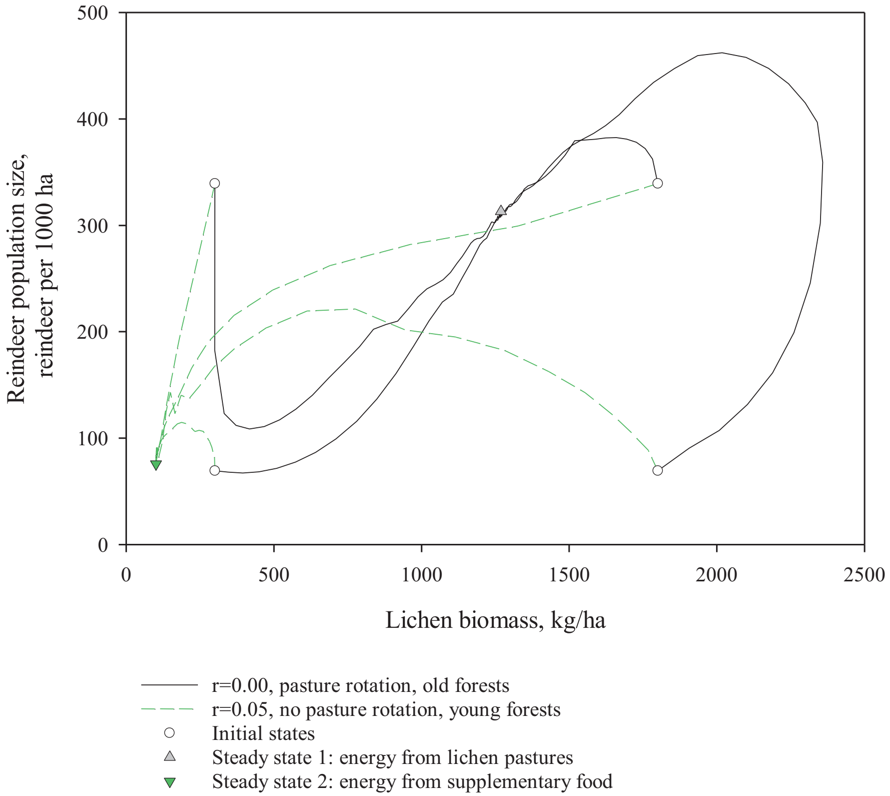

Fig. 12.1 Examples of economically optimal dynamic solutions and steady states in different situations. Eight dynamic solutions from four initial states that lead to two steady states are shown. Solid black lines represent solutions leading to steady state 1, where reindeer herding is based on natural pastures. In these solutions interest rate is 0%, a pasture rotation system is used, and the abundance of old forests with good lichen pastures is high. Dashed green lines represent solutions leading to steady state 2, where reindeer herding is based on intensive supplementary feeding. In these solutions the interest rate is 5%, no pasture rotation system is used, and lichen pastures are located in young forests

With this in mind, it should be noted that although the steady-state solutions of this study are presented in terms of total reindeer population sizes, it is necessary to understand that the internal herd structure and slaughtering strategy in these steady states correspond with the structure presented above. This herd structure and slaughtering strategy are also very close to the ones used in practice by contemporary herders in Finland (Tahvonen et al. 2014).

12.3.2 Economically Optimal Steady-State Solutions in Various Situations

The results presented in Fig. 12.1, above, clearly demonstrates that we need to consider ecological, economic, and management factors when seeking to specify economically rational reindeer numbers and lichen biomass in various situations. The steady-state solutions provided in Table 12.1, below, show that higher interest rates, the use of pasture rotation, the existence of large area of old-growth pine forests, and governmental subsidies all contribute increasing the economically optimal reindeer population size. Usually, with similar pasture conditions, a higher reindeer population size implies lower lichen biomass. Thus, it is suggested that lichen biomass declines when interest rates are higher or when governmental subsidies are paid for each reindeer kept alive within the herd. However, the use of pasture rotation and the high availability of old pine forests also increases the production capacity of the system. Thus, the steady-state lichen biomass increases in those cases in spite of the fact that reindeer populations may also increase.

Both Table 12.1 and Fig. 12.1 suggest the two main optimal steady-state operating regimes. In the first regime, reindeer herding is based on natural pastures and in the second on using intensive supplementary feeding. When the optimal solution is based on intensive supplementary feeding the lichen biomass falls to a very low level. However, reindeer still gain energy from other crater food resources and from arboreal lichens if available. The factors promoting the use of supplementary feeding are high interest rate, governmental subsidies, lack of pasture rotation, and lower growth rate of ground lichens.

