Mapping and Prioritizing Young and Middle-aged Forests for Lichen-Promoting Management

Balancing Forestry and Reindeer Husbandry

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Mapping and Prioritizing Young and Middle-aged Forests for Lichen-Promoting Management: Balancing Forestry and Reindeer Husbandry

Kartläggning och prioritering av ung- och medelålders skog för lavfrämjande skötsel: Balansera skogsbruk och renskötsel

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Abstract

In northern Sweden, reindeer rely heavily on ground lichen as a key resource for winter forage. However, forestry practices focused on production can negatively impact lichen abundance through denser stands, and the last 60 years have seen a decline of lichen-rich forests by 71 %. As a result, extensive research on adapted management for the benefit of ground lichen abundance has found improvement potential surrounding forestry practices on land overlapping between reindeer husbandry and forest companies.

This study aimed to develop a method for prioritizing stands for reindeer-adapted management by analysing lichen coverage and forest structure across more than 300 000 ha of productive forest land owned by Sveaskog. Spatial filtering was applied using lichen intensity data derived from a 10 x 10 m raster in combination with a forest stand dataset from Sveaskog. Forest stands were categorized by lichen abundance and developmental stage, and those classified as young or middle-aged were analysed based on structural parameters such as basal area, stem density and site index.

The results found that ground lichen was most prevalent in stands with low site productivity and lower stand density, reaffirming the literature. Management classes proved effective for identifying operationally viable stands and exhibited structural patterns consistent with literature on lichen ecology. However, uncertainties in data such as stem density indicate improvement potential with regards to more precise classification. The workflow developed in the study provides a practical framework for integrating ecological considerations into forest management for planning alongside reindeer husbandry.

Keywords: Boreal forest, habitat management, GIS, spatial analysis, decision-support

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1. Introduction

1.1 Reindeer husbandry and forestry

Before the expansion of the sawmill industry in the 1850s in northern Scandinavia, the use of forests was largely limited to Sami people and local agriculture. However, when the forests gained industrial value, major changes took place. During the last 100-150 years, management practices have changed substantially (Berg et al. 2008).

After the second world war, most productive forests were affected by the transition from mainly uneven-aged forestry to even-aged forestry. The change in management resulted in a higher growing stock and growth rates, as well as a densification of forests with larger areas of young and dense forests (Eggers et al. 2024). Except for the large-scale exploitation taking place during the latter part of the 19th century, the transformation of forest management practices has resulted in a change in forest structure on landscape level. Forestry replaced forest fires as the dominating disturbance factor, and with its progression, important consequences for the reindeer husbandry have followed (Berg et al. 2008).

In northern Sweden, forestry and reindeer husbandry overlap on the same land (Roos et al. 2022), a combination of land use where modern forestry creates complications for reindeer winter grazing and mobility, as well as conflicts (Jonsson 2013). To mitigate conflicting objectives regarding land use, a process referred to as “samråd” is applied, which in practice involves an exchange of information before decision-making (Roos et al. 2022). Conflicts originate from differing priorities between forestry companies and reindeer herding communities, such as timber production being the overall goal and main priority of modern forestry, which in turn affects the conditions for reindeer husbandry (Sandström et al. 2016).

The forest industry is an important part of the Swedish economy: the export value was 184 billion Swedish crowns as of 2023, and the number of employees in the industry was 140 000 in 2022 (Skogsindustrierna 2025). In areas where reindeer husbandry and forestry operate on the same land, the diverging objectives are often reflected in the use of forest land, and one of the main objectives of forest owners as well as forest policy has been to increase wood production. (Eggers et al. 2024). This facilitates the need for alternative management strategies where the preconditions of reindeer husbandry can be improved while ensuring sufficient wood production for the forest industry. In the context of this study, reindeer-adapted management refers to the improvement of ground lichen availability while at the same time maintaining high wood production, by seeking ways to prioritize alternative management where there is a need and potential for it. The main objectives of adapted forest management were described as keeping an open forest through earlier and more intensive cleanings and thinnings (ibid.). In this study, this is referred to as “reindeer-adapted management” and aims to benefit reindeer husbandry by creating forests that are sparse enough for ground lichen to thrive.

