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RESEARCH

Quantifying the Implications of Different Land Users' Priorities in the Management of Boreal Multiple-Use Forests

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Abstract In the management of natural resources, conflicting interests and objectives among different stakeholders often need to be considered. Here, we examine how two contrasting management scenarios of boreal forests in northern Sweden differ in their consequences on forest structural composition and the economic gains at harvest. Management strategies prioritize either (i) forest characteristics that promote grazing resources for reindeer herded by the indigenous Sámi, or (ii) timber production as practiced in Sweden today. When prioritizing reindeer grazing, forest stands develop a higher abundance of older age classes with larger trees and lower stem density, which reduces harvest and revenue levels by approximately 20 % over a 100-year period. The differences between these strategies illustrate the complexity in finding a trade-off for coexistence between industrial land users and other livelihoods that share the same landscape. Political support and institutional solutions are necessary to initiate changes in policy in finding such trade-offs in the management of environmental resources and thereby influence the optimal distribution of costs and benefits between different actors.

Keywords Multiple-use management · Trade-off · Land use conflict · Reindeer husbandry · Forest management scenarios · Boreal forests

Introduction

The use of natural resources by people is constantly adapting and transforming in response to ecological and social change (Chapin et al. 2009). Depending on the understanding of human well-being and the capacity to make use of environmental goods and services, the scope and intensity of resource management differs. Particularly, in multiple-use situations, where land and resources are shared by several stakeholders, trade-offs in management goals may be inevitable to avoid conflicts between the involved parties, such as between commercial uses of a landscape on the one hand and social, cultural, and biological values on the other (Wiens 2009).

Forest ecosystems are examples of such multiple-use systems, where various social and ecological elements interact. Globally, forests have often been shaped by silvicultural management practices aimed at increased timber production. These processes, however, often lead to substantial changes in forest structure, ecological function, age composition, and biodiversity (Kuuluvainen 2002; Duncker et al. 2012). After the rise of industrialized forestry in Sweden, and especially after large-scale clear-cutting strategies became common in the 1950s, disputes between different stakeholders over land use have escalated. This is especially true in the case of reindeer husbandry, which is

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practiced by the indigenous Sámi people in Northern Sweden (Widmark 2006; Sandström and Widmark 2007). Today, reindeer husbandry is an extensive form of land use focused on meat production and dependent on access to large grazing grounds (Moen and Keskitalo 2010). Although only a small percentage of the Sámi population relies on reindeer husbandry for their primary source of income, it continues to be the cultural keystone in the identity and traditions of the Sámi (SSR 2012). The Sámi have the usufructuary right to use the boreal forests as grazing grounds, but no ownership rights. In the Swedish reindeer husbandry area (the northern 50 % of Sweden), about 25 % of the forests are owned by large private corporations, 41 % by non-industrial private owners, and about 34 % by the State (Swedish Statistical Yearbook of Forestry 2013).

In some areas of the Swedish reindeer husbandry area, the boreal forest is used year-round for reindeer grazing, but in most places, the forest is used only for grazing during winter, when reindeer (*Rangifer t. tarandus*) mainly forage on terrestrial lichens (*Cladonia* spp., *Cetraria* spp.). If difficult snow conditions due to depth or hardness hinder the reindeer in digging for terrestrial lichens through the snow cover, arboreal lichens (e.g., *Bryoria fuscescens, Alectoria sarmentosa*) are important as emergency forage (Heggberget et al. 2002; Helle and Jaakkola 2008). The availability of winter grazing resources, therefore, represents a bottleneck in reindeer husbandry. Modern forestry practices, such as clear-cutting and soil scarification, have greatly decreased the abundance of forest types rich in terrestrial and arboreal lichens, and have increased the fragmentation of the landscape (Kivinen et al. 2011).

Depending on the philosophy and aim of forest management, ecological principles and functions are interpreted differently (Puettmann et al. 2012). Consequently, different forest characteristics are considered desirable by the forestry and reindeer husbandry sectors. Finding optimal solutions to satisfy both land users therefore is an intricate task (Widmark and Sandström 2012). For example, the complexities and dynamics of boreal forests have been changed by forestry practices, e.g., when clear-cuts are regenerated with even-aged monocultures (Kuuluvainen 2002). To restore functions of forest diversity at broad spatial and temporal scales in the boreal forests of Fennoscandia, the potential of alternative forest management strategies to be used as restoration tools has been recognized (Kuuluvainen et al. 2012; Halme et al. 2013).

Spatial and temporal patterns of clear-cuts are especially important for understanding the impacts of fragmentation and habitat loss (Radeloff et al. 2006; Kivinen et al. 2011). Therefore, planning and management of forests has received much attention regarding alternative management scenarios, including trade-offs between forestry and other relevant land users (Pretzsch et al. 2008; Mäkelä et al. 2012). For instance, Widmark (2009) found that costs for forestry would rise if the influence of reindeer herding in the co-management of the land were to increase. These costs were still evident when the maximum net present value (NPV) gained by both forestry and reindeer husbandry was combined; the higher NPV gained by reindeer herders could not compensate for the economic losses to forestry. Theoretically, therefore, forestry and policy makers have little incentives to encourage the increased influence of reindeer herding in managing the multiple use commons of forests, for instance by the allocation of property rights to the Sámi (Sandström and Widmark 2007).

Resulting from their close interaction with reindeer and the landscape, Sámi pastoralists have accumulated a rich body of knowledge on how forest management affects their reindeer husbandry practices and the availability of grazing resources in particular (Roturier and Roué 2009). Based on this knowledge, a forest policy document was published by the National Association of Swedish Sámi (SSR) (http://www.sapmi.se/skogspolicy.pdf), outlining a reindeer husbandry-adapted approach to forest management. In this paper, we analyze the consequences of this particular forest management approach for two areas in northern Sweden. Earlier studies have applied models with slight adjustments of current forest management to make concessions to reindeer husbandry, such as modeling extended rotation times or selective harvest instead of clear cutting (Bostedt et al. 2003; Zhou 2007; Korosuo et al. 2013). Contrastingly, our study is focused on a scenario with management recommendations that are expressed by the reindeer herders themselves in their policy document (http://www.sapmi.se/skogspolicy.pdf).