Table 12.1 Economically optimal steady-state solutions under various economic and ecological conditions

		No subsidies			**Reindeer subsidy** *(28.5€)*		
Forest age	**Pasture rotation**	1 %	3 %	5 %	1 %	3 %	5 %
Old	Yes	**311** / *1051*	**321** / *801*	**341** / *703*	**346** / *924*	**352** / *691*	**409** / *100**
	No	**88** / *860*	**119** / *102**	**119** / *102**	**93** / *808*	**126** / *100**	**126** / *100**
Young	Yes	**192** / *914*	**206** / *688*	**248** / *101**	**209** / *757*	**250** / *101**	**252** / *100**
	No	**52** / *858*	**72** / *151**	**72** / *101**	**73** / *102**	**74** / *102**	**74** / *101**

Number of reindeer (per 1000 ha lichen pastures) / *Lichen biomass* (kg per ha)
* Supplementary food used as a main energy resource, lichen biomass very low

The shaded shells represent the solutions where supplementary food is used in optimal steady state as a main energy resource for reindeer during winter. Lichen pastures are their main energy resource in other solutions. The first number (in **bold**) gives the number of reindeer in a steady state (per 1000 ha of lichen pasture) and the second (*italicized*) gives the corresponding lichen biomass. The percentages indicate different interest rates (1%, 3%, 5%)

Number of reindeer (per 1000 ha lichen pastures)/*Lichen biomass* (kg per ha)
*Supplementary food used as a main energy resource; lichen biomass very low

12.3.3 Qualitative Analysis of Current Drivers and Economic Incentives in Finnish Reindeer Herding

With this discussion as background, we next aim to understand the sources of present reindeer numbers in Finland by studying the current drivers and economic incentives. In the section above we showed that economically rational reindeer numbers are driven by ecological, economic, and management factors of the system. In Table 12.2, below, we show how these drivers have changed within the Finnish reindeer herding system over time.

Here in Table 12.2 we considered how both ecological and economic changes have affected the rational size of reindeer populations, lichen biomass, net revenues, and supplementary feeding. The information shown in Table 12.2 is based on bioeconomic model solutions presented by Pekkarinen et al. (2015) except for the effects of predation mortality (Pekkarinen et al. ahead-of-print) and stochastic winter conditions (Pekkarinen et al. submitted).

From Table 12.2 it is clear that the pasture conditions in the Finnish reindeer herding area have clearly changed over recent decades. The areas of natural

Table 12.2 Drivers in Finnish Reindeer Husbandry over Recent Decades

	Reindeer numbers	Lichen biomass	Net revenues	Supplementary feeding
Changes in pasture conditions				
Decreasing area of old pine forests	–	–	–	+
Decreasing area of old spruce forests	–	+[a]	–	–[a]
Increasing stochastic variation in winter conditions	?	?	–	+
Increasing predation mortality	+[b]	–	–	?
Changes in mangement and economics				
Increasing management costs	–	+	–	–
Increasing meat price	+	–	+	+
Decreasing costs of supplementary feeding	+	–	+	+
Increasing governmental subsidies	+	–	+	+
Increasing use of pasture rotation system	+	+	+	–

+ driver increases the target variable
– driver decreases the target variable
? unsure direction or not studied
[a]effect during transition phase may be opposite to steady-state effect
[b]number of reindeer left alive after slaughtering increases, but the number of reindeer before slaughtering decreases
A plus sign indicates that the driver in question increases the optimal steady-state value of the given variable and a negative sign indicates a decrease in the optimal steady-state value

old-growth pine and spruce forests have decreased in number (Kumpula et al. 2014) over the same period, and the stochastic variation in winter conditions has increased (Turunen et al. 2016). The number of reindeer killed by large predators has also increased during the last decades (Kumpula et al. 2017).

Looking at our findings, it appears that all of these changes have negatively affected the net revenues gained from reindeer herding. These changes have also reduced the size of the economically sustainable reindeer population. Increasing predation pressures reduce the number of reindeer before the autumn slaughter. However, according to our solutions (Pekkarinen et al. ahead-of-print), a larger winter herd size is needed to compensate for the high predation occurring throughout the year.