1.2 Winter pastures

Ground lichen (Cladina spp., Cetraria spp.) is one of the most important resources for reindeer and constitutes up to 80 % of their diet during the winter months (Sandström et al. 2016). Because of this, lichen-rich lands are critical for maintaining sustainable reindeer husbandry (ibid.). Ground lichen is a bottleneck for the longevity of reindeer husbandry, and lichen-rich forests have declined with 71 % during the last 60 years (Sandström et al. 2016; Roos et al. 2022). This loss is largely due to clear-cut forestry, where the increase of dense, young forests creates unfavourable conditions for ground lichen and reindeer husbandry accordingly (ibid.). Furthermore, 47 %, or 190,000 hectares, of remaining lichen-abundant forest is located on state-owned land (Sandström et al. 2016). The Swedish Forest Agency´s impact analysis showcases the same trends, where the proportion of ground lichen is expected to halve by 2025, and over the next 100 years it is projected to be one fifth of the current ground lichen coverage (Eriksson et al. 2022).

Beyond lichen-abundant forests importance during the winter months, areas between summer- and winter grazing grounds are of great importance. These are characterized by pine-dominance and lichen richness and also serve as transition zones during the yearly migration of the reindeer (Sandström 2016).

The area in Sweden where Sami people possess the right to practice reindeer husbandry, RHA (Swedish Reindeer Husbandry Area) is defined by the Sami parliament and includes approximately 55 % of the Swedish land area and circa 50 % of the productive forest land (Sandström et al. 2016). Another classification referred to as the Plan 78 (ibid.) represents an alternative extent of the RHA, that amounts to 47 % of the Swedish land area where approximately 3 % is made up of settlement, roads and agriculture. About 41 % of Sweden´s timber supply is located within the RHA, and 82 % of the land above the submontaneous coniferous boundary is state owned.

Sufficient access to reindeer grazing land is critical, and the importance of abundant lichen-rich areas are stressed by Widmark (2019). The dramatic decline of lichen has been stated to reach a point where traditional reindeer husbandry based on natural pasture is severely threatened (Eggers et al. 2024). As a way to tackle the decline of grazing areas, reindeer herders have turned to supplementary fodder, which is both costly and less efficient (Widmark 2019). In situations where limited resources – in this case land-use – are used by more than one actor, transaction costs are common. They refer to a type of negotiation cost, and are typical to situations where bargaining of resources is used to handle conflicts. In the reindeer-forestry situation, reindeer husbandry often carry the highest costs (ibid.).

1.2.1 Conditions for ground lichen

In order for ground lichen to thrive in a forest, a number of criteria needs to be fulfilled. The presence of ground lichen is dependent on a lower stand density; a basal area of 15 m^2 has proved optimal for lichen growth (Jonsson Čabrajič et al. 2010). Despite also occurring on higher basal areas, the abundance of ground lichen subsides considerably when stand density exceeds 20 m^2. Moreover, the Swedish Forest Agency´s impact analysis defined a maximum basal area of 18 m^2 as a threshold for ground lichen potential (Eriksson et al. 2022).

The Swedish Forestry Agency´s impact analysis determined site indexes (SI) between 12-20 as thresholds for ground lichen (Eriksson et al. 2022). Site index is a measure of site productivity, defined as the expected height (in meters) of the dominant trees at a reference age – which is usually 100 years in Sweden. For Scots pine, this is expressed as a T-value (e.g., T20 = 20 m at 100 years). This statement is reinforced by data from the Swedish national forest inventory (NFI), showing that about 90 % of forests with abundant to moderate occurrences of ground lichen in the RHA were situated in Scots pine-dominated forests with a site index of 12-19 (Eggers et al. 2024, see SLU 2022).

Several scientific articles highlight the importance of dry or mesic soils as key criteria for the occurrence and growth of ground lichen. Studies have shown that ground lichen thrive in well-drained soils with moderate moisture levels, often found in Scots-pine dominated forests (Eggers et al. 2024, see SLU 2022; Eriksson et al. 2022).

In Swedish forestry, “slutenhet” refers to the density of a forest stand, i.e., the number of trees within a given area. For stands where the average height is below 7 meters, it is measured as stem density, the number of main stems per hectare. For stands with an average height above 7 meters, “slutenhet” is estimated based on basal area and average height, producing a value between 0 (open canopy) and 1 (closed canopy) (Andersson & Persson 2023). This parameter indicates the extent to which the area is occupied by the canopy, and serves as an important addition to basal area (BA), since the basal area parameter provides less clarity on its own. Values between 0.2 and 0.5 have proved to correlate with lichen-abundant forests (ibid.).