Materials and Methods

Study Areas and Data Preparation

The Swedish reindeer husbandry area is divided into 51 herding districts, most of them practicing a migratory pasture rotation between their summer grazing grounds in the Scandinavian mountains close to the border with Norway and the winter grazing grounds in forest lowlands east of the mountains. The particular landscapes considered in this study constitute a part of the winter grazing grounds of the Sirges and Vilhelmina Norra herding districts (Fig. 1). The boundaries of the two winter grazing areas were determined through discussions with reindeer herders from each district. Both areas are key elements in the surrounding landscape that is used by a single winter group in the respective herding district for winter grazing (roughly

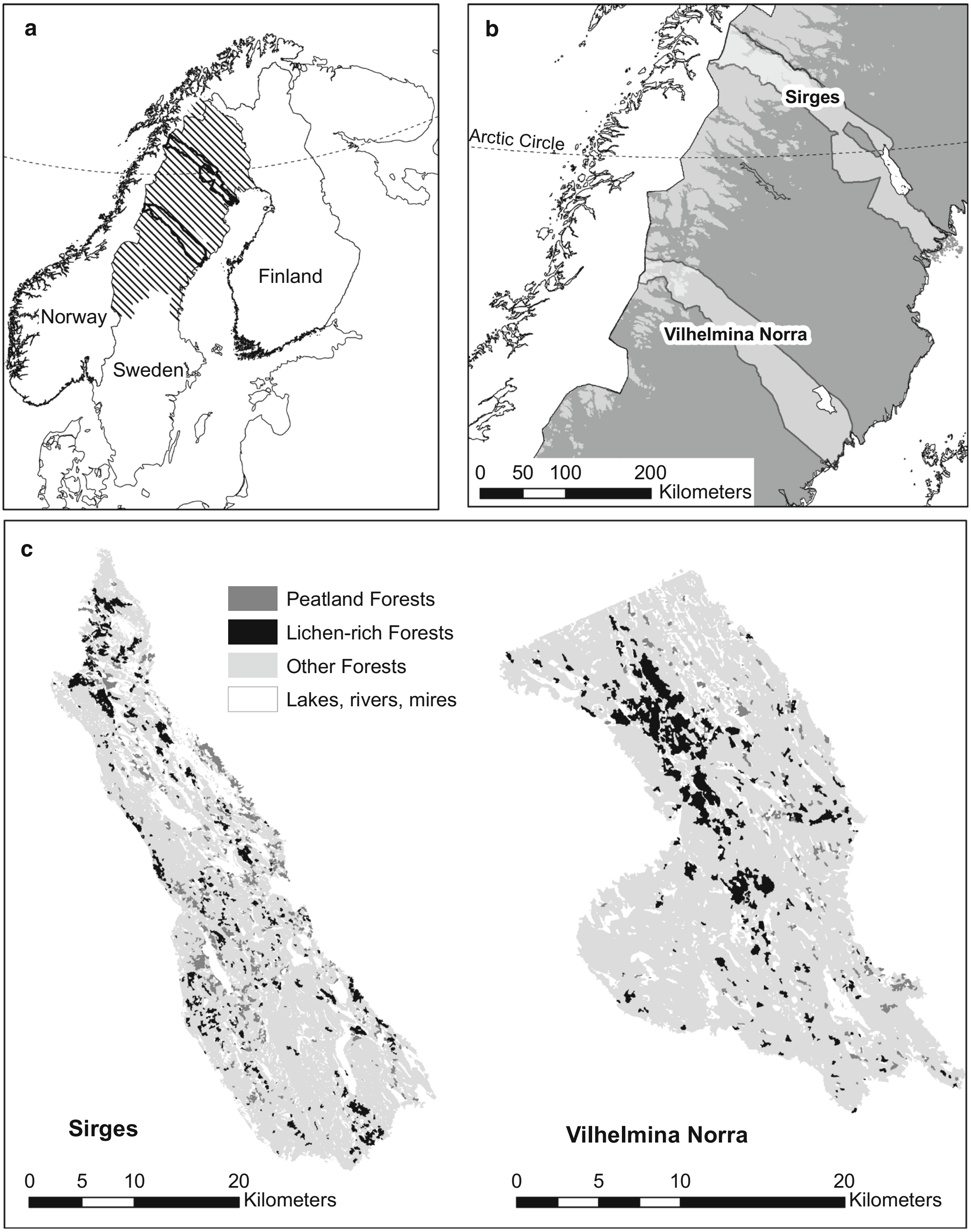

Fig. 1 **a** Location of the herding districts within the Swedish Reindeer Husbandry Area (hatched part). **b** Location of the specific study sites (*white*) in the respective herding district Sirges and Vilhelmina Norra (*light grey*). **c** Distribution of forest types within the respective study site

December through March). During this time, reindeer herds of the whole district are split into smaller herds, thus forming single winter groups (*siidas*).

We digitized the area boundaries specified by the reindeer herders and extracted vegetation and soil data for all forest stands within the designated areas from landscape classification databases. Land cover data are derived from Landsat TM satellite images taken in the year 2000, with a minimum grain size of 1–5 ha, in combination with field data from the National Forest Inventory (NFI) of Sweden (https://maps.slu.se). The 58 land cover classes available, such as coniferous forest, peatlands or clear-cuts, correspond to the EU-wide database of the CORINE (Coordination of Information on the Environment) Land Cover program (CLC 2006). Likewise, stand level data pertaining to forest age and volume were derived from satellite imagery from SPOT 4 and SPOT 5 taken in the year 2005, with a resolution of 25 m × 25 m, in combination with NFI data. NFI reference plots are used to calculate stand variables for each pixel according to the *k* nearest neighbor method (kNN) (http://skogskarta.slu.se/). Each pixel and its forest variables were, therefore, calculated as the weighted mean value of the *k* nearest reference NFI plots in the same satellite spectral space (Reese et al. 2002). Though having low accuracy at a pixel scale, ranging from 17 to 39 % Root Mean Square Error (Reese et al. 2002), the estimates of forest variables at scales larger than 100 ha are appropriate for our analysis. However, estimates tend to be skewed toward the average of the *k* nearest plots, thus underestimating the area of old forests. Notwithstanding the inherent problems of the uncertain estimations of the presence and extent of older forests, these inaccuracies are the same for both scenarios. Thus, the evaluation of the consequences of the two scenarios is based on the relative differences between them, not on absolute values. The calculation unit used is based on a segmented version of the kNN dataset with 25 m × 25 m pixels.