Changes in pasture conditions from previous decades have also affected the economically optimal lichen biomass and the use of supplementary feeding. Decreasing the area of natural old pine forests clearly reduces the economically optimal lichen biomass and favors the use of supplementary feeding in both long-term (steady state) and short-term (transition to steady state) scenarios. However, decreasing the area of old spruce forests has an opposite effect in the long term. A decrease in the area of old spruce forests increases the economically optimal steady-state lichen biomass, as arboreal lichens are no longer available as an additional energy resource. This increase in ground lichen biomass then makes supplementary feeding more unprofitable. However, in the short term, a decreasing area of spruce forests increases the need of supplementary feeding until a new stable situation is reached.

Changes have also occurred in the economics and management of reindeer husbandry during past several decades. Costs of operation have increased but so has also the price of reindeer meat. Certain forest-dominated districts in northernmost Finland have adopted a seasonal pasture rotation system. Other changes in the system include a reduction in supplementary feeding costs due to subsidies paid to farmers. The Finnish government also now pays subsidies for reindeer herding according to the number of reindeer left alive after autumn slaughtering. According to our analysis, most of these changes in the management and economy of reindeer husbandry have been favorable to reindeer herding and have increased the net revenues and herd sizes. However, the increasing management and slaughtering costs have had the opposite effect, decreasing the optimal herd size and net revenues. Many of the changes both in reindeer herding economics and pasture conditions have also favored an increase use of supplementary feeding of the reindeer.

12.3.4 Case Study of the Maximum Number of Reindeer in Finland

Finally, in our analysis we considered the current numbers of Finnish reindeer within specific herding area and how they relate to our economically sustainable model solutions. Such analysis was made to provide background information for the

Finnish Ministry of Agriculture and Forestry, as it decides the maximum numbers of reindeer for the next 10-year period from 2021 to 2030. This type of work clearly demonstrates the policy relevance of the work conducted at the ReiGN NCoE. It produces and uses high-level scientific research to communicate matters of relevance to the public, policymakers, and the herders. While this work provides some practical policy recommendations, our main aim is to understand and show how various aspects of this complex bioeconomic system are linked together and how they affect the outcomes of different selected actions.

With this in mind, we studied how close the current reindeer numbers and lichen biomasses within various parts of Finnish Lapland were to the economically optimal model solutions discussed above. Our first step was to divide the 54 Finnish reindeer herding districts into four groups representing the average features of each district. One of the groups reflected conditions found in mountainous districts, while the other three represented forest districts with different availabilities of lichen and arboreal lichen pastures. The division of the 54 Finnish reindeer herding districts into four "average districts" is presented in Fig. 12.2 below.

After engaging in this classification effort, we moved on to consider the specific features of these districts. Table 12.3, below, provides the average values for current pasture conditions and maximum reindeer numbers within these four "average districts".

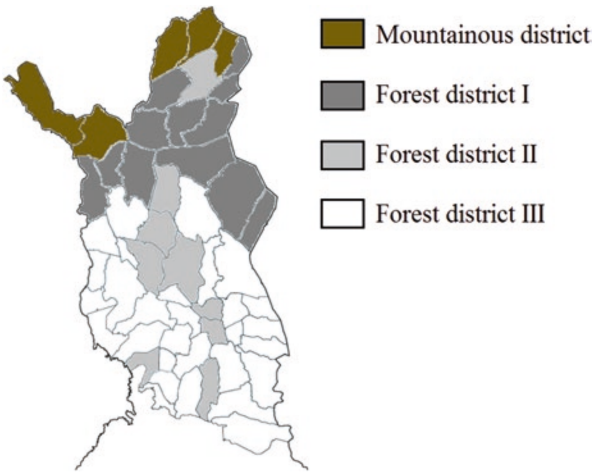

Fig. 12.2 The 54 Finnish reindeer herding districts divided into four groups with each representing the average main aspects of their pasture conditions. Mountainous districts have at least 45% of pastures located in mountainous vegetation types. Forest district I represents districts where ground and arboreal lichen pastures are largest and most productive due to large conservation areas. Forest district II represents districts where average ground lichen and arboreal lichen pasture availability and productivity is moderate, and Forest district III represents districts where the availability and productivity of these pastures is lowest. The age and size structure of the forests and forest pasture quality has been greatly affected by forestry in the two last districts

Table 12.3 Average values for current pasture conditions and maximum reindeer numbers in different "average districts"

