11 Bioeconomics of reindeer husbandry in Fennoscandia

Antti-Juhani Pekkarinen, Jouko Kumpula, Øystein Holand, Birgitta Åhman and Olli Tahvonen

Introduction

Most studies in reindeer husbandry research have concentrated on the biology or ecology of reindeer (Pape & Löffler 2012). Understanding of the economics of reindeer husbandry and economically optimal pasture use has been lacking. Interdisciplinary analysis of reindeer husbandry requires a clear understanding of reindeer ecology, pasture use and its economics. Indeed, reindeer husbandry systems should be studied as a whole (Pape & Löffler 2012). In these systems, ecology and economics are in constant dynamic interaction. An appropriate way to analyse the dynamics of these interactions is the use of mathematical system models and bioeconomic analysis (Schmolke et al. 2010; Pekkarinen 2018).

Bioeconomics is the study of economically optimal utilization (including other values besides monetary income) of biological resources. Bioeconomic models solved by dynamic optimization are at the centre of bioeconomic research (Clark 1976). Interdisciplinary bioeconomic models include a description of the ecology and economics of the studied system. The level of detail required from the model depends on the system being studied as well as on the questions asked. Simple models are easier to analyse and are, therefore, valuable for educational purposes and for analysing the basic driving forces of system dynamics. Among other things, they have been used for analysing hypothesized "tragedy of the commons" situations in Fennoscandian reindeer husbandry and thus showing how unmanaged use of the common pasture resources could affect the reindeer husbandry system (Johannesen & Skonhoft 2009; Skonhoft et al. 2017).

However, in this chapter our focus is on studying the optimal utilization of reindeer populations and their pastures in Fennoscandia. To achieve this, we concentrate on models that aim to describe the main properties of the real reindeer husbandry systems in detail. Thus, to study the slaughtering and feeding decisions made by herders, we need models that can describe the age and sex structure of the population, diet choice and the use of natural food resources and supplementary feeding.

One of the key aspects determining the productivity of a reindeer husbandry system is how reindeer herds utilize their pastures (Pape & Löffler 2012).

DOI: 10.4324/9781003118565-16

Winter lichen pastures are considered to be the limiting factor for the growth rate and productivity of most reindeer populations (Kumpula 2001b). Thus, to analyse sustainable lichen biomass levels with bioeconomic model of reindeer husbandry, lichen dynamics must be included. Including lichen dynamics also makes it possible to estimate whether or not lichen pastures are currently overgrazed, i.e., is there enough lichen on pastures to fulfil the nutritional needs of reindeer during winter. In addition, the recovery from overgrazed pastures can be studied using dynamic reindeer–lichen models.

The first bioeconomic model for the Scandinavian reindeer–lichen system was a model with two state variables, produced by Virtala (1992). Moxnes et al. (2001) adopted a similar approach in their model and included a detailed description of energy intake from various natural energy resources. They included summer pastures and lichen wastage but no description of population structure. Skonhoft et al. (2017) and Johannessen et al. (2019) specified a stage-structured reindeer population model to study the effects of predation. However, their model does not include pasture resource dynamics or sufficient description of the age structure of the reindeer population which would enable the analysis of optimal slaughter strategies.

Reindeer as well as their pastures can be viewed as biological resources affecting economic profitability. Thus, both should be included in any detailed bioeconomic analysis of Fennoscandian reindeer husbandry system. In addition, an age- and sex-structured modelling framework provides insights into optimal herd structure and slaughter strategy, which cannot be fully studied with biomass models or with simplified stage structure. None of the models mentioned above includes all these features. Thus, in this chapter we utilize an age- and sex-structured reindeer-pasture model created by Tahvonen et al. (2014) and Pekkarinen et al. (2015), to analyse sustainable herding practices and pasture use under various economic and ecological conditions.

Reindeer herding practices (e.g., slaughter strategy, use of pastures, supplementary feeding) vary between and within Fennoscandian countries. These differences in herding practices are often adaptations to local conditions. Economic–ecological analysis sheds light on the reasons behind different management decisions under varying conditions. In this chapter, we analyse how variations in economic and ecological conditions affect economically sustainable reindeer husbandry. We consider economically sustainable adaptations and herding practices as well as economically optimal solutions under different conditions. We generate economically optimal model solutions to analyse optimal reindeer numbers, lichen biomass, feeding strategies, structure of the reindeer population, slaughter strategy and the effects of different subsidy systems.

We begin by defining three hypothetical reindeer herding districts that represent herding conditions from mountainous areas with migratory pasture rotation systems to forested areas with stationary herding systems. These three hypothetical herding districts represent the typical variation in conditions between and within Fennoscandian countries. We then generate economically optimal model solutions using the parameter values for each of the three hypothetical districts and demonstrate how costs, prices, interest rate (the marginal rate of return from alternative investments, e.g., other natural resources or stock markets) and government subsidies affect economically sustainable reindeer husbandry. We study which slaughter strategies, lichen biomass levels, feeding strategies and reindeer population sizes give the highest net revenues over the long term under varying economic and ecological conditions. We also ask how different subsidy systems used in Fennoscandian reindeer husbandry direct economically sustainable reindeer husbandry. Finally, we discuss and compare economic incentives, winter pasture conditions and impacts of government subsidies in Nordic countries in the light of our model analysis.

Bioeconomic reindeer husbandry model

In this chapter, we utilize a bioeconomic reindeer husbandry model presented in Tahvonen et al. (2014) and Pekkarinen et al. (2015). The model includes four sub-models: population, energy intake, lichen and economic. General descriptions of each are presented in the following sections, but for complete mathematical descriptions and optimization codes, see the original publications.

Population sub-model

The reindeer population sub-model includes 17 female and 13 male age classes and a description of the population dynamics. The number of reindeer in age class s, in sex class i, in a year t is denoted by $x_{s,t}^{i}$, $s = 0,1,\ldots,n_i, i = f,m,t = -1,0,1,\ldots$, where f and m denote males and females, respectively. The model year starts immediately after the autumn slaughter, at the beginning of the winter period. The population structure evolves according to:

$$x_{1,t+1}^{i} = \left(1 - m_0^i\right)u_i x_{0,t} - h_{0,t}^{i}, i = f,m,t = 0,1,\ldots$$

$$x_{s+1,t+1}^{i} = \left[1 - m_s^i\left(wd_t\right)\right]x_{s,t}^{i} - h_{s,t}^{i}, s = 1,2,\ldots,n_i, i = f,m,t = 0,1,\ldots$$

where m_0^i is the summer mortality of calves and $h_{s,t}^{i}$, $s = 0,1,\ldots,$ $i = f,m,t = 0,1,\ldots$ denotes the number of reindeer harvested from age and sex classes at the end of the period. The share of calves (age class 0) belonging to sex class i is denoted by u_i, $i = f, m$.