Overall, the study site Vilhelmina Norra had a higher standing tree volume than Sirges due to a higher site productivity index of 3.6 m^3 ha^{-1} $year^{-1}$ compared to 3.3 m^3 ha^{-1} $year^{-1}$ based on the NFI reference plots in the areas. The forests in both study areas were dominated by Scots pine (*Pinus sylvestris*) with 58 and 63 m^3/ha for Sirges and Vilhelmina Norra, respectively, and Norway spruce (*Picea abies*) with 14 and 29 m^3/ha, respectively. Other tree species included birch (*Betula pendula* and *B. pubescens*) and the exotic lodgepole pine (*P. contorta*), which have considerably lower standing volume. The total number of segments, i.e., stands, was 7959 in Sirges with a mean area of 7.6 ha and 4802 in Vilhelmina Norra with 8.9 ha mean area. The initial age structure of the study areas is given in Fig. 2.

Forests with a ground vegetation rich in terrestrial lichens as forage resources for reindeer are the most important landscape element for reindeer herding during winter. Peatland forests are important sources of arboreal lichens as emergency forage since these forests are rarely harvested (L-E Nutti, *pers. comm.*). However, these land cover classes comprise only a small percentage of the total area (Figs. 1, 2). Descriptive details of the forest structure in our study areas are presented in Table 1.

The Sirges area (55,136 ha) is approximately 50 % larger than that of Vilhelmina Norra (36,316 ha) reflecting different reindeer herd sizes in the *siida*. However, the area distributions of land cover classes are fairly similar in the two areas (Fig. 2).

Model Description

To compare the outcomes of different management strategies, we used the software Heureka, a forestry decisions support system developed by the Swedish Agricultural University SLU (www.slu.se/sha). Heureka is a tool for long-term planning and analyses of forest management strategies, reaching from the stand and forest level to regional scenario analyses. Many silvicultural treatments can be simulated, such as soil scarification, pre-commercial thinning, fertilization, clear-cutting or choice of tree species to be grown. Subsequently, these treatments can be analyzed regarding their economic efficiency, consequences for forest stand structure or implications for biodiversity, and carbon sequestration (Wikström et al. 2011).

Heureka models forests as a hierarchically structured entity. The growth and development of simulated forest stands essentially depend on the treatments applied and specific models for tree growth and mortality (Fahlvik et al. 2014). Forest stands, in this study based on a segmented version of the kNN data, compose a region whose boundaries are defined by the user. Importantly, Heureka allows defining specific forest classes, called forest domains, based on diverse stand characteristics. For each forest domain, specific silvicultural treatments and rules can be applied. This makes Heureka an effective tool to analyze and compare different forest management scenarios (i) without any specifically defined forest domains, i.e., where all stands will be treated similar, with scenarios that (ii) include user-defined forest domains that are assigned specific treatments. In this study, we used the software RegWise within the Heureka system to conduct analyses and theoretical exploration of management scenarios at the regional level.

Using the two study areas described above, we quantified the effects of two contrasting forest management scenarios on trajectories of forest characteristics, as well as economic consequences thereof. One scenario originates from forest management adjusted to the needs from a reindeer husbandry perspective as recommended by the herders themselves (http://www.sapmi.se/skogspolicy.pdf). The other scenario applies practices for timber production that follow the guidelines relating to environmental considerations as outlined in the Swedish Forestry Act of 1993 and certification rules of the Forest Stewardship Council (FSC).

Scenarios

The management strategies we chose do not represent extreme cases, as forestry and reindeer husbandry are conducted in the landscapes in both scenarios. However, the intensities and type of forest management differ, as in

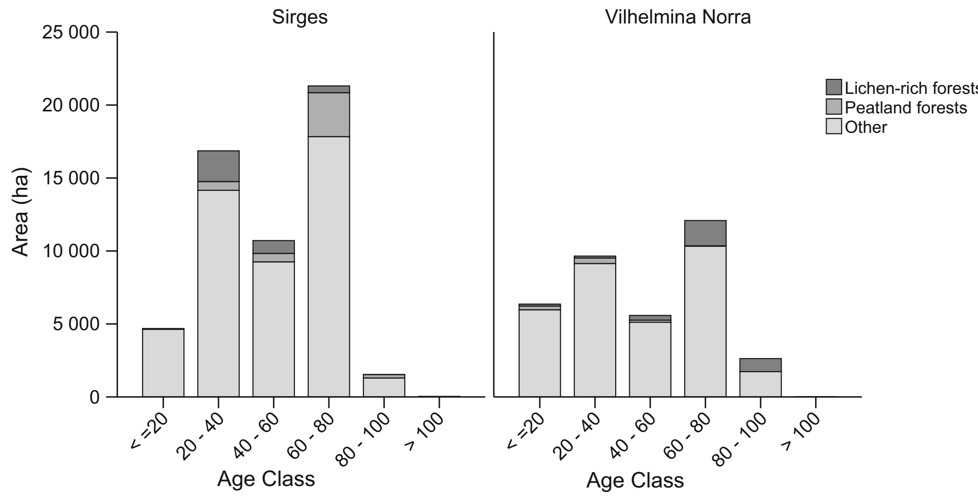

Fig. 2 Distribution of initial age classes and specific forest classes in the two study areas Sirges (*left panel*) and Vilhelmina Norra (*right panel*) for the year 2005

Table 1 Standing volume and stems/ha for forest domains in the study areas Sirges and Vilhelmina Norra, divided into age classes of 20 years