	Mountainous	Forest I	Forest II	Forest III
The average land area of herding districts, km^2	3005	2789	2124	1979
Total area of lichen pastures, km^2	1200	643	277	101
lichen pastures in old/mature pine forests, km^2	72	276	77	26
lichen pastures in other forest areas, km^2	744	315	194	74
lichen pastures in mountainous areas, km^2	384	51	6	1
[a]Area of arboreal lichen pastures, km^2	66	471	177	104
Lichen biomass, kg/ha	153	169	100	<100
Arboreal lichen availability, kg/ha	6	12	9	9
Maximum number of reindeer allowed	6700	5892	3822	2325

[a]Includes only those old/mature coniferous forests where the availability of arboreal lichens was estimated to be sufficient (6 kg/ha or more on average). We assumed that sufficient arboreal lichen availabilities were in 50% (Mountainous and Forest I), 40% (Forest II) and 30% (Forest III) of old/mature coniferous forests

Total land areas and pasture areas were obtained from the classification of satellite images, while lichen biomasses for the 20 northernmost herding districts were obtained from field measurements made during 2016–2018 (Kumpula et al. 2019). The lichen biomasses have not been measured for the southern herding districts, but according to general observations they are clearly lower than in the northern districts. Arboreal lichen availability is assumed to be highest in herding districts where the area of old coniferous forests is highest.

In our study we determined that Mountainous Districts are those where at least 45% of pastures are located in mountainous vegetation types. The area of lichen pastures is high (28–57%) relative to total land area in all of the districts belonging to this group. Most lichen pastures in mountainous districts are located in dry mountain birch forest areas or on mountain heaths. The effects of forestry are very small in these districts, as coniferous forest areas are low. Only five districts in the Finnish reindeer herding area were classified as mountainous.

In our study, all other 49 districts are classified as forest-dominated and are called Forest Districts in this analysis. These districts are divided into three groups according to ground and arboreal lichen pasture availabilities. Forest District I represent those areas where ground and arboreal lichen pastures are largest and most productive on average. Mature/old-growth forests cover more than 20% of the total land area in these districts and ground lichen pastures cover more than 15%. On average, lichen pastures cover 23% of the total land area in these districts and old/mature coniferous forests cover 33%. The ground lichen and arboreal lichen pasture areas overlap significantly, as the best ground lichen pastures are located in old or mature pine forest.

Forest District II represents districts with moderate quantities and productivity of lichen pastures and Forest District III represents districts with low quantities and productivity. Forestry has considerably changed the age structure and quality of ground and arboreal lichen pastures in these two districts. In the following analysis, we mainly focus on Forest District I, but we also discuss results from the other "average districts". The available data are most sufficient for Forest District I, and the model was also originally developed for describing this area. In addition, this area is also of special interest because all the districts are located in an area specifically reserved for reindeer herding. Finnish law therefore dictates that state lands in the area should not be used in a manner that may significantly hinder reindeer herding (Finlex 1990).

We additionally estimated the meat price and average costs of reindeer herding based on the data from the Reindeer Herder's Association from years 2015–2016. We used 10€/kg for meat price, while the estimated variable management costs were 39.5€ per reindeer, slaughtering costs 16.7€ per slaughtered reindeer, and feeding costs 0.5€ per kg of supplementary food delivered to the pastures. Fixed management costs were estimated separately for each "average district", as the number of reindeer per land area differs significantly between the districts. The estimated fixed costs per ha of land area were 2.2€, 1.4€, 1.3€, and 0.9€ for the Mountain district, Forest District I, Forest District II, and Forest District III, respectively.

12.3.5 Steady-State Analysis of Current Maximum Numbers of Reindeer

According to Tahvonen et al. (2014), the maximum quantity of lichen in the climax stage (carrying capacity) is ca. 6400 kg/ha and highest annual production is achieved when lichen quantities reach approximately 2400 kg/ha. Table 12.3, above, shows that the current lichen biomasses found in pastures under year-round grazing conditions are very low on average in all parts of the Finnish reindeer herding area. It also shows that reindeer numbers relative to total the land area are clearly higher in northern parts of the Finnish reindeer herding area (Mountainous District, Forest District I) than in southern districts (Forest Districts II and III). However, the number of reindeer relative to the area of lichen pastures is lower in northern districts. Still, without an economic-ecological analysis it is unclear whether or not reindeer numbers and lichen biomasses are close to economically sustainable levels in different parts of the reindeer herding area.