Reproduction is specified by a modified harmonic mean mating system (Bessa-Gomes et al. 2010) which accounts for the polygynous features of reindeer reproduction. The number of calves born during spring in year t is given as:

$$x_0 = \sum_{s=1}^{n_f} \beta_{t-1} f_s\left(wd_t\right)\left[1 - m_s^f\left(wd_t\right)\right]x_{s,t}^{f}, \quad t = 0,1,\ldots,$$

where β_{t-1} gives the fraction of females mated at the end of period *t-1* and $f_s\left(wd_t\right)$ is the average number of calves per female in age class s. Winter mortalities are denoted by $m_s^i\left(wd_t\right)$. Winter food availability and the associated energy intake in relation to energy need during winter define an individual's weight change during winter (wd_t) and its effects on mortality and reproduction (Tahvonen et al. 2014). Thus, low energy intake decreases spring weight, which in turn reduces the number of calves born and calf birth weight. In addition, significant weight loss during winter increases mortality. The weight change during winter is a function of average daily energy intake during winter, which is calculated by the energy intake sub-model.

Energy intake sub-model

The energy intake sub-model defines the daily energy intake and diet choice during winter (Pekkarinen et al. 2015). The diet choice between arboreal lichens, ground lichens and other resources excavated from beneath the snow (dwarf shrubs, mosses and graminoids) and supplementary feed follows the principles of the optimal foraging theory (e.g., Stephens & Krebs 1986). Thus, reindeer are assumed to choose the combination of energy resources that gives the highest energy intake relative to the time taken for foraging. In addition, reindeer living on natural pastures are assumed to have a preference for natural food resources over supplementary feed (Danell et al. 1994). The amount of supplementary feed given (kg/ha) is decided by the herders and is thus a control (optimized) variable. Arboreal lichen availability and consumption are affected by the availability of old forests and their arboreal lichen biomass.

Lichen sub-model

The lichen sub-model describes the growth and consumption of ground lichens. Lichen biomass (kg/ha) in year t (at the beginning of winter period) is denoted by z_t and lichen growth during summer by $G\left(z_t - l_t^{wi} - l_t^{sp}\right)$. The development of lichen biomass is given as:

$$z_{t+1} = z_t - l_t^{wi} - l_t^{sp} - l_t^{su} + G\left(z_t - l_t^{wi} - l_t^{sp}\right) - l_t^{au}, \quad t = 0,1,\ldots,$$

where l_t^e, $t = 0,1,\ldots, e = wi, sp, su, au$ denote the consumption of lichen (kg/ha) during season e and wi, sp, su and au denote winter, spring, summer and autumn seasons. The total lichen consumption during the different seasons depends on the age- and sex class-specific energy requirements and daily energy intake from lichen. Daily energy intake from lichen is specified in the energy intake sub-model and depends on the relative availabilities of all energy resources and on the size and structure of the reindeer population. To account for the total reduction in lichen caused by grazing reindeer, the model also includes the wastage of lichen by reindeer, in addition to what is ingested and converted to energy. This wastage is mainly the result of trampling and dropping of lichen by reindeer. Pekkarinen et al. (2017) estimated two wastage functions (constant and linear) to describe the situation in northernmost Finland. In this study, we use the constant wastage function as it is simpler and reduces computing time compared to the linear wastage function.

Growth of ground lichens $\left(G\left(z_t - l_t^{wi} - l_t^{sp}\right)\right)$ depends on the lichen biomass after consumption during winter and spring. In addition, lichen pasture type affects lichen growth. Following the formulation presented in Pekkarinen et al. (2015), the annual lichen growth in mountain heaths is 40% of that in old or mature pine forest. Lichen production in young pine forests, logging areas and mountain birch forests is assumed to be 60% of that in old or mature pine forest. The growth function for mature and old pine forests is based on a long-term monitoring study (see more details in Tahvonen et al. 2014). Carrying capacity (undisturbed maximum biomass) of lichen is 6,400 kg/ha. Lichen biomass of 2,300 kg/ha produces the maximum annual lichen growth, which is 142 kg/ha/year in old or mature pine forest.

Economic sub-model

The economic sub-model includes prices, costs and descriptions of subsidy systems analysed. In addition, it describes the objective function and optimization method. In this study, we use Knitro optimization software (version 12.2) and the AMPL programming language (Byrd et al. 2006) for all calculations and optimizations. For economic optimization, we assume that the reindeer herding district maximizes the present value of net revenues, given by:

$$J = \sum_{t=0}^{\infty} \left(R_t - C_t\right)^{\alpha} \left(\frac{1}{1+r}\right)^t,$$

where R_t is the annual revenues from slaughtering and C_t is the total annual costs. Total costs include the constant and variable management cost, slaughter costs and feeding costs. The decision variables are the number of animals chosen for slaughter from the age and sex classes and the quantity of supplementary food given.

The assumption of maximizing net present value for herding districts is a simplification of the complex social, cultural and economic objectives that herders experience in reality. However, these other objectives are often difficult to quantify. In addition, this assumption allows us to study a clearly defined question about how to manage a reindeer herding system in order to obtain the highest possible monetary value over an infinite time horizon. Monetary costs of changes in the herding environment and alternative management actions can then be calculated using this same approach.

Tahvonen et al. (2014) showed that their model solutions converge into an economically optimal steady state or cycle around that steady state depending on the linearity of the objective. The difference in the present values of net revenues between the solutions calculated using a linear ($\alpha = 1$) and non-linear ($0 < \alpha < 1$) objective function is minor. We use the non-linear objective in this study because high fluctuations in annual revenues would be problematic in actual reindeer herding livelihoods. Using a non-linear objective (in this study $\alpha = 0.8$) also means that we assume that herders prefer a steady income flow.

The objective function is maximized subject to the model presented in detail in Pekkarinen et al. (2015) and in the model extensions presented in Pekkarinen et al. (2017). The initial state of the system is given. The optimization codes are available as supplementary material in the original publications (Tahvonen et al. 2014; Pekkarinen et al. 2015), on the website of the Economic-Ecological Optimization Group (www2.helsinki.fi/en/researchgroups/economic-ecological-optimization-group/codes), and upon request.

Economic and ecological conditions within and between Fennoscandian countries

Most of the features and parameters in the model are based on Finnish data from the northernmost forest-dominated herding districts. However, to study how variation between and within Fennoscandian countries affects sustainable reindeer husbandry, we define three hypothetical herding districts (mountainous, mixed and forest herding districts). These districts represent the typical variation in conditions that we are interested in.