Study area	Domain	Area (ha)	Forest structure	≤20 years	20–40 years	40–60 years	60–80 years	80–100 years	>100 years
Sirges	Lichen-rich forests	4455	Volume (m^3/ha)	5	40	77	116	129	–
			Stems (ha)	4969	2857	2639	1803	1199	–
	Peatland forests	3503	Volume (m^3/ha)	8	33	66	107	147	184
			Stems (ha)	5761	3037	2679	2135	1514	729
	Other forests	47,178	Volume (m^3/ha)	3	26	90	132	165	171
			Stems (ha)	3852	3463	2634	1827	1437	726
	All forest	55,136	Volume (m^3/ha)	3	27	88	129	159	172
			Stems (ha)	3869	3388	2638	1830	1402	719
Vilhelmina Norra	Lichen-rich forests	3238	Volume (m^3/ha)	4	22	98	136	141	–
			Stems (ha)	5230	4311	2272	1390	881	–
	Peatland forests	807	Volume (m^3/ha)	13	32	86	131	0	–
			Stems (ha)	4833	2957	3051	1647	0	–
	Other forests	32,270	Volume (m^3/ha)	9	32	123	174	239	235
			Stems (ha)	4634	3353	2976	1739	1353	1105
	All forest	36,316	Volume (m^3/ha)	9	32	120	168	205	235
			Stems (ha)	4655	3352	2938	1689	1192	1105

each case, particular elements in landscapes are prioritized and thus require appropriate strategies. Table 2 summarizes the differences between the two scenarios. Both scenarios and related forest domains created will be portrayed in more detail below, while numerical specifications are presented in the Appendix. Henceforth, the two scenarios of forest management in this study are named after the natural resource in focus, i.e., a "reindeer scenario" and a "timber scenario."

The initial forest age class distribution (Fig. 2) and other forest characteristics (Table 1) depend on past decisions and therefore constrain the options for management today. For both scenarios, maximum allowable forest harvest per period is defined as less or equal to the total accumulated tree growth of the stands for the present period. Each period in the simulation of the future corresponds to a time step of 5 years, and the total length of the simulations is 100 years. According to the standards set by the guidelines for FSC certification in Sweden, 5 % of the productive forest land is required to develop without any management whatsoever in both scenarios (www.fsc-sverige.se).

We present our results as relative differences (i.e., ratios) between the two scenarios with regard to landscape patterns, forest characteristics, and economic consequences

Table 2 Differences between the respective management strategies. See text for details on domains and their respective management strategies

	Reindeer scenario	Timber scenario
Domains created	Lichen-rich forests, forests on peatland, and other forest stands	All stands treated similar in one domain
Forest regeneration	Increased share of regeneration by plantation	Regeneration by plantation, seed trees and sowing
Tree species planted	*Pinus contorta* not allowed	*Pinus contorta* allowed
Scarification	Less soil scarification, more extensive burning	More soil scarification allowed, less burning
Pre-commercial thinning	In all dense young forests	Smaller areas and less intensive thinning
Rotation time	30 % longer rotation times than in the timber scenario	Short rotation times (90–120 years)
Extraction of residues	Increased removal of logging residues, no stump harvest	Less removal of logging residues, spruce stump harvest allowed
Fertilization	No fertilization	Up to three times during one rotation

for the forest owners. The two winter grazing areas were used as replicates to assess the sensitivity of the simulation results to initial conditions. For assessment of revenues for both areas, we used the price list of the forest owner association Norra Skogsägarna for the year 2012. For assessment of costs for regeneration, harvesting, and fertilization, Heureka's default parameters and models were used (Wikström et al. 2011).

Certain simplifications had to be accepted in the model. Although ownership of the forest land in the landscapes in our study sites is diverse, with both large-scale and small-scale private forest owners, we manage the landscape in our scenarios as if there were only one owner. Further, we have not been able to perform calculations of the effects of the forest management strategies on reindeer production or revenues. The landscapes that we model only represent a small portion of the yearly grazing grounds for one particular *siida*. Therefore, the changes in forest structure of the modeled landscape cannot be converted directly into reindeer herd production. The dynamics of reindeer populations and slaughter weights are not easily modeled, as they also depend on several external variables besides the availability of grazing grounds, such as weather patterns, snow conditions, herding strategies, and predation (Helle and Kojola 2006, Moen 2008). Another simplification was that no consideration of any spatial dependences between forest stands was made.

The Reindeer Scenario

For our reindeer scenario, we based forest management strategies on published research on forestry impacts on winter grazing resources and landscape practices by reindeer herders, as well as on a policy document published by the National Association of Swedish Sami (SSR) (http://www.sapmi.se/skogspolicy.pdf). We also confirmed the rules described below with Karin Baer, Vilhelmina Norra herding district, who was a member of the group that developed the policy document (*personal communication*). Creating forests that sustain the growth and ensure the availability of lichens as the most important winter forage recourses for reindeer is the principal goal in this scenario.

In Heureka, we created domains for stands with terrestrial lichens as the dominant ground vegetation according to CORINE and dominated by Scots Pine (more than 50 % of total growing stock). Another domain was created for stands rich in arboreal lichens, classified in this study as stands on peatlands and older than 60 years (Horstkotte et al. 2011). CORINE classifies peatland forests as forested areas on wetlands with a crown cover denser than 30 %. These domains were treated differently from domain other forest stands in the model.

Lichens growth is limited mainly by moisture and light regimes at the forest floor. A relatively open canopy with less than 60 % crown cover, corresponding to a basal area of about 15 m^2/ha, is optimal for lichen growth (Jonsson Čabrajić et al. 2010). To prevent forests from becoming too dense, pre-commercial thinning is applied in all young stands (with more than 2100 stems/ha at a height of 2–5 m) resulting in 1600 stems/ha after pre-commercial thinning. Plantations of the exotic *P. contorta*, which tends to develop into dense stands and restricts the movement of both reindeer and reindeer herders, are not allowed. As lichens may be outcompeted by vascular plants under high nutrient conditions, soils rich in lichens are not fertilized. Instead, burning is applied on 5 % of the area to create favorable competitive conditions for lichens (Kivinen et al. 2010). Soil scarification that exposes mineral soils to plant seedlings is only undertaken on mesic and moist soils, as this practice destroys and reduces the cover of terrestrial lichens on dry soils (Roturier and Bergsten 2006). To allow the accumulation of slow-growing arboreal lichens, rotation times are extended more than 30 % compared to a standard timber production regime of 90–120 years. This practice creates older stands at the landscape level and allows an increased accumulation of arboreal lichens (Dettki and Esseen 2003; Horstkotte et al. 2011).