Our proposed model solutions in Fig. 12.3, below, show that current maximum reindeer numbers in northern districts (Fig. 12.3, Table 12.3) are close to economically sustainable solutions. With a 3% interest rate, the model steady-state solutions proposed for a reindeer population are ca. 7000 for the Mountainous District and 6000 for Forest District I. However, economically sensible reindeer numbers are only ca. 2400 and 1000 for Forest Districts II and III, respectively. Thus, according to our steady-state analysis the current maximum numbers of reindeer in the southern districts of Finland (Table 12.3) are clearly higher than the economically sustainable solutions. However, we must note that due to corral feeding, the reindeer

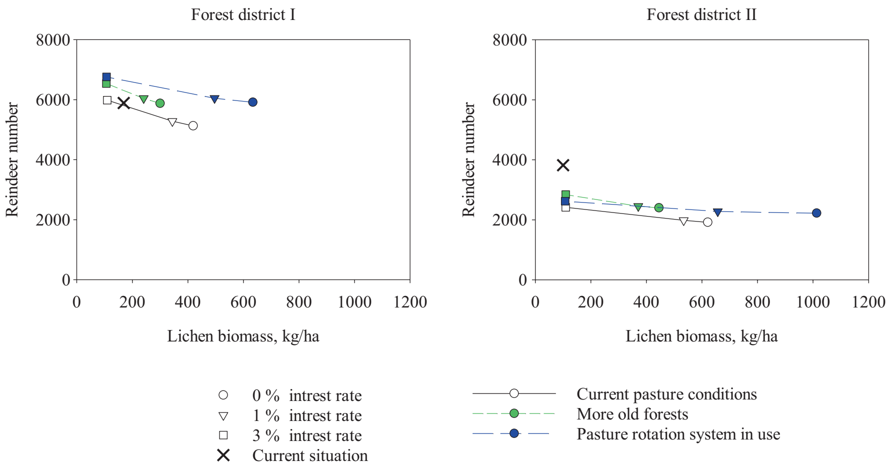

Fig. 12.3 Economically optimal steady-state solutions for average Forest districts I and II with three interest rates (0%, 1%, 3%). Symbols on the solid black line represent solutions with current pasture conditions without pasture rotation. Solutions on the green dashed line are computed with higher old forest availability (50% of the area of young and clear-cut forests is assumed to be old forest). Solutions on the blue dotted line are computed assuming seasonal pasture rotation (30% of all lichen pastures used only during the winter season). Additionally, the figure shows the current average lichen biomass and maximum number of reindeer in these districts

are no longer kept on natural pastures in many of the southern districts for the entire wintertime. The economic profitability of such a feeding system cannot be fully studied with our model, as the model is based on the assumption that natural pastures always form a significant winter energy resource.

Figure 12.3, above, shows the economically sustainable steady-state reindeer numbers and lichen biomasses for Forest Districts I and II. Additionally, it shows the current average lichen biomass and maximum number of reindeer in these districts.

The symbols on the black solid line of Fig. 12.3 show the economically optimal steady-state solutions with 0%, 1%, and 3% interest rates, with current pasture conditions, and without pasture rotation. Even in this situation, current maximum reindeer numbers can be seen to be close to model solutions in Forest District I. Figure 12.3 also shows that if old-growth forest availability were higher, or if a pasture rotation system were used, the current maximum number of reindeer would actually be lower than the economically optimal population size. In contrast, neither increasing old forest area nor using pasture rotation would alone improve natural pasture conditions in Forest District II enough to support the current maximum numbers of reindeer in an economically sustainable way. Thus, most areas in Forest Districts II and III have to rely on very intensive supplementary feeding.

Finnish law states that the maximum number of reindeer should be based on pasture capacity. Thus, it is imperative to understand the differences between the northern and southern parts of the Finnish reindeer herding area. Current reindeer numbers in the southern districts are based on supplementary feeding, not on natural pastures. However, the situation is the opposite in northern districts, despite these areas also using feeding during difficult winter conditions. Next, we continue exploring the relation between the reindeer population size and pasture capacity also outside steady states.

12.3.6 Dynamic Analysis of Various Options for Increasing Lichen Biomass

The steady-state analysis provided in Fig. 12.3 showed that the current number of reindeer and lichen biomass existing in Forest District I are close to an economically sustainable steady-state situation. In addition, our analysis suggest that the current lichen biomass could be increased either by reducing the number of reindeer, increasing the area of old-growth forests, or by using a pasture rotation system. However, dynamic solutions are needed to study how long it would take for lichen to recover from current grazing pressure.