Defining mountainous, mixed and forest herding districts

Figure 11.1 illustrates how pastures and movement of reindeer differ between Fennoscandian countries. On average, winter pastures in Norway are more commonly found in open mountainous areas, while in Finland most winter lichen pastures are in forested areas. In most parts of Norway, reindeer migrate between winter and summer pastures. In Finland, it is more common to have a stationary system where reindeer have access to the same pastures throughout

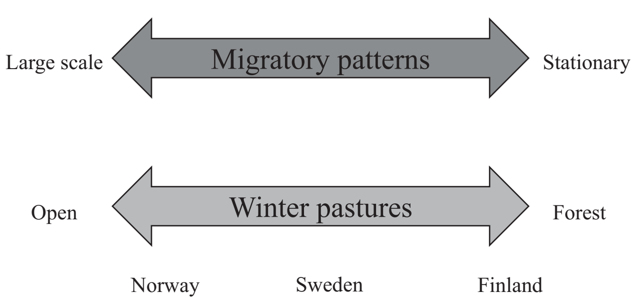

Figure 11.1 Illustration of the differences between reindeer herding in Norway, Sweden and Finland. The figure shows typical features in the countries, but most can also be found within each country.

the year. However, even without pasture rotation, reindeer typically select different pastures during summer and winter. Sweden is located between Norway and Finland both geographically and in terms of typical pasture types and pasture use. Most herding districts in Sweden have large-scale migratory patterns, similar to Norway, and winter pastures in the forest, like in Finland.

In this study, we demonstrate how these different migratory systems and pasture conditions affect economically sustainable reindeer husbandry. We define and parameterize three hypothetical districts to represent typical conditions in mountainous, mixed and forest-dominated districts. We define Mountainous districts, as districts where winter pastures are in open mountainous areas and reindeer migrate between winter and summer pastures. These features are typical in Norway. Forest districts represent districts without pasture rotation and with pastures in forested areas. This is common in Finland but also in some parts of Sweden. Mixed districts are districts where pasture rotation is used, and winter pastures are located in both forested and mountainous areas. Mixed districts include features common in Sweden but also in some areas of Finland.

Although the parameterization of the three districts follows the gradients presented in Figure 11.1, these districts do not directly describe any specific herding district or country. Most of the features of these herding districts can be found in all countries even though they are more common in others. For example, mountainous winter pasture areas are typical in northernmost Norway, but in some of the Finnish districts the majority of winter pastures are also in mountainous areas. Mountainous areas are also typical Sweden, but they are used as summer pastures, and winter pastures are located in forests. In Norway and Sweden, migratory pasture rotation systems are common, but some Finnish districts also have a seasonal pasture rotation system, controlled by means of fences.

Table 11.1 shows the parameter values describing the pasture conditions in these three hypothetical herding districts. The total land area of each district is set to be 3,000 km^2. In the Forest district, the area of lichen pastures available for reindeer during winter is 1,000 km^2. In herding districts with mountainous and mixed lichen pastures, a seasonal pasture rotation is used and the area of lichen pastures available for winter grazing is assumed to be 400 km^2. Winter lichen pastures in mountainous herding districts are in mountain heaths and in mountain birch forests (including other similar vegetation types). Lichen pastures in forest districts are assumed to be in forests at various stages of succession (old, mature, young, logging area). Arboreal lichen pastures are only in old or mature forests.

Lichen pasture type affects lichen growth in the model used in this chapter. The maximum annual lichen growth in old or mature pine forest is 142 kg/ha/year and lower in mountainous pastures and in younger forests. Thus, the maximum annual lichen growth for the three hypothetical herding districts is 71, 92 and 114 kg/ha/year for mountainous, mixed and forest districts, respectively. For optimization, the minimum lichen biomass is restricted to 200 kg/ha. This ensures that optimal solutions lie within the use range of the model. In addition,

Table 11.1 Parameter values describing the pasture conditions in the three hypothetical herding districts

Pasture rotation system	*Mountainous*	*Mixed*	*Forest*
	Seasonal migration	*Seasonal migration*	*No pasture rotation*
Total land area of herding district, km^2	3,000	3,000	3,000
Area of winter lichen pastures, km^2	400	400	1000
• in mountain heaths, %	50	25	
• in mountain birch forests, %	50	25	
• in young forests, %		25	50
• in old forests, %		25	50
Area of arboreal lichen pastures, km^{2}[a]	0	200	1000

Note:
a Includes only those old/mature coniferous forests where the availability of arboreal lichens is considered to be sufficient (6 kg/ha or more on average).

with extremely low lichen biomasses, the associated reindeer density is very high. At very high population densities, other density-dependent factors besides winter food limitation would begin restricting population growth. However, these effects are not included in the bioeconomic model used.

Costs and prices

Pekkarinen et al. (2020a) calculated the unit costs and producer meat prices for the 20 northernmost herding districts in Finland for the years 2015–2016, based on data from the Reindeer Herders' Association. They found that the average annual variable management costs were approximately €40 (per reindeer in the winter population) and the slaughter costs were €22 (per slaughtered reindeer). The fixed management costs were €1.6 (per ha of the total land area used by the reindeer herding cooperative) and the estimated producer meat price was €10 (per kg of meat). In this study, we use these same costs, although costs and prices actually vary between the countries. Keeping the costs and prices constant, we can analyse how different pasture conditions in Fennoscandia affect economically optimal model solutions.

The different pasture conditions are represented by the three hypothetical districts. To study how these pasture conditions alone affect economically optimal solutions, we keep economic parameters the same between the hypothetical districts. However, because costs and prices vary between the years and areas, we also derive the solutions with different costs, meat prices and subsidy systems. We study how changing management costs, slaughter costs, feeding costs and meat price affect model solutions.

Indeed, costs and prices vary between Fennoscandian countries. For example, the producer meat price is lower in Sweden (Sametinget 2020) than in Finland. In contrast, slaughter costs for reindeer herders are small in Sweden since these are mainly covered by the slaughter company. In addition, herding costs vary within and between the countries depending on the characteristic of herding districts. We do not change the level of fixed management cost, as it does not affect economically optimal herding strategies, even though it changes the absolute level of annual net revenues. In this model, fixed costs depend only on the size of herding district and thus remain at a fixed level no matter how the reindeer population is managed.

The costs of supplementary feeding depend on the price of supplementary feed and on the costs of delivering the feed to winter pasture areas. In this study, we use €0.5 per kg as an estimate for the costs of supplementary feeding. The price of commercial supplementary feed accounts for about half of the costs and the other half is for transporting and distributing feed to winter pasture areas. We vary the costs of supplementary feeding to study how lower costs would change slaughter strategies, herding strategies and optimal pasture use.

Subsidy systems in Finland, Sweden and Norway

Government subsidies aim to support local livelihoods, while regulation is used to reduce the possible harmful effects of these livelihoods. The use of natural resources is often strongly regulated and subsidized. In addition to the direct effects, subsidies and regulation also affect the economically optimal ways to manage these natural resources. In this study, we describe different subsidy systems used in Fennoscandian reindeer husbandry and study how they can affect economically rational reindeer management.

All Fennoscandian countries have subsidy systems for reindeer husbandry. The Finnish government subsidizes reindeer herders according to the size of their reindeer herds during winter. Thus, reindeer owners with large enough herds are subsidized by €28.5 per reindeer. In Sweden, a subsidy is paid for meat production. Reindeer herders are paid €1.45 per kilo carcass weight for calves and €0.9 per kilo for reindeer over one year of age. Payment is made for reindeer slaughtered at approved slaughterhouses. The slaughterhouse sends a list of slaughtered reindeer to the Sámi Parliament, which pays the subsidy to the owner of the slaughtered reindeer. The subsidy is paid to all reindeer owners irrespective of the number of live or slaughtered animals.