Canopy cover refers to the proportion of the sky that is covered by trees when viewed from the middle of the plot. Canopy cover is estimated in %, where 0 % indicates that no tree crowns are covering the sky, and 100 % suggests a completely closed canopy, where no light is able to reach the ground (Andersson & Persson 2023). Lichen abundance has been found in canopy covers of 70 % and lower, the majority being represented in the range between 60 and 70 %. Furthermore, a clear increase of lichen-abundant forests has been shown where stem numbers fall below 2000 stems ha^{-1}. Another important factor is forest age, where the presence of ground lichen is the highest at ages between 10 and 40 years (ibid.). Eriksson et al. (2022) conclude that an increased proportion of areas with lower basal area, resulting from shorter rotation periods, could provide the conditions for a scenario where the abundance of ground lichen increases.

1.3 Alternative forest management methods

Today, managing and reducing conflicts is a significant part of the operations for forestry companies in northern Sweden. This often results in transaction costs, in this case referring to the costs involved in land-use negotiations between forestry companies and reindeer herders (Widmark 2019). Proposals for adjustments of management methods have been brought forward by the Swedish Sami Association through the program “A reindeer Husbandry Adapted Forestry” (Jonsson 2013). Clear-cutting is the most common forest management system in Sweden, but due to its negative influence on reindeer husbandry, alternative management systems are a central part of today´s debate.

Eggers et al. (2024) highlight clear potential for improvement resulting from adapted management methods on a large scale, where the occurrence of ground lichens, can increase significantly in a relatively short amount of time; within a 15-year period, adapted forest management has the potential to increase the area of forest with ground lichen habitat with 22 %, reaching a culmination after this point. One of the scenarios applied in the study was to adjust forest management practices to increase the area with ground lichen habitat and mobility of reindeer. This was determined by using the decision support system (DSS) Heureka PlanWise (Lämås et al. 2023).

The main adaptations used by Eggers et al (2024) were to replace Lodgepole pine with Scots pine at 30 or 55-60 years of age, maintaining a lower basal area, and to pre-commercially thin to lower stems ha^{-1}. When “reindeer-adapted management” is mentioned in this study, the framework described above as well as the ground lichen criteria described previously is what is referred to. The reference scenario, based on conventional forest management, aimed to maximize timber production and resulted in further decrease of ground lichen. This is because of the limited light penetration to the ground, inhibiting establishment and growth of ground lichen. Moreover, the alternative management scenario was calculated to result in a lowering of net income from timber production by 11-22 % (ibid.).

“Chequered-Gap-Shelterwood-System” is a type of alternative management, defined as a type of non-clear-cut forestry, in which half of the area is harvested while the rest is left to develop, following a “chessboard pattern” (Gunnarsson 2022). The method is a clear example of how alternative management methods can be a tool in the process toward a more sustainable cooperation between forestry companies and Sami villages. Respondents from an interview study regarding the method were generally positive towards Chequered-Gap-Shelterwood-System regarding its effects on both ground and tree lichen, where ground lichen was believed to benefit by the resulting distribution of shade and light (ibid.). Furthermore, snow conditions were identified as an important factor, as Chequered-Gap-Shelterwood-System leaves half of the forest standing. This leads to less compaction of snow compared to clear-cut forestry, favouring access for reindeer (ibid.).

1.4 Mapping and predicting lichen cover

The benefit of integrating diverse types of spatial data to inform decision-making processes has been highlighted in recent advances in forest management studies. For example, He et al. (2021) highlighted the need of calibration and validation for ground lichen mapping to surpass constraints. A method to map ground lichen cover over large areas in Eastern Canada was developed by combining drone (UAV) data, high-resolution satellite imagery and Landsat satellite data in order to support habitat management for woodland caribou which rely on ground lichen for winter forage. The differing resolutions and viewing angles of these three data sources made the combination of them useful for mapping lichen cover over vast areas, and shows how the combination of spatial data at different scales can improve decision-making for land and wildlife management (ibid.).

Another study (Silva et al. 2019) detected improvement potential in mapping lichens across continuous boreal forests, and created a regression model approach to map ground lichen abundance (biomass, kg ha^{-1}) in northwestern Ontario, Canada. By combining field sampling with remote sensing and GIS data, lichen presence and abundance was related to forest structure, topographic and remote sensing attributes, ultimately creating a map of lichen abundance in order to inform decision making for caribou.