Figure 12.4, below, shows simulation solutions of how different management actions affect lichen biomass and the need for supplementary feeding in Forest District I. It suggests that decreasing the maximum number of reindeer by 10% (from 5892 to 5303) has a similar effect to increasing the area of old growth forests. Although expanding the area of old-growth forests would take a long time to accomplish, the results suggest that forestry practices clearly has affected the grazing potential of winter pastures even in the northernmost forest districts of Finland. Thus, if half of the areas of current young forests and logging areas had remained old-growth forests, the current maximum number of reindeer would have enabled a clearly higher lichen biomass than we currently see.

Figure 12.4 also shows that developing the pasture rotation system may be the most efficient way in many areas to increase lichen biomass even without decreasing the maximum number of reindeer. In that case, it would be economically beneficial to keep using supplementary feeding for almost 30 years, despite most of the energy coming from natural pastures.

12.4 Conclusions

12.4.1 Using Detailed Bioeconomic Models in Natural Resource Management in the Arctic

Bioeconomic models have been widely used in fisheries and forestry to study sustainable management and to inform policymakers (Clark 1976; Getz and Haight 1989). Earlier studies (Pape and Löffler 2012) and reports from reindeer herders

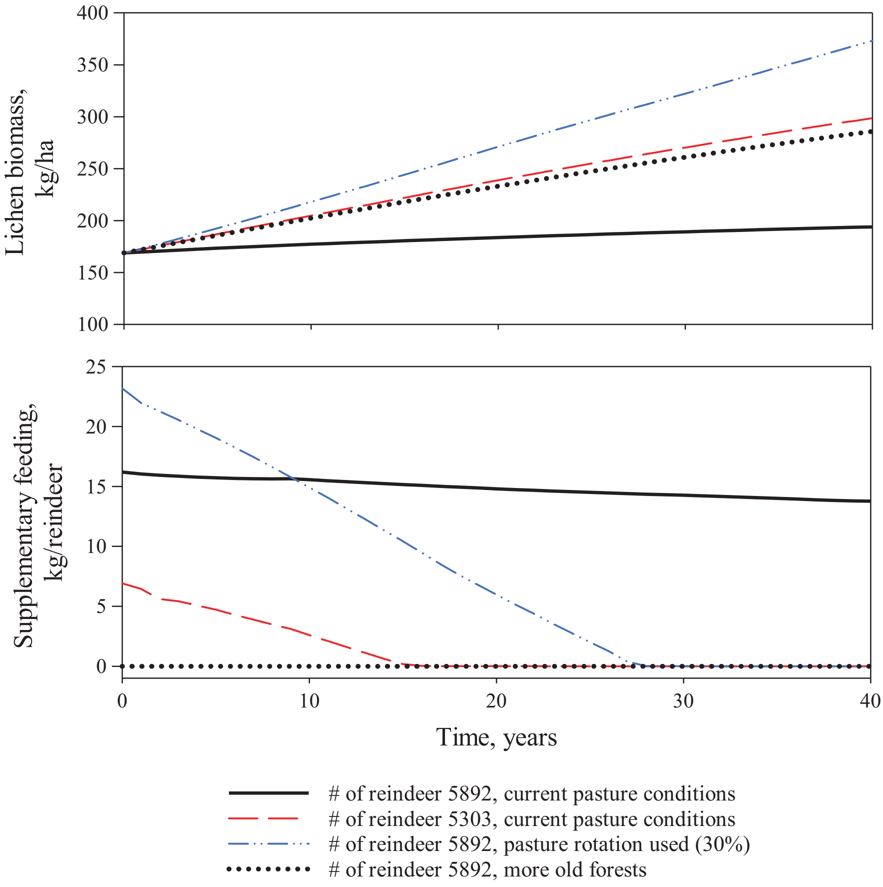

Fig. 12.4 The effect of management strategies on lichen pastures and supplementary feeding. Management strategies presented for the next 40 years for the herding districts in northernmost Lapland with high availability of lichen and arboreal lichen pastures (Forest I district). The solid black line represents a simulation with current pasture conditions and reindeer numbers and without pasture rotation. The red dashed line is computed with a lower reindeer density and with current pasture conditions. The solution with a blue dash/dotted line is computed with a higher availability of old forests (50% of the area of young or clear-cut forests is assumed to be old forest). The solution with a black dotted line is computed assuming that a seasonal pasture rotation is used (30% of the lichen pastures used only during the winter season)