Norway has combined several subsidy systems with the intention of developing reindeer herding in directions considered favourable in different situations. The system is complex and more than ten different subsidies are paid according to different requirements. They can be divided into three main categories: (1) operating subsidies, mainly covering districts' common administrative costs as well as costs for welfare and social security, (2) production incentives for high productivity and calf slaughter and (3) innovation and infrastructure support. In addition, some subsidies are allocated for compensation and preventive measures. Although, the Norwegian system is more complex than the ones used in Sweden or Finland, it includes similar elements. There are similarities especially with the Swedish system, as many of the subsidies increase with increasing meat production and slaughter rate.

In this study, we analyse the incentives associated with different subsidy systems. We focus on the two main systems used in Scandinavia: meat production subsidy and reindeer subsidy. We define the former as a subsidy paid to herders per kilo of meat produced. This subsidy system is the main one used in Sweden and many of the Norwegian subsidies have similar features. We define reindeer subsidy as a subsidy paid per reindeer in the winter population. A reindeer subsidy system is used in Finland, and some of the Norwegian subsidies have similar elements as they increase with increasing management costs (the logic holds when management costs increase with increasing herd size).

For bioeconomic model calculations, the effects of reindeer subsidy are equal to the lower management costs (€ per reindeer). To study the consequences of this reindeer subsidy system, we decrease the variable management costs in the model by €28.5 per reindeer (the sum paid in Finland). Similarly, the effects of meat production subsidy are equivalent to the meat price being higher (€ per kg of meat produced). To study the effects of meat production subsidy we increase the meat price by €1.6 per kg. This is somewhat higher than the current subsidy level in Sweden. However, with €1.6 per kg, the total sum of subsidies paid in our optimal model solutions is equal to the total subsidies paid if the reindeer subsidy is €28.5 per animal. This way we can compare the incentives created by these systems while keeping the total costs to the government and the total sum of subsidies paid to the herders the same between the subsidy systems.

Results and discussion

Dynamic and steady-state solutions

Dynamic models, like the model used in this chapter, include time as a variable. Such models can be used for studying how systems develop over time, but also what type (if any) of long-term steady states the system can reach. To fully understand a reindeer herding system using bioeconomic analysis, we need to study both steady states and dynamic transition solutions.

Steady-state analysis describes the long-term stability and balance between reindeer numbers and pastures. According to previous model solutions (Tahvonen et al. 2014; Pekkarinen et al. 2015) and empirical observations on isolated islands (Klein 1968), natural stable steady states are typically not found in reindeer–lichen systems without harvesting by humans, predation or significant alternative energy resources. In uncontrolled situations, reindeer numbers tend to increase to a very high level, consuming their lichen resources. Because the low growth rate of lichen cannot compensate for the increased consumption, reindeer populations may crash and possibly even face local extinction (Tahvonen et al. 2014; Pekkarinen et al. 2015). However, human influence and sustainable management may lead to more stable situations. Thus, analysis of economically sustainable long-term steady states considerably increases our understanding of these systems.

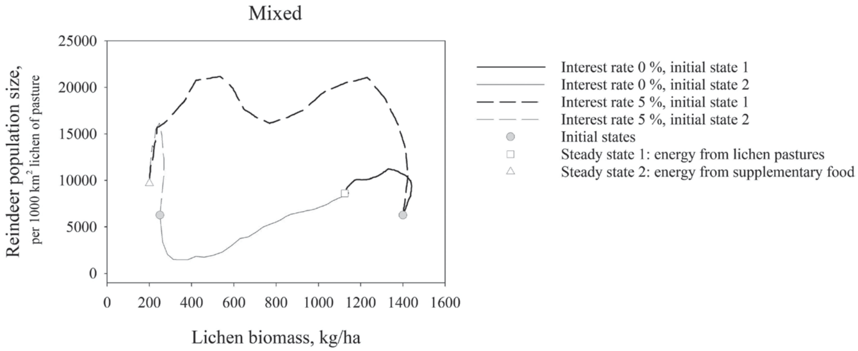

Figure 11.2 Examples of economically optimal dynamic solutions and steady states in different situations. Four dynamic solutions from two initial states that lead to two steady states are shown. Solid lines represent solutions leading to steady state 1, where reindeer herding is based on natural pastures. In these solutions the interest rate is 0%. Dashed 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%.

In addition to steady-state analysis, dynamic solutions are needed for solving transitions from various initial states to these steady states. This is especially important in reindeer herding systems where the transition to a steady state may take a long time because of the slow recovery of lichen pastures and fairly long lifespan of reindeer. In addition, dynamic solutions are necessary for achieving optimal steady-state solutions with a positive interest rate.

Figure 11.2 shows an example of four dynamic transition solutions from two initial states leading to two optimal steady states. These solutions are derived for a mixed herding district (see Table 11.1) using the reindeer–lichen model presented in this chapter. The initial state on the left-hand side represents a situation with low initial lichen biomass. In contrast, the initial state on the right-hand side has a higher lichen biomass. The solutions show economically optimal transitions from these initial states to the two steady states. In steady-state 1, economically optimal management of the reindeer population is based on natural pastures. In this example, it is economically optimal to direct the system towards this state when the interest rate is low (0%). With a high interest rate (5%), the development towards steady-state 2 gives a higher present value of net revenues. In steady-state 2, supplementary feeding is the main energy resource for reindeer and the lichen biomass level is very low.

Optimal slaughter strategies and population structures

Tahvonen et al. (2014) found that in the Finnish reindeer husbandry system, it is economically optimal to rely on intensive calf slaughter and on the minimum effective proportion of adult males. This same applies to the solutions in Figure 11.2, which are calculated using the costs and prices in Finnish reindeer husbandry. Thus, in these solutions, the population structure and slaughter strategy (relative to population size) remain similar, although the population size of reindeer, lichen biomass and the main energy resource of reindeer differ greatly. Figure 11.3 (Slaughter strategy I) shows this steady-state population structure and slaughter strategy. More than 60% of female calves and more than 95% of male calves are slaughtered during their first autumn. Adult females are kept alive until the age of 9.5 years and adult males until the age of 5.5 years. The number of adult males is kept as low as possible without significantly reducing the fertilization rate of females and the reproduction rate of the population.