Miina et al. (2020) applied an ecological model for ground lichen on a forest planning system, with the goal of assessing how well this model predicted the impact of forest management on ground lichen cover, specifically the percent cover on mineral soils in Finland. Predicted changes in lichen cover were compared against observed changes on stand level, under different forest management scenarios. The model proved effective for assessing long-term impacts of forest management on lichen cover and ecosystem services, and the study supports the use of such models in forest-planning systems to evaluate trade-offs and outcomes for biodiversity and reindeer pasture quality.

These studies relate to the analysis in this study with regards to the combination of different spatial data sources to support decision making for the benefit of lichen-dependent species.

1.5 Study area context

Sweden has a total area of approximately 41 million ha, of which Roughly 28 million hectares, or 68 % of Sweden's total area is forest land (SCB 2023). The RHA spans 23 million hectares (Hobbs et al. 2012). This represents 55 % of the total area and 50 % of the productive forest land in Sweden. Sveaskog owns 3.9 million ha of land (Sveaskog 2025). This constitutes 9.5 % of the land area in Sweden, the majority being situated in the north where reindeer husbandry is also the most active. Vapsten and Ubmeje Tjälddie Sami villages correspond to approximately 2.4 and 1.9 % of Sweden's land area respectively.

Table 1 summarizes the spatial extent of Sveaskog's land in relation to the land area of Sweden, its forest land, and the the Reindeer Husbandry Area (RHA), as well as their proportions relative to the land area of Sweden.

Table 1. Spatial extent of Sweden, its forest land, the Reindeer Husbandry Area (RHA), Sveaskog's land ownership, and the spatial extents of Vapsten and Ubmeje Tjälddie Sami villages, as well as the research area used in this study. The table displays the proportion of each area relative to the land area of Sweden.

Area extent	Area (ha)	Share of total land area in Sweden (%)	Source
Swedish land area	41 000 000	100	SCB (2023).
Swedish forest land	27 900 000	68	SCB (2023).
RHA	23 000 000	55	Hobbs et al. (2012).
Sveaskog	3 900 000	9.5	Sveaskog (2025).
Vapsten	972 500	2.4	Sametinget (2025b).
Ubmeje Tjälddie	780 600	1.9	Sametinget (2025b).

The research area is situated within Vapsten and Ubmeje Tjälddie Sami villages that overlap with Sveaskog's productive forest land and the RHA, see table 3.

1.6 Problem

The overlap between forestry and reindeer husbandry in northern Sweden has created long-lasting conflicts of interest, complicating for both sectors. The change in forest structure has contributed to significantly reduced ground-lichen presence and thereby deterioration of reindeer grazing conditions (Eggers et al. 2024). As a result, there is a great need of methods for mapping and measuring ground lichen. Simultaneously, forestry is a central part of the Swedish economy (Skogsindustrierna 2025), and a sustainable future for both parties requires a balance between ecological, social and economic impact. Transaction costs resulting from land-use conflicts typically affect reindeer husbandry more dramatically than forest companies, but adapted management practices have shown to lower net income from timber production (Widmark 2019; Eggers et al. 2024). To effectively work towards a situation where both reindeer husbandry and forestry benefits and to mitigate conflict, reindeer-adapted management methods should be implemented in areas where there is both a need for and potential to implement integrated forestry practices where ground lichen as well as biomass production are encouraged.

Reindeer lichens generally have low growth rates, and have certain requirements in order to thrive, particularly light availability (Kumpula et al. 2000; Jonsson Čabrajič et al. 2010). The densification and increased proportion of younger stands has reduced light penetration to the ground, thereby limiting lichen growth. This suggests an importance of identifying forest stands where structural interventions, such as thinning, could improve light conditions early in stand development.

Despite previous research on alternative management approaches that positively impact reindeer husbandry, there is no comprehensive mapping of land within the RHA that overlaps with reindeer husbandry areas, as well as methods to prioritize sites for reindeer-adapted management. Combining spatial data on lichen presence with a focus on younger to middle-aged stands that are approaching or already in need of thinning may offer opportunities to establish or maintain ground lichen habitats before canopy closure becomes too advanced, thereby increasing long term potential for valuable grazing areas.

1.6.1 Purpose

The purpose of the study is to map the geographical distribution of dense young and middle-aged forest that overlap with reindeer grazing areas and, based on their lichen cover, develop methods for prioritizing forests for adapted management.