Some treatments are applied to all forests stands, irrespective of their domain. Clear-cuts tend to develop snow conditions that are adverse for reindeer foraging in terms of depth and hardness (Horstkotte and Roturier 2013). Therefore, the time until the development of a new forest canopy is reduced by planting seedlings, instead of relying on natural regeneration. After clear-cutting a stand, logging residues are removed if Norway spruce exceeds 40 % of the total growing stock, as logging residues hinder reindeer in digging, and adversely affect lichen growth (Helle et al. 1990). Stump harvesting is not allowed, as this practice destroys the lichen cover (Kivinen et al. 2010). Numerical details of treatments and rules are specified in the Appendix.

The Timber Scenario

Generally, the timber scenario gives priority to those principles for timber production as practiced in business-as-usual forestry today. All forest stands are treated according to the same rules, i.e., no specific domains are created. Compared with the reindeer scenario, the share of regeneration with seed trees and sowing is higher. Pre-commercial thinning of young forest stands occurs on smaller areas and an intensity that depends on site fertility. Also, thinning is applied at later developmental stages, giving a high volume available for clear cutting. Forest stands are harvested as soon as they reach the lowest allowed age for clear cutting according to the Swedish Forestry act (Skogsstyrelsen 2001), ranging between 90 and 120 years. Soil scarification is conducted at the intensity currently employed, with up to 89 % of stands on dry soils being scarified. Contrastingly, burning of clear-cut areas is only applied on 1 % of the area. Fertilization occurs up to three times per rotation, within the current restrictions on fertilization (Pettersson 1994). The exotic *P. contorta* returns a yield about 36 % greater than *P. sylvestris* with a shorter rotation time (10–15 years) (Elfving et al. 2001) and is allowed to increase under this scenario. Logging residues are removed only if Norway spruce exceeds 60 % of the growing stock, and spruce stumps are allowed to be removed for bioenergy. Numerical details of treatments and rules are specified in the Appendix.

Results

Forest management is the main driver of landscape patterns in Scandinavia. Therefore, the two management scenarios differ considerably in their effect on the composition of forest age classes and the structural characteristics of forest stands. These differences affect harvesting levels, forest structure, and economic flow during the simulation period, driven by the contrasting management objectives.

Harvesting Levels

The reindeer scenario is characterized by a reduction in the potential harvest volume compared to the timber scenario. This is especially true for lichen-rich forests and peatland forests, where virtually no clear cutting takes place in either of the study sites during the first six management periods. Averaged over 100 years, the area in both landscapes subject to clear cutting under the reindeer scenario is 83 % compared to the timber scenario (Table 3). Clear-cut areas in lichen-rich forests and of peatland forests are reduced by nearly half under the reindeer scenario.

During the simulation period, there are substantial fluctuations in the harvest level of timber at both sites, until harvest rates tend to stabilize after 40 years in Sirges and after 50 years in Vilhelmina Norra (Fig. 3a). This is a result of the forest age distribution at the beginning of the simulation (Fig. 2). Averaged over 100 years, harvested timber volumes in the reindeer scenario are close to 80 % of that in the timber scenario in both study sites (Table 3). With the stabilization of harvest levels after 50 years, the reindeer scenario further reduces harvest levels compared to the timber scenario from 80 % in the first half to 77 % in the second in Sirges and from 84 to 78 % in Vilhelmina Norra.

Pre-commercial thinning is applied over an area twice as large in the reindeer scenario as in the timber scenario in both landscapes, averaged over the simulation period (Table 3). The dominance of pre-commercial thinning is mainly due to large areas being thinned initially in the first 5-year period of the simulations, in order to achieve the desired structure of less dense young forests to promote lichen growth. However, the area of pre-commercial thinning is still nearly double in the reindeer compared to the timber scenario, even if the first 5-year period is excluded. Thinning of older trees is applied to a considerably greater area in the reindeer scenario (Table 3). This is especially true for the first half of the simulation period, whereas the area of thinning tended to be at a similar level as in the timber scenario in the latter half.

Forest Structure: Standing Volume and Stems per Hectare

Management practices in the reindeer scenario result in stands characterized by lower stem density (Table 3), but the longer rotation times result in older and, therefore, larger trees. However, the larger tree sizes do not

Table 3 Average relative differences for harvesting levels and forest structure over the 100-year simulation period between the two management scenarios in Sirges and Vilhelmina Norra

	Sirges			Vilhelmina Norra		
Relative differences (%)	Overall	Lichen-rich forests	Peatland forests	Overall	Lichen-rich forests	Peatland forests
Harvest levels						
Clear-cut area (ha/yr)	83	50	54	83	44	49
Harvest level (m^3)	78	65	59	80	62	54
Pre-commercial thinned area (ha/year)	210	369	525	202	484	535
Thinned area (ha/year)	142	307	144	123	189	123
Forest structure						
Timber volume (m^3/ha)	78	71	81	78	76	77
Stems (ha)	81	68	79	80	69	69

Values (%) represent the ratio between the reindeer scenario and the timber scenario