With current prices and costs, slaughter strategy I (Figure 11.3) becomes optimal. However, lower management costs, lower meat price or high reindeer

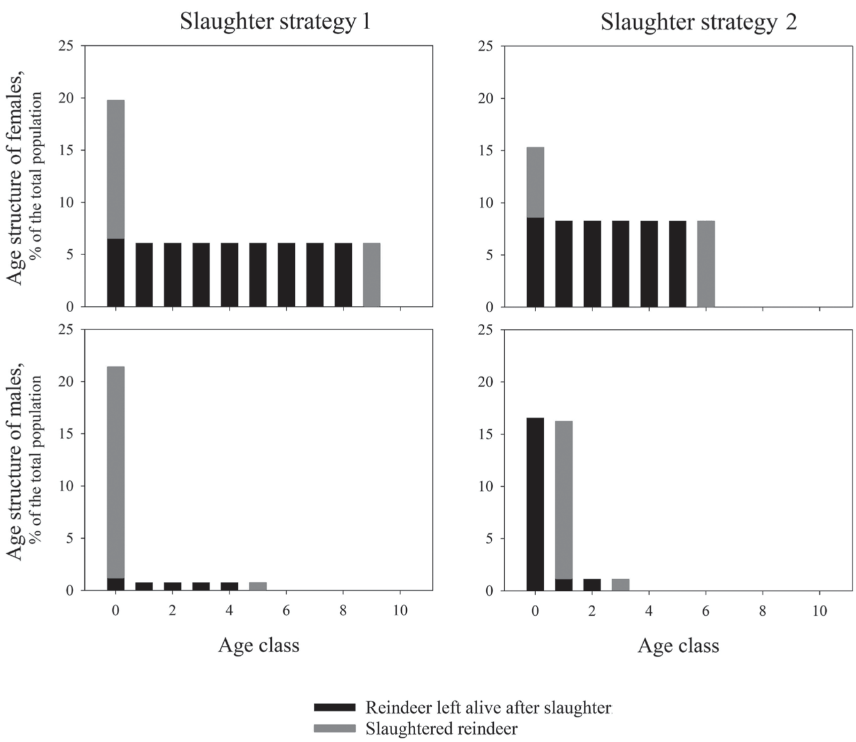

Figure 11.3 Optimal steady-state age and sex structures and slaughter strategies without any other mortality factors (predators, deceases, traffic) besides winter food limitation. Calf slaughter dominates in Slaughter strategy I, whereas in strategy II most of the reindeer slaughtered are adults (1.5 years or older). Strategy I is optimal with current costs and prices in Finland, but Strategy II may be come optimal with lower meat prices, variable management costs or higher reindeer subsidies.

subsidy can change the optimal slaughter strategy towards adult slaughter. The example of an alternative optimal slaughter strategy is presented in Figure 11.3 (slaughter strategy II). In this example, management costs and meat price are low and thus it becomes optimal to use this alternative approach. With this slaughter strategy, more than 80% of the slaughtered reindeer are adults (at least 1.5 years old) and less than 20% of the calves are slaughtered during their first autumn. Thus, the proportion of adults in the population and adults slaughtered are much higher in strategy II than in strategy I. In addition, the total number of reindeer is higher and thus lichen biomass is lower in strategy II. Lower lichen biomass implies reduced calf production and calf weights. Thus, slaughter strategy II is not based on maximizing calf production, calf weight or calf slaughter. Instead, it is based on higher reindeer numbers and higher proportional weight increase from calf to adult than in strategy I. When meat production is mainly based on adult slaughter (e.g., in slaughter strategy II), it is optimal to slaughter adults earlier (from younger age classes) compared to situations in which the adult population is mainly used for reproduction (slaughter strategy I). In slaughter strategy II, females are slaughtered at the age of 6.5, because after that their weight no longer increases.

In the solutions presented in this chapter, winter food limitation is the only mortality factor for adults (2% of calves are assumed to die during summer). As it is not economically rational to let reindeer starve, natural mortality in optimal steady states is close to zero. Including other mortality factors (predators, diseases and traffic) may change optimal herd structure and the slaughter strategy. Indeed, Pekkarinen et al. (2020a) showed that high predation pressure reduces the relative importance of calf slaughter. A high density of grey wolves changes the optimal slaughter strategy of adults towards younger age classes, but high brown bear density does not have the same effect. The difference is caused by the differences in age class-specific predation mortalities. Grey wolves, and also lynx and wolverine, predate all age classes more equally, whereas brown bears mostly target calves or young reindeer during summer before autumn slaughter (see Chapter 6). Incentives associated with different predator compensation systems may alter these solutions.

The effects of costs, meat price and subsidies on optimal slaughter strategies

Solutions presented in Figure 11.2 are derived using prices and costs estimated for northernmost Finland in the years 2015–2016. However, costs and prices differ within and between Fennoscandian countries. The choice between the two types of slaughter strategy presented in Figure 11.3 depends on the level of variable management costs and meat price. Government subsidies can affect these as reindeer subsidy reduces costs per reindeer and production subsidies increase the revenues gained per kilogram of meat. Figure 11.4 shows various combinations of meat prices (including meat production subsidies) and management costs (including the effects of reindeer subsidies) and the corresponding optimal slaughter strategies. It shows that in districts where winter pastures are

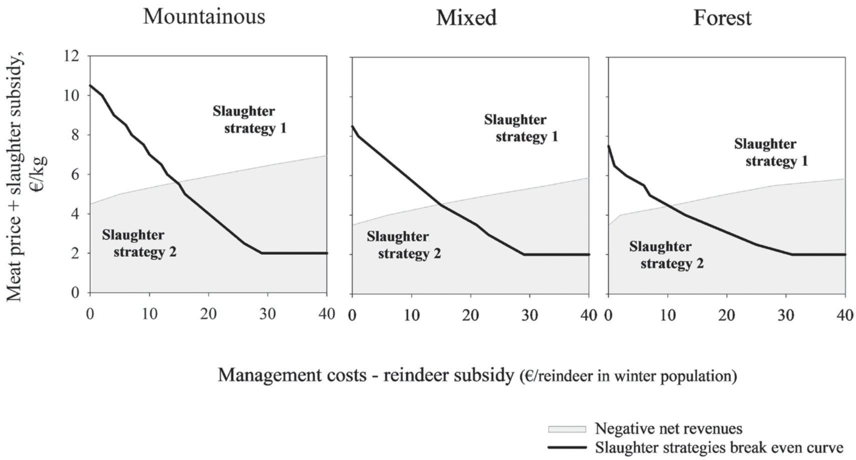

Figure 11.4 Effects of meat price (including meat production subsidy) and management costs (minus reindeer subsidy) on the choice of slaughter strategy in optimal steady states with 0% interest rate. Reindeer subsidy favours Slaughter strategy II, as it reduces costs per reindeer. Meat production subsidy increases meat price and thus favours strategy I. Calf slaughter dominates strategy I, whereas in strategy II most of the reindeer slaughtered are adults (1.5 years or older).

less productive (mountainous districts), it is more often beneficial to postpone slaughter until most reindeer are adults (slaughter strategy II). In those cases, calf production and calf weights are lower. This may have been the situation in some mountainous districts in Norway in the past, where calf weights were low due to poor pasture conditions and supplementary feeding was not used. However, nowadays incentives have been implemented in Norway to reduce pressure on the winter pastures, which has resulted in a higher proportion of calf slaughter. In contrast, in the Forest district, intensive calf slaughter is optimal even with a lower meat price. This has been typical in Finnish and Swedish districts with productive ground lichen and arboreal lichen pastures in old and mature forests. In southern districts in Finland where pastures are less productive due to forestry, supplementary feeding has been used to ensure higher calf weight and calf production.