The analysis will be conducted on Sveaskog's forest holdings within the Ubmeje Tjälddie and Vapsten Sami villages in Västerbotten county, Sweden.

The following research questions will be addressed:

What proportion of the study area consists of dense young or middle-aged forest where pre-commercial thinning or thinning is either needed or likely, and should be prioritized for reindeer-adapted management?

What is the distribution of high, moderate and low lichen cover respectively, across dense young or middle-aged forests where pre-commercial thinning or thinning is either needed or likely, and what are the characteristics of the forests in these areas?

How does the prioritization established in the study align with the Sami villages´ own prioritizations of important sites for adapted management?

2. Materials and methods

2.1 Study design

To identify key areas for the study, and to prioritize forest for adapted management, the study focused on remote sensing through GIS. Forest land within the Ubmeje Tjälddie and Vapsten Sami villages were analysed to classify the forest land based on management class, its current lichen coverage and previous management. This classification was then used to map areas with high potential for lichen growth in combination with their need of future management. Based on this, important stands and their parameters were then analysed based on their lichen cover and importance for reindeer husbandry.

To characterize stands by their need of further management as well as by type and amount of lichen cover, the dataset was divided into parts based on previous management, the forest's silvicultural stage as well as lichen coverage within stands. This allowed for the dataset to be analysed with regards to future lichen potential but also future need of adapted management.

2.2 Data collection, mapping and selection criteria

2.2.1 Data sources

From Sveaskog, stand data in the form of a shapefile was obtained. The shapefile contained polygons representing stands, and each polygon contained values for a number of stand parameters. The shapefile was distributed across two Sami villages, Ubmeje Tjälddie and Vapsten, and served as the outline of the study area. Stand parameters that were used in the study are defined in Table 2:

Table 2. Forest parameters of the research area. The table displays the value fields that were present in each of the polygons in the shapefile and used for the analysis.

Alias	**Parameter**	**Unit**
AGOSLAG	Land-use type	Categorical
SKOGSMHA	Forest hectares	Hectares
GRUNDYTA	Mean basal area	M^2ha^{-1}
ALDER	Mean age	Years
STAMANTAL	Stem density	stems ha^{-1}
DIAMETER	Mean diameter	Centimeters
SIMETER	Site index	Dominant height at age 100 years (meters)
UTVKL	Management Class	Categorical
SITSL	Site index species	Categorical
HOJD	Mean height	Meters

To supplement the data provided by Sveaskog, a model-based lichen cover raster developed by Sametinget (2022) was used in order to combine forest stand data with data on lichen cover. The raster combines field inventory data from both the National Forest Inventory (NFI) and Sami village inventories with remote sensing data. This approach improves on earlier versions of the map, which were based solely on NFI data and tended to underestimate areas of higher lichen cover. The inclusion of Sami village data increased the model´s description of higher coverage levels and greater variation across the landscape. Further validation by Sametinget (2022) also demonstrated a strong correspondence between reindeer GPS positions and areas of high lichen coverage, indicating the raster´s relevance for identifying grazing resources.

Additionally, a shapefile highlighting forest stands within the study area identified as being of particular relevance to the Sami villages was obtained from Sveaskog. This included stands with operations requested by Sami villages Vapsten and Ubmeje Tjälddie at joint planning meetings in recent years.

2.2.2 Research areas

The research area encompasses 309,476 ha and represents forest owned by Sveaskog that overlaps with grazing grounds belonging to Sami villages Ubmeje Tjälddie and Vapsten (Figure 1, Table 1, Table 3).