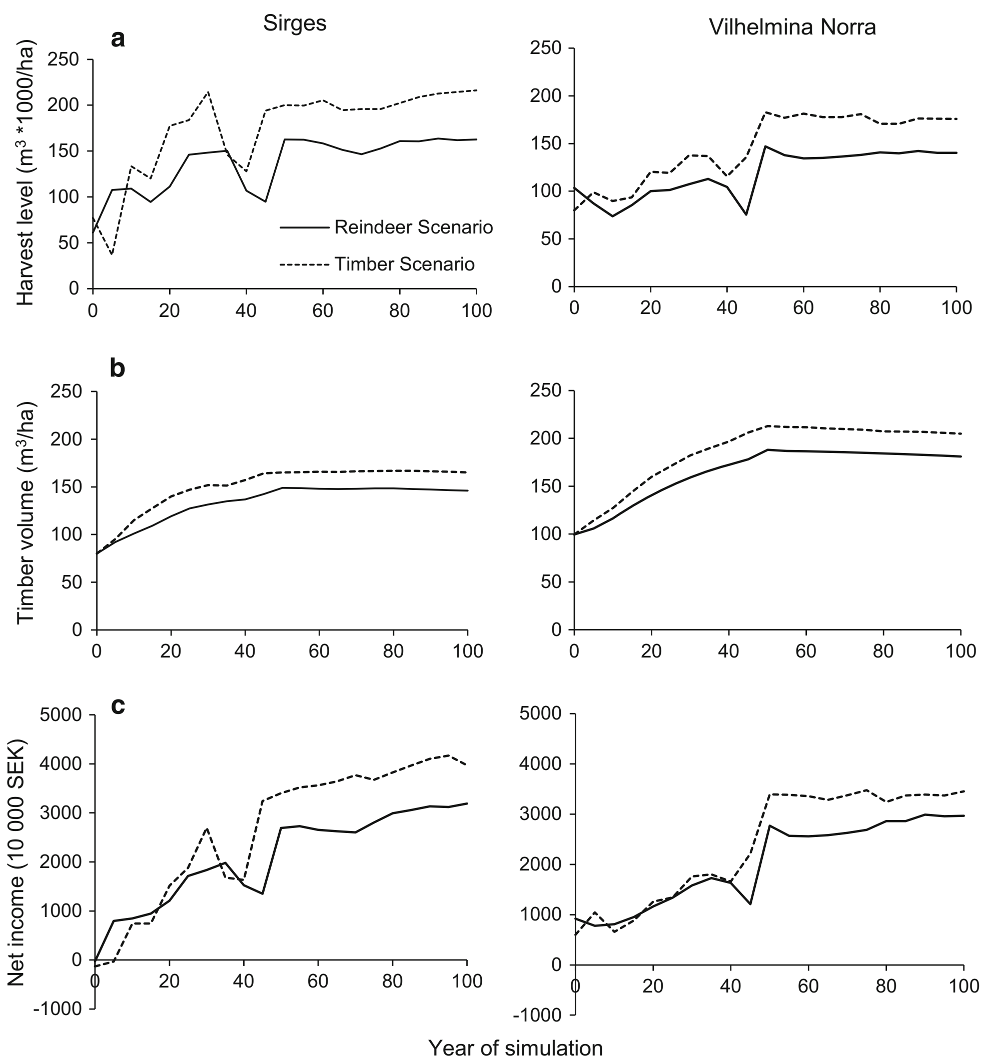

Fig. 3 Differences between both scenarios in Sirges (*left panel*) and Vilhelmina Norra (*right panel*): **a** harvest level of timber (m^3* 1000/ha) **b** development of timber volume (m^3/ha) and **c** net income (10, 000 Swedish crowns)

compensate for the loss in standing volume resulting from the less dense stands (Fig. 3b). The difference in stems per hectare between the two scenarios is especially pronounced in lichen-rich forests, where open structures are created to sustain lichen growth through a higher light availability.

Table 4 Rotation times (years) and proportion of old forests (%) after the 100-year simulation period for the two management scenarios

	Reindeer scenario			Timber scenario		
	Overall	Lichen-rich forests	Peatland forests	Overall	Lichen-rich forests	Peatland forests
Sirges						
Rotation time (years)	137	195	259	113	97	139
Forest >120 years at end (%)	18	61	49	8	27	5
Vilhelmina Norra						
Rotation time (years)	124	183	292	103	81	143
Forest >120 years at end (%)	11	41	41	8	5	12

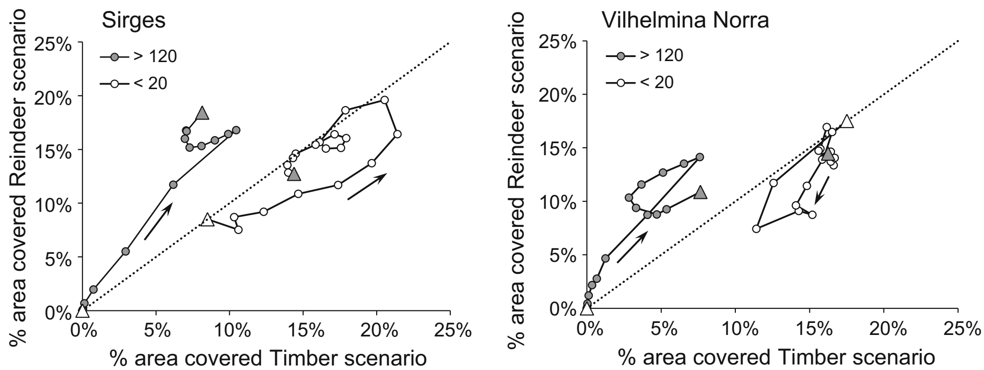

Fig. 4 Trajectories for young forests (*open circles*) and old forests (*grey circles*) for 20 simulation periods in Sirges (*left panel*) and Vilhelmina Norra (*right panel*). *Points* on the *right side* of the *dotted line* indicate dominance under the timber scenario, *points* on the *left side* dominance under the reindeer scenario. The *white triangle* indicates the starting position, the *grey triangle* the position at the end of the simulation after 100 years. *Arrows* indicate the direction of movement

Forest Age Composition

Comparing both scenarios, age composition and landscape patterns have clearly developed into different states at the end of the simulation period. This is mainly an effect of the prolonged rotation times, more pronounced thinning regimes, and reduced clear-cuts in the reindeer scenario. Rotation times depend on the area that can be cut, and the reindeer scenario has a longer rotation compared to the forestry scenario. In Sirges, the reduction in the area to be clear-cut in the reindeer scenario resulted in an average rotation time of 137 years compared to 113 years in the timber scenario (Table 4). Similar results were obtained for Vilhemina Norra, where the rotation times were on average 124 and 103 years, respectively. Differences were larger for the lichen-specific forest types, where rotation times approached 200 years for lichen-rich forests and 300 years for peatland forests (Table 4).