themselves (Kitti et al. 2006) have suggested the need for interdisciplinary analyses of the reindeer herding system and sustainable sizes of reindeer populations. Thus, ReiGN researchers have focused on an interdisciplinary and comparative research approach that aims to identify key drivers and their effects on this pastoral system. Understanding current herd size and structure, slaughtering strategies, and time delays inherent in the population dynamics of long-living mammals needs an approach that includes the age and sex structure of the ungulate population within the modeling efforts. Indeed, previous research has shown that the management of large ungulates should be tailored to the age and sex structure of the population (Gordon et al. 2004) and that previous population models have underestimated the importance of including details of the mating system and male reproduction rates (Gerber and White 2014). As a part of an interdisciplinary NCoE, Work Package 5 in ReiGN has focused on the economic-ecological analysis of the reindeer herding system using a detailed dynamic age- and sex-structured model.

All previous economic-ecological models of reindeer herding tend to describe the reindeer population only by a single-stage variable (biomass or total number of individuals) or by an oversimplified stage structure. Also, none of the previous reindeer models include a description of the polygamous mating system of reindeer. However, it is not only the reindeer population that should be considered as a central resource in the Arctic reindeer herding system. The availability and quality of pastures are equally important. The study presented in this chapter is the most detailed bioeconomic model analysis of the economically sustainable management of the reindeer population or any other similar herbivore. This study combines the age and sex structure of the reindeer population, different winter energy resources, and the economics of a sustainable reindeer herding livelihood into one modeling approach describing the optimal management of a reindeer population. The model solutions of this study further underline the importance of an interdisciplinary approach to research. They show that sustainable population sizes cannot be evaluated solely from either ecological or economic perspectives. Indeed, economically rational solutions differ greatly according to the ecological, economic, and management conditions encountered.

12.4.2 Sustainable Numbers of Reindeer in Finland

In addition to conducting high-level interdisciplinary research, ReiGN also aims to have an impact on Arctic communities by producing tangible results and useful knowledge. In Work Package 5, we have used and further developed our bioeconomic model so that we may analyze the sustainable use of natural pastures and economically rational reindeer numbers within northern areas. We have extended this analysis to provide background information for the Finnish Ministry of Agriculture and Forestry as they determine the maximum numbers of reindeer for the 2021–2030 period.

We have shown that the long-term changes in the quantity and quality of pastures in Finland have reduced the productivity and grazing capacity of pastures. This has been seen to negatively affect the economics of reindeer herding.

Reindeer herding has adapted, in the past, to many of these unfavorable changes by developing new management strategies including pasture rotation, calf slaughtering, and supplementary feeding. Also, it has been shown that the development of certain economic conditions have been beneficial for the profitability of the reindeer herding. However, it has also been shown that pasture conditions, economic circumstances, and the impacts of these drivers can vary greatly between the herding districts and areas. Our study attempts to show that despite negative developments in pasture conditions, current maximum reindeer numbers in the northernmost districts of Finland are now close to economically sustainable levels. At the same time, however, our study suggests that present natural winter pastures cannot support current reindeer levels in the southern parts of the Finnish reindeer herding area over the long term due to many unfavorable changes occurring there within the pasture environment. Many of these districts have therefore had to resort to intensive supplementary feeding for decades.

Current Finnish law maintains that state-owned land should not be used in a manner that may significantly hinder reindeer herding in a specific area. Furthermore, Finnish law states that reindeer numbers should not exceed the sustainable production capacity of winter pastures. However, the research results that we have discussed in this essay imply that significant changes arising from current forestry practices have already decreased the grazing capacity of winter pastures and affected the reindeer herding economy.

As a result of these and other land use practices within reindeer herding area, the grazing capacity of pastures is likely to decrease even more in the future. If this should be the case, then adapting reindeer numbers according to reduced winter pasture resources may lead to a situation where reindeer herding may no longer be feasible. This would be an alarming and problematic situation, as reindeer herding represents a traditional livelihood in the Arctic area and is seen an intrinsic part of the indigenous Sami culture. Therefore, we suggest that future management plans for reindeer pastures should not only address consequences of the herding system, but also consider the results of other land-use practices in the northern and Arctic areas. As we have seen in our research these are interactive with one another and must be dealt with in a holistic and comprehensive manner.

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