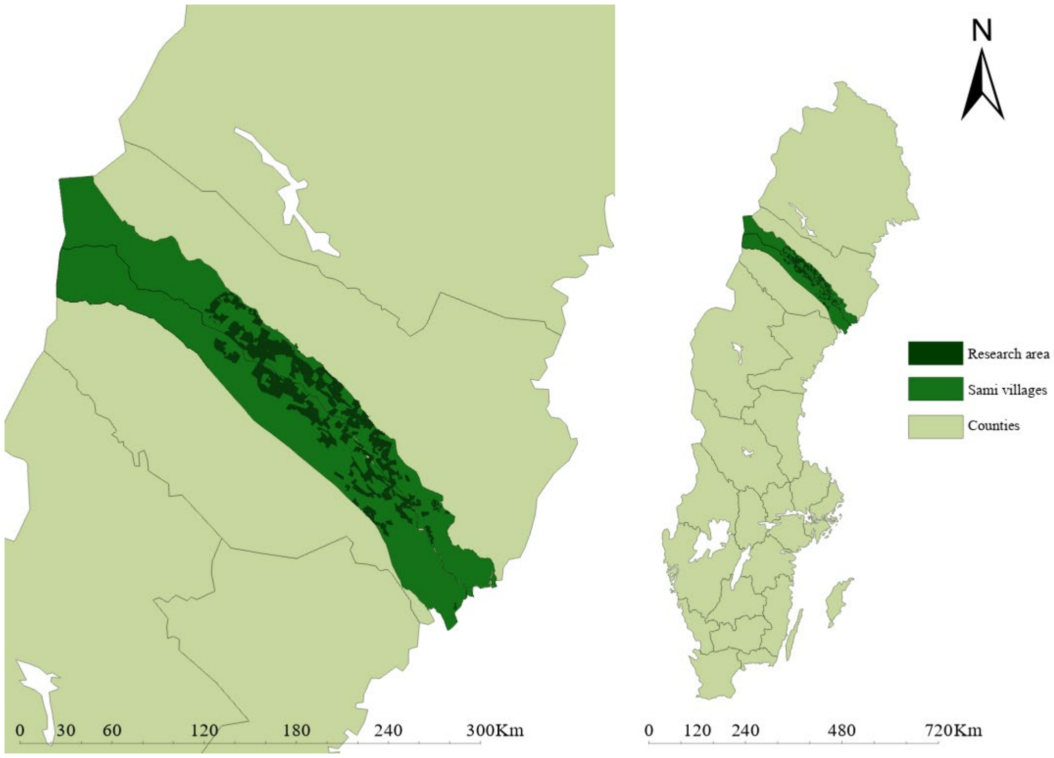

Figure 1. The research area in northern Sweden, with an overview map (right) and a detailed view (left). The map displays the spatial extent of the research area, Sami villages and county borders (Sametinget 2025a).

Table 3 shows the total area represented by the research area and its productive forest land, as well as their shares of the total land area owned by Sveaskog. The research area and its productive forest land makes up around 8 and 6 % of the total respectively. The research area refers to the total extent of the unfiltered dataset, and its productive forest land is the data used for the spatial analysis. It refers to the remaining area after filtering out non-forest land. Roughly 77 % of the research area consists of productive forest land, which makes up around 62 % of the total amount of stands. The remaining part of the research area is defined as other land-use categories, i.e., unproductive land. The size of the research area is equal to 32 % and 40 % of the extents of Ubmeje Tjälddie and Vapsten Sami Villages respectively.

Table 3. Spatial extents and stand counts of the research area and the productive forest land within it, and their proportions relative to Sveaskog's total land ownership.

Area extent	Area (ha)	Share of total Sveaskog land (%)	Share of Research area (%)	Number of stands	Share of total stands in research area (%)
Research area	309,476	7.9	100	32,347	100
Productive forest land	237,372	6.1	76.7	20,200	62.4

2.2.3 Selection criteria

In order to classify dense, young and middle-aged forest within the research area with regards to lichen cover, it was divided into subcategories based on the lichen raster, management classes and a small number of criteria.

The original shapefile contained stands across a range of land-use classes and showed all stands within the study area, meaning no previous classification was done with regards to parameters or previous management. The first criteria that was set was land-use class = forest land, to exclude all types of land-use not relevant for the study. The dataset contained stands within Sveaskog's forest tenure in which they only recognise productive forest land. For that reason, the forest land in this new layer could with high certainty be deemed as productive forest land.

Lichen coverage was evaluated both as a spatial intensity value (classes 1-4) (Table 4), and as a polygon-level summary of how much of each polygon was covered by those values, (Table 5). This dual classification allowed for a more nuanced understanding of individual stands' grazing value. While intensity classes alone indicate lichen density in a small location, they do not describe how widespread that density is across entire stands. Contrarily, coverage classes alone do not reflect the suitability of the lichen cover in terms of its density. By using both classifications in combination, the analysis could identify stands where ground lichen was of both sufficient quality and quantity.

In order to locate and define areas depending on their lichen cover, the lichen map was divided into four subcategories (Table 4). The lichen raster had values in a range from 1-70, each value indicating a percentage of lichen cover within a 10 x 10 meter area. For example, this means a value of 10 corresponds to 10 m² of lichen for that pixel. These values indicate local intensity but do not represent true areal coverage of lichen within the forest stands.