At the end of the simulation period, prolonged rotation times in the reindeer scenario increase the amount of old-growth forests (i.e., older than 120 years) by about 18 and 11 % compared to the initial state in Sirges and Vilhelmina Norra, respectively (Table 4). Importantly, lichen-rich forests older than 120 years increased to cover more than 60 % of this age class in Sirges and nearly 50 % in Vilhelmina Norra under the reindeer scenario. A similar increase in old-growth forests is observed for peatland forests. The timber scenario does not increase the area of old-growth forests to more than 8 % in either study area (Table 4).

The dynamics of forest age classes underlie the harvest strategies and, therefore, vary over time. We illustrate these dynamics under the two scenarios for forests younger than 20 years and forests older than 120 years (Fig. 4). Young forests consistently predominate under the timber scenario. This is especially true during the first half of the simulation period, because a larger percentage of forests are maintained under the reindeer scenario. After 50 years, however, the extent of young forests is very similar between the two scenarios and stabilizes around 15 % of the landscape in both Sirges and Vilhelmina Norra. The area of forests older than 120 years increases

Table 5 Average relative differences for the economic effects over the 100-year simulation period between the two management scenarios in Sirges and Vilhelmina Norra

	Sirges			Vilhelmina Norra		
	Overall	Lichen-rich forests	Peatland forests	Overall	Lichen-rich forests	Peatland forests
Relative difference net income/m^3 timber (%)	79	71	59	85	77	53
Relative difference NPV (%)	89	72	51	90	68	41
Reindeer scenario (NPV/ha)	8,5	8,4	3,4	13,5	11,2	3,3
Timber scenario (NPV/ha)	9,6	11,6	6,8	14,9	16,4	8,1

Values (%) represent the ratio between the reindeer scenario and the timber scenario

in both scenarios. However, the prolonged rotation times applied in the reindeer scenario lead to a faster accumulation of old-growth forests.

Economic Effects

The summarized net income per year for the reindeer scenario generated 79 % of the net income per year of the timber scenario in Sirges and 85 % in Vilhelmina Norra (Table 5). In comparison, differences in net present values (NPV, with 3 % interest rate) between the two scenarios are less pronounced when considering the whole landscape with all its stands, because the first periods differ very little in net income between the scenarios (Table 5).

High costs at the beginning of the simulation period occur under both scenarios, but are due to different methods being applied. Under the reindeer scenario, high costs arise from extensive pre-commercial thinning, while fertilizer application incurs high costs at the beginning of the simulations under the timber scenario. However, costs stay at a fairly similar level between the two scenarios. The reduced income from the timber harvest under the reindeer scenario is mainly an effect of reduced levels of clear cutting, as well as from harvesting forests with lower standing volumes. Larger trees in the reindeer scenario do not compensate for the loss of income resulting from less dense forests. Net income tends to stabilize in Sirges after 45 and 50 years under the timber and reindeer scenarios, respectively. In Vilhelmina Norra, it takes 50 years under both scenarios to stabilize net income. As Fig. 3c illustrates, the net revenues differ to a larger extent after the stabilization in the second half of the simulation period compared to the first half. This is the result of the increasing difference in harvest level (see Sect. 3.1). In Sirges, net income generated under the reindeer scenario decreases from 87 % in the first half to 76 % in the second half relative to the timber scenario, and from 92 to 82 % in Vilhelmina Norra (Fig. 3c).

Discussion

Consequences Resulting from Different Forest Management Priorities

With the increasing industrialization of northern Sweden, there has been a shift in the perceived value of old-growth forests. Before introduction of clear-cutting practices in the 20th century, these forests were a source of high-quality timber and were logged by selective cutting of the largest trees (Östlund et al. 1997; Berg et al. 2008). As the extent of such forests declined, their importance for nature conservation purposes is recognized (Chapin and Danell 2001; Andersson and Östlund 2004), as emphasized in this study, for reindeer grazing.

Depending on the management scenario, forest characteristics differ at the end of the 100-year simulation period, which in turn will affect the supply and flow of ecosystem services to the reindeer husbandry and forestry. The forestry sector benefits economically from harvesting old-growth stands and the implementation of relatively short rotation times because a high harvest volume of biomass can be sustained by comparatively younger forests with a higher stem density and growth rate (Table 3; Fig. 3a).

Forests developed under the reindeer scenario with its focus on creating conditions for enhanced lichen growth are structurally different due to a lower density of stems/ha, but with larger trees because of the longer rotation times (Table 3). The reindeer scenario thus directs management strategies toward the early developmental stages of forests, e.g., early pre-commercial thinning, in order to create specific structures and functions of older forests. Therefore, as forests stabilize during the second half of the simulation period, differences in net income and harvest levels between both scenarios become more pronounced (Fig. 3). Less soil scarification and increased thinning, both promoting the growth of terrestrial forage resources, can be expected to have positive impacts for reindeer husbandry already at earlier stages. It is, therefore, reasonable to assume that terrestrial forage availability is increased in the reindeer scenario. Differences in revenues and harvest levels are therefore principally an effect of the harvesting strategies applied to those forests not included in these particular domains, i.e., effects of more pronounced pre-commercial thinning and earlier thinning of older trees to create more open forests (Table 3).

The retention of forests classified as arboreal lichen habitat in combination with prolonged rotation times is likely to promote the abundance of these organisms as forage resources for reindeer. At the landscape scale, forest stands on lichen-dominated soils and peatland forests cover only small proportions in both areas (Fig. 1). Therefore, very long rotation times and intensive thinning at both early and later stages do not have large impacts on the net income or the harvest.

How are Trade-Offs Achieved in the Landscape?