Figure 11.4 also shows that, in order to achieve positive net revenues, a slightly higher meat price is required in Mountainous districts than in Forest districts. However, the costs may also vary between the districts depending on pasture and winter conditions. Overall, the differences in required meat price are relatively small. These solutions suggest that to gain positive net revenues, meat price (+ meat production subsidy) must be at least €4–€7 per kg. However, at that level the revenues from meat production only just cover the costs of reindeer husbandry.

Optimal model solutions under different pasture conditions and interest rates

Pasture conditions and migratory patterns vary within and between Fennoscandian countries (Figure 11.1). In addition, the interest rate available to herders may differ between areas, individuals and time. Table 11.2 shows economically optimal model solutions for the three hypothetical herding districts which represent different pasture conditions in Fennoscandia. With lower interest rates, the lichen biomass is clearly lower in the Forest district compared to mountainous and mixed districts. This is mainly due to a lack of pasture rotation in the Forest district. Without pasture rotation, lichen is not protected from grazing and trampling during snow-free periods. In addition, high availability of arboreal lichens in the Forest district helps reindeer to survive and reproduce even with lower ground lichen availability. Because of these two factors, it is not beneficial to invest in higher lichen biomass.

With higher interest rates, it becomes optimal to use intensive supplementary feeding, as demonstrated in Figure 11.2. In that case, lichen biomass falls to a very low level and reindeer rely on a mixed diet during winter, gaining energy from resources excavated from beneath the snow, supplementary feed and also arboreal lichens if available.

Table 11.2 and Figure 11.4 also show that, according to our model solutions, mountainous districts are less productive than mixed or forest districts. This is due to more favourable conditions for ground lichens in old and mature pine forests (Kumpula et al. 2014) and because of high arboreal lichen availability in

Table 11.2 Optimal steady state lichen biomass, number of reindeer and annual net revenues in different types of herding districts with interest rates from 0 to 5%.

	Interest rate	*Mountainous*	*Mixed*	*Forest*
Lichen biomass, kg/ha	0	1180	1144	479
	1	862	859	403
	3	210*	620	214*
	5	201*	202*	210*
Number of reindeer	0	6352	8628	8275
	1	6580	8860	8506
	3	7924	9944	9362
	5	8496	11132	9411
Annual net revenues, €	0	356240	653600	567900
	1	351120	652000	566400
	3	101000	570440	524200
	5	65120	293880	524000

Note:

* The main energy resource for reindeer in these solutions is supplementary feed. Thus, lichen biomass falls to the lowest possible level. To ensure that the optimization solutions lie within the use range of the model, the minimum lichen biomass in model solutions is set to 200 kg/ha.

old and mature forests (Esseen et al. 1996). Pasture conditions are most favourable in the forest district, but seasonal pasture rotation increases the productivity in mixed and mountainous districts. Thus, under the model assumptions, the least productive systems would be mountainous systems without pasture rotation. However, this solution is highly dependent on the daily digging area (reindeer excavate resources from beneath the snow). In our model daily digging area is assumed to be on average 30 m^2 (Kumpula 2001a). However, our preliminary results suggest that if the average digging area in mountainous pastures is larger, e.g. due to more favourable snow conditions, it may increase the productivity of reindeer husbandry (Pekkarinen et al. 2020b) compared to forest pastures with a lower average digging area. However, more research on average digging areas and availability of food resources beneath the snow in various conditions is needed to validate this result.

Pasture degradation and the associated high reindeer numbers are one of the main concerns in northernmost Scandinavia and a pressing topic in reindeer husbandry research (Pape & Löffler 2012). According to our model solutions, a higher interest rate and favourable pasture conditions are associated with a higher number of reindeer (Table 11.2), when reindeer herding districts maximize their long-term net revenues. In addition, various other possible reasons exist for high reindeer population densities, which can lead to increased grazing pressure and possibly to overgrazing. For example, Johannesen and Skonhoft (2011) found that herders may keep large herds to gain higher social status within the community. In addition, "tragedy of the commons" scenarios may result in high reindeer densities (Johannesen & Skonhoft 2009), when pasture use is not limited by the herding district or government. According to Næss and Bårdsen (2010), in a randomly variable environment, large herds may also be used as a risk-reduction strategy. However, Pekkarinen et al. (unpublished) found that poor pasture conditions caused by high reindeer density may expose reindeer husbandry to greater negative effects of randomly variable winter conditions. In addition, reduced pasture area or quality, e.g., due to forestry, may result in increased grazing pressure even if reindeer numbers remain the same (Pekkarinen et al. 2021). Thus, it is not only the number of reindeer that determines the sustainability of reindeer husbandry but the balance between the grazing resources and reindeer density. Consumer-resource models, like the one used in this study, are an appropriate method for analysing this relationship and thus including a dynamic description of the grazing resource is crucial in studying reindeer husbandry systems.

Optimal use of supplementary feed

In addition to optimal slaughter strategy and optimal lichen biomass levels, detailed bioeconomic models can be used to study whether it is optimal to rely on intensive supplementary feeding. Pekkarinen et al. (2015) found that, assuming average winter conditions, optimal steady-state solutions are typically based either on the use of natural pastures or on intensive supplementary feeding. The choice between these two strategies depends on economic and ecological factors. In addition, it is economically sensible to use supplementary feeding during a transition phase when restoring heavily grazed lichen pastures. In randomly variable winter conditions, supplementary feeding also becomes economically optimal during those winters when weather and snow conditions significantly restrict the use of natural pastures (Pekkarinen et al. unpublished).

Figure 11.5 gives an example of optimal solutions in two different situations. Both solutions start from the same initial state, but due to the different prices

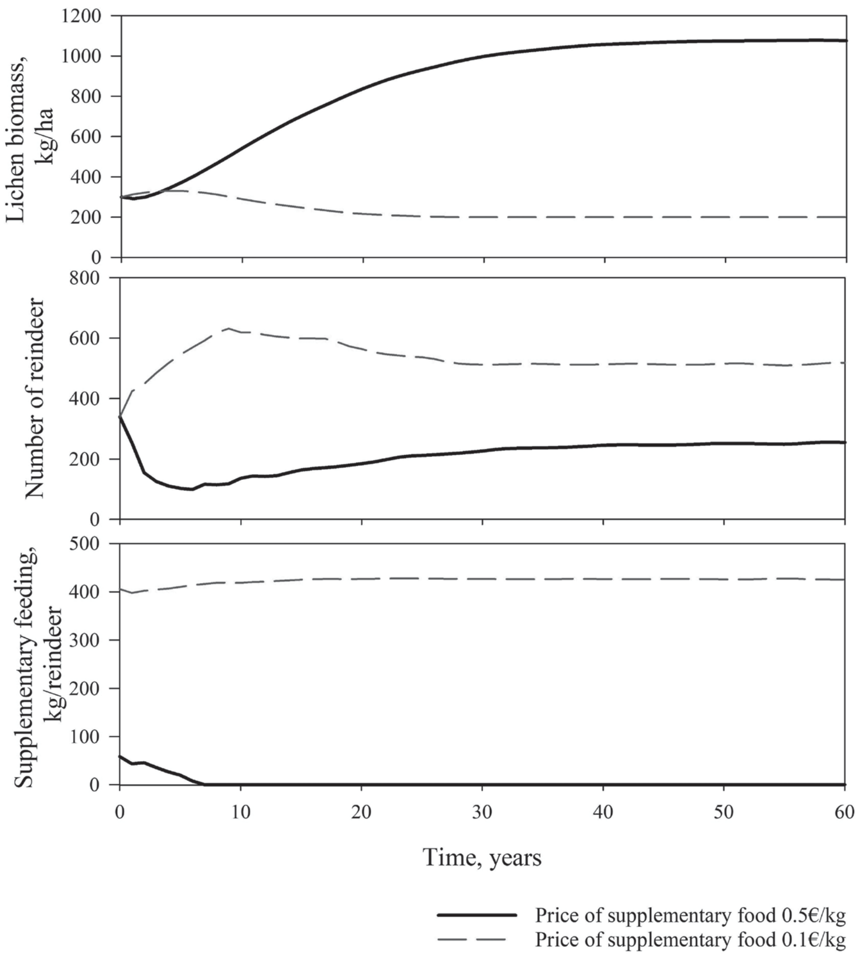

Figure 11.5 Dynamic optimal model solutions starting from relatively low lichen biomass. Solutions represented by solid lines are based on the estimated current costs of supplementary feeding (€0.5 per kg). Solutions represented by dashed lines are based on very low feeding costs (€0.1 per kg).

of supplementary feed, optimal solutions lead to two different steady states. In the solution based on €0.5 per kg feeding costs, supplementary feeding is used during the first years of the transition towards steady state, but not once the steady state is reached. However, if feeding is very inexpensive (€0.1 per kg) or the interest rate is high (see Figure 11.2) it becomes economically rational to base reindeer herding on intensive feeding.

It is also noteworthy that with higher feeding costs, the initial situation can be regarded as representing overgrazing as the pastures do not support economically sustainable production and supplementary feeding is not profitable. However, in a situation with low feeding costs, it might not be reasonable to consider the initial situation as representing overgrazing, at least from the perspective of reindeer husbandry, because the economically viable lichen biomass is lower than the lichen biomass in the initial state. This clearly demonstrates that the questions of overgrazing and sustainable levels of lichen pastures are not purely ecological concepts but are also affected by economics and by management objectives (see Mysterud 2006 for discussion on overgrazing in general).

The choice of feeding strategy under different interest rates, prices and costs

Figures 11.2 and 11.5 show that whether or not it is economically rational to use intensive supplementary feeding depends on interest rates and on the price of supplementary feed. In addition, the availability of different winter pastures and their condition affect whether supplementary feeding is appropriate. Figure 11.6 shows the effects of interest rate and feeding costs on the use of supplementary feeding for the optimal steady states in the three different

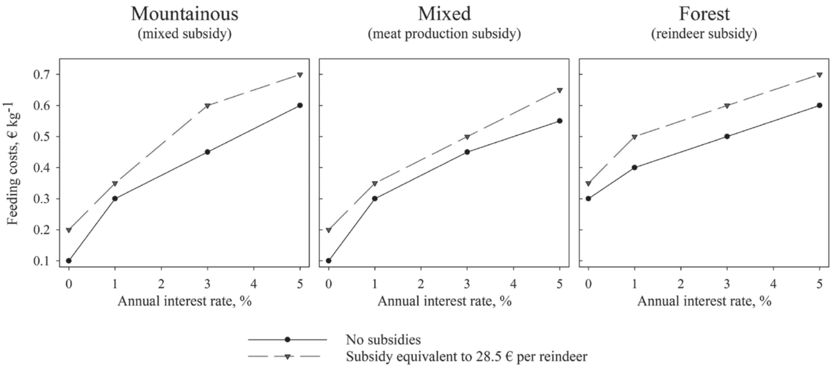

Figure 11.6 Effect of interest rate and feeding costs on the use of supplementary feeding in the optimal steady states. Curves represent the feeding costs for which it is optimal to offer supplementary feed as a main winter energy resource for reindeer. Feeding is not used in situations located above the curves, and reindeer management relies on natural pastures. Below the curves, intensive supplementary feeding is used, resulting in very low lichen densities.

types of herding districts. Compared to mountainous or mixed districts, feeding in the forest district becomes optimal with higher feeding costs, especially when the interest rate is low. However, the effect of high interest rates seems to outweigh the effect of pasture conditions and feeding becomes optimal with similar feeding costs in all of the three herding districts.

Figure 11.6 also shows the effect of different subsidy schemes on the optimality of supplementary feeding. The level of the subsidy is calibrated so that the direct costs of subsidies for the governments are equal in all subsidy schemes. Thus, for the forest district we use €28.5 per reindeer (reindeer subsidy), for the mixed district we use €1.6 per kg of meat produced (meat production subsidy) and for the mountainous district we use €14.25 per reindeer and €0.8 per kg of meat produced (mixed subsidy). This shows that the reindeer-based subsidy gives a slightly higher incentive for the use of supplementary feeding than the meat production subsidy. However, differences appear to be small and all three subsidy schemes favour the use of intensive supplementary feeding.

Conclusions

In this chapter, we have demonstrated how bioeconomic analysis, economic–ecological system models and economic optimization can be used as efficient tools to study the dynamics of complex reindeer husbandry systems. We have shown that economically optimal model solutions depend on various economic and ecological factors. As an example, economically optimal lichen biomass can vary significantly depending on interest rate, costs, prices, lichen pasture productivity, availability of other natural energy resources and government subsidies.

Pekkarinen et al.'s (2015) model solutions show that, in an undisturbed herding environment, reindeer husbandry relying on natural pastures is, in most cases, more profitable than reindeer husbandry based on intensive supplementary feeding. However, according to their recent study (Pekkarinen et al. 2021), most of the current changes, pressures and economic incentives affecting Fennoscandian reindeer husbandry seem to favour lower lichen biomass and the use of supplementary feeding. In the southern part of the Finnish reindeer husbandry area, in particular, intensive supplementary feeding and low lichen biomass are common. Our solutions suggest that this is economically rational as intensive forestry has reduced the area and productivity of winter pastures. In addition, government subsidies seem to favour larger herds and supplementary feeding, especially in Finland.