During the second half of the simulation period, the reindeer scenario generated 76 and 82 % of the economic income of the timber scenario in Sirges and Vilhelmina Norra, respectively. Similarly, Bostedt et al. (2003) found that increasing the proportion of forests older than 80 years caused losses to forestry that cannot be compensated for by higher economic benefits generated by reindeer husbandry. Korosuo et al. (2013) found an economic decrease of 4–5 % in their adjustment to reindeer husbandry needs. However, their model is based on comparatively minor modifications of the 'business as usual' scenario, and thus does not incorporate the strategies expressed by reindeer herders themselves. In that respect, our two scenarios represent rather different cases. As expected, the decrease in economic revenue between the two scenarios in our study exceeds the differences in earlier studies.

Given a multiple-use situation, agreement about a given management strategy requires trade-offs between opposing interests and different valuations of specific services at particular times and places, as well as sociopolitical factors. Harvest levels of both timber and non-timber forest products are largely determined by forest ecology and the structure of property rights (Nelson et al. 2011). Thus, taking account of such rights adds a social and political dimension to the interaction between natural and economic systems. The power to implement decisions is likely to differ between stakeholders, and therefore cannot be ignored in the management of natural resources (Widmark and Sandström 2012). Cultural diversity of land uses can, therefore, create challenges in agreeing on trade-offs. Nevertheless, merely recognizing indigenous peoples' knowledge in resource management is not sufficient. The initiation of a "bottom-up" process that fosters co-production of knowledge offers the opportunity to go beyond narrow contexts of conventional decision-making processes (Ellis 2005). Our "reindeer scenario," therefore, is such an opportunity for discussion between the two land users in Sweden's boreal forests

As our different management scenarios illustrate, forestry as practiced today is only one of the several potential choices along a continuum of management intensities. Likewise, forest management has not always been conducted in the way we currently observe (Moen and Keskitalo 2010). The adaptations of forest management to strengthen the forest services relevant for reindeer husbandry included in this study are presented as changes in forestry relative to present day forest management. By not recognizing that the current forest management is but one of many possible options, we become locked in an inflexible "rigidity trap" (Gunderson and Holling 2002; Allison and Hobbs 2004): the management regime resists change a priori, although changes in management may be necessary to navigate multiple-use situations, as presented in this study. Rather, an understanding is required of how institutions and management regimes developed to their current form, so that they are not regarded as unconditionally 'optimal,' but seen as processes (Folke et al. 2007).

Regarding forest management as practiced today as a "reference scenario" may therefore leave the impression that an adaptation of forest management to support other stakeholders than forestry primarily has negative consequences. However, the lowered income to forestry when adapted to reindeer husbandry (Fig. 3c) can be contrasted with costs to reindeer husbandry caused by forest management practices that have eliminated vital ecosystem services. For example, if grazing conditions are challenging, financially costly and labor-intensive adaptations need to be found (Löf 2013). The interactions between biophysical and socioeconomic factors that affect reindeer meat production are complex, and difficult to be expressed in quantitative models (Rees et al. 2008). This makes the estimation of the economic value of old-growth forests to reindeer husbandry, although offering essential services, problematic. However, a higher percentage of old forests under the reindeer scenario (Fig. 4) may indicate an increased functionality of the landscape to provide diverse grazing conditions. Monetary benefits to reindeer herders can thus become apparent as a reduction of investments in terms of workload and finances.

Reindeer husbandry cannot only be considered as meat-producing industry, as it also is a livelihood and culture-bearer for the Sámi population. Therefore, its value cannot be measured in purely economic terms. Using monetary scales to evaluate policy options in forest management ignores that prices are not synonymous with values (Lélé and Norgaard 1996) that are delivered as cultural services. Political support that initiates changes in policy could influence the performance of tools that assess the optimal distribution of costs and benefits between different actors, such as Multicriteria Decision Analysis (Davies et al. 2013). Thus, the choice of institutional solutions for negotiating trade-offs over environmental resources often is rather a concern of social justice than of economic efficiency (Paavola 2007).

Evaluation of Model Simplifications

We did not include increasing landscape fragmentation due to a growing infrastructure, such as roads or constructions of wind mill parks. Furthermore, predicted changes in climate were not included, which may affect lichen growth negatively (Cornelissen et al. 2001; Moen 2008), but increase the productivity and timber-yield of boreal forests (Skogsstyrelsen 2008).

In our model, forests were managed on a landscape scale, irrespective of the forest owner structure. From a practical perspective, the coordination of management strategies of several forest owners, including cooperation with respect to the spatial arrangement of certain forest types, would require time, resources, and changes in forest policy. This approach increases transaction costs, as the winter grazing grounds extend over forests that are owned by different companies or non-industrial private forest owners (Widmark and Sandström 2012). Therefore, the ownership structure may be a substantial obstacle administratively and legally that could obstruct landscape planning at large scales.

The model used in this study is not spatially explicit, i.e., it does not take into account relative arrangements of forest stands over time. This is not necessarily a major weakness, due to difficulties in orchestrating the timing and spacing of management by several owners in reality. However, studies using spatial modeling have found only low costs in terms of generated NPV of timber when spatially explicit models are included (Öhman and Wikström 2008; Öhman et al. 2011). However, size and spatial considerations with respect to habitat types may affect behavior and habitat selection by reindeer. For instance, the mean area of patches chosen by reindeer for prolonged periods of grazing exceeds the mean area of forest stands (Kivinen et al. 2011), as well as human disturbance during winter may affect habitat selection (Kumpula et al. 2007).

Habitat connectivity and landscape patterns are, therefore, important determinants of habitat suitability for the reindeer and an important aspect to consider when integrating multiple uses and increasing the cultural and biological significance of Swedish boreal forests. Optimization models to investigate costs and benefits for both land users should include alternative forestry methods, such as selective harvest to increase landscape variability, both at the stand level (e.g., multi-layered stands) and at the landscape level (e.g., diversity of forest age classes, coherence of important grazing grounds). Such diversity could buffer reindeer herders against difficult grazing conditions that arise due to variability in environmental conditions.

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