In Norway and Sweden, reindeer herding districts use seasonal migratory pasture rotation systems. Previous research has shown that pasture rotation protects valuable winter lichen pastures from excessive consumption during snow-free periods (Kumpula et al. 2014). However, pasture rotation is more difficult to arrange in smaller and fragmented herding districts, which are common in southern areas of Finland. According to our results, when a pasture rotation system cannot be used, it may become economically sensible to let lichen biomass fall to a lower level and rely more on other natural food resources or, in some cases, on supplementary feeding.

Most herding districts in Fennoscandian countries rely on intensive calf slaughter and on a minimum effective proportion of adult males in the winter population. According to our solutions, this slaughter strategy is the most economically productive in most cases. In addition, government subsidies in Sweden and Norway promote calf slaughter. However, the economically optimal slaughter strategy depends on economic and ecological factors, which have changed in the past and will change in the future. Pekkarinen et al. (2020a) showed that, in some cases, high predation pressure may change the optimal slaughter strategy and reduce the importance of calf slaughter. Similarly, in this chapter we demonstrated that lower meat price and management costs or higher reindeer subsidy may shift the optimal slaughter strategy from calves to adult reindeer.

Reindeer herding practices and herding conditions vary within and between Fennoscandia countries. Similarly, bioeconomic analysis of reindeer husbandry systems presented in this chapter shows that economically optimal solutions depend on various ecological and economic factors. Thus, different situations in reindeer husbandry require different herd structures, slaughtering strategies, reindeer densities, feeding strategies and pasture use. Our analysis suggests that many of the differences seen in practical reindeer husbandry may be economically rational adaptations to local conditions.

References

Bessa-Comes, C., Legendre, S. & Clobert, J. (2010). Discrete two-sex models of population dynamics: on modelling the mating function. *Oecologica*. 36, 439–445.

Byrd, R.H., Nocedal, J. & Waltz, R.A. (2006). KNITRO: An integrated package for nonlinear optimization. In: di Pillo, G. & Roma, M. (eds) *Large-Scale Nonlinear Optimization*. New York: Springer. 35–59.

Clark, C. (1976). *Mathematical bioeconomics: The optimal management of renewable resources*. New York: Wiley.

Danell, K., Utsi, P.M., Palo, R.T. & Eriksson, O. (1994). Food plant selection by reindeer during winter in relation to plant quality. *Ecography*. 17(2), 153–158.

Esseen, P.A., Renhorn, K.E. & Pettersson, R.B. (1996). Epiphytic lichen biomass in managed and old-growth boreal forests: effect of branch quality. *Ecological Applications*. 6(1), 228–238.

Johannesen, A.B. & Skonhoft, A. (2009). Local common property exploitation with rewards. *Land Economics*. 85(4), 637–654.

Johannesen, A.B. & Skonhoft, A. (2011). Livestock as insurance and social status: Evidence from reindeer herding in Norway. *Environmental and Resource Economics*. 48(4), 679–694.

Johannesen, A.B., Olaussen, J.O. & Skonhoft, A. (2019). Livestock and carnivores: Economic and ecological interactions. *Environmental and Resource Economics*. 74(1), 295–317.

Klein, D.R. (1968). The introduction, increase, and crash of reindeer on St. Matthew Island. *The Journal of Wildlife Management*. 32, 350–367.

Kumpula, J. (2001a). Winter grazing of reindeer in woodland lichen pasture: Effect of lichen availability on the condition of reindeer. *Small Ruminant Research*. 39(2), 121–130.

Kumpula, J. (2001b). Productivity of the semi-domesticated reindeer (Rangifer t. tarandus L.) stock and carrying capacity of pastures in Finland during 1960–90s. PhD. diss. University of Oulu.

Kumpula, J., Kurkilahti, M., Helle, T. & Colpaert, A. (2014). Both reindeer management and several other land use factors explain the reduction in ground lichens (Cladonia spp.) in pastures grazed by semi-domesticated reindeer in Finland. *Regional Environmental Change*. 14(2), 541–559.

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

Mysterud, A. (2006). The concept of overgrazing and its role in management of large herbivores. *Wildlife Biology.* 12, 129–141.

Næss, M.W. & Bårdsen, B.J. (2010). Environmental stochasticity and long-term livestock viability – herd-accumulation as a risk reducing strategy. *Human Ecology*. 38(1), 3–17.

Pape, R. & Löffler, J. (2012). Climate change, land use conflicts, predation and ecological degradation as challenges for reindeer husbandry in northern Europe: What do we really know after half a century of research? *Ambio*. 41(5), 421–434.

Pekkarinen, A.-J. (2018). Ecology and economics of reindeer herding systems. PhD. diss. University of Helsinki.

Pekkarinen, A.-J., Kumpula, J. & Tahvonen, O. (2015). Reindeer management and winter pastures in the presence of supplementary feeding and government subsidies. *Ecological Modelling*. 312, 256–271.

Pekkarinen A.-J., Kumpula J. & Tahvonen O. (2017). Parameterization and validation of an ungulate-pasture model. *Ecology and Evolution*. 7(20), 8282–8302.

Pekkarinen, A-J., Kumpula, J. & Tahvonen, O. (2020a). Predation costs and compensations in reindeer husbandry. *Wildlife Biology*. 2020(3), 1–14.

Pekkarinen, A-J., Kumpula, J. & Tahvonen, O. (2020b). Bioekonominen analyysi poronhoidon ja talvilaidunten tilan taloudellisesta kestävyydestä Suomessa. In: Kumpula, J. & Siitari, S. (eds) *Kestävä biotalous porolaitumilla -hankkeen osaraportit, johtopäätökset ja toimenpide-ehdotukset*. Luonnonvara- ja biotalouden tutkimus 29/2020. Helsinki: Luonnonvarakeskus. 6–27.

Pekkarinen, A-J., Kumpula, J. & Tahvonen, O. (2021). What Drives the Number of Semi-domesticated Reindeer? Pasture Dynamics and Economic Incentives in Fennoscandian Reindeer Husbandry. In: Nord, D.C. (eds) *Nordic Perspectives on the Responsible Development of the Arctic*. Springer Polar Sciences. Cham: Springer. 249–270.

Sametinget (2020). *Rennäringens tillstånd 2019*. Kiruna: Sametinget.

Schmolke, A., Thorbek, P., DeAngelis, D.L. & Grimm, V. (2010). Ecological models supporting environmental decision making: A strategy for the future. *Trends in Ecology and Evolution*. 25(8), 479–486.

Skonhoft, A., Johannesen, A.B. & Olaussen, J.O. (2017). On the tragedy of the commons: When predation and livestock loss may improve the economic lot of herders. *Ambio*. 46(6), 644–654.

Stephens, D. & Krebs, J. (1986). *Foraging Theory*. Princeton, NJ.: Princeton University Press.

Tahvonen, O., Kumpula, J. & Pekkarinen, A.J. (2014). Optimal harvesting of an age-structured, two-sex herbivore–plant system. *Ecological Modelling*. 272, 348–361.

Virtala, M. (1992). Optimal harvesting of a plant-herbivore system: Lichen and reindeer in northern Finland. *Ecological Modelling*. 60(3–4), 233–255.