Table 4. Lichen intensity classes used for classification. Values represent the proportion of lichen (%) within a 10 x 10 m plot.

Lichen intensity class	Values (%)	Corresponding NFI classification
1	1-10	-
2	10-25	Lavristyp
3	25-50	Lavrik typ
4	50-70	Lavtyp

Lichen intensity classes were derived from the lichen raster pixel values. The classification was done with the purpose of dividing the research area into classes based on the local abundance and continuity of lichen. Tendencies for reindeer to spend more time grazing in areas with greater lichen cover have been observed, suggesting that lichen cover needs to be relatively connected as opposed to being distributed in small patches (Kumpula 2001). The classification was based on NFI classifications where "lavristyp", "lavrik typ" and "lavtyp" represents coverage of 10-25, 25-50 and over 50 % of bottom layer plots respectively (table 4). All three of these classes are considered good for reindeer grazing (Projektet Kompetensutveckling Skogsbruk och Rennäring 2014). However, this does not always mean that areas with lower coverage levels than 10 % are unimportant for reindeer husbandry, since this also depends on reindeer behaviour and assessments of reindeer herders.

In order to distinguish between local lichen abundance and stand-level coverage, a complementary lichen classification was developed; lichen coverage classes were produced by calculating the share of each forest stand overlapping with each intensity class (Table 5). The lichen coverage classes shown in this table (A-C) differ conceptually from the lichen intensity classes displayed in Table 4 (1-4). While the lichen intensity classes represent lichen coverage within each 10 x 10 m raster pixel, the lichen coverage classes describe how much of an individual forest stand's area is occupied by pixels in any of the lichen intensity classes. In other words, lichen intensity was a local ground cover value explaining continuity of lichen over small areas, while lichen cover class represented a spatial extent at stand level. After this classification step, each forest stand could fall into 12 different categories, i.e., if more than 50 % of the stand was covered by pixel values between >10-25 %, this stand would fall into lichen cover class C and lichen intensity class B.

Table 5. Lichen cover classes representing the total proportion of each forest stand covered by any given lichen intensity class.

Lichen cover class	Proportion of intensity class within stand (%)
A	>0-25
B	>25-50
C	>50-100

Further classification was made in order to divide the research area into categories based on their management class. One of the fields assigned to each polygon in the shapefile was called "UTVKL" (Table 6) and represented development classes for each stand. In this study, the parameter is referred to as "management class". Related to the purpose of the study, three management classes were the most relevant and chosen for the classification: 21, 31, and 32. In this step, every current layer was divided into sublayers based on what management class was assigned to them. The shapefile contained polygons classified into 11 management classes, of which the classes relevant to the study are defined in Table 6:

Table 6. Key forest management classes (UTVKL) from Sveaskog stand data. For every forest stand, a management class was assigned, referring to the silvicultural stage of the forest.

UTVKL (Management Class)	Type of forest
21	Young forest with proposed or planned pre-commercial thinning
31	Middle-aged forest requiring thinning where first thinning has not yet occurred
32	Middle-aged forest where first thinning has been carried out and further thinning is proposed or likely

The extent of the aforementioned management classes within the research area is shown in Table 7. Every one of these represented forests where further management of young or middle-aged forests was either needed or likely, which fit the research questions and purpose of the study. Furthermore, it helped identify forests where the absence of management likely would result in stands too dense for lichen growth. The purpose of classifying the land based on these criteria was to create groups of stands, each with a different combination of management classes and lichen coverage. This classification step led to the final selection of stands, i.e., the stands that through this analysis were to be prioritized.

Table 7 represents the area and number of forest stands inside the three management classes chosen for analysis, as well as their proportion relative to the total area of productive forest land: young forest with proposed or planned pre-commercial thinning (class 21), and middle-aged forests before and after first thinning, where thinning is needed, proposed or likely (classes 31 and 32). Management classes 21, 31 and 32 collectively account for approximately 42 % of the productive forest land in the study area. These classes were prioritized for the analysis since they reflect key intervention stages where forest structure in the near future can be modified to support reindeer grazing conditions. Class 21 makes up around 15 % of the total forest land in the research area and represents early-stage stands where the future of reindeer grazing conditions depend on following pre-commercial thinning. Classes 31 and 32 represent 17.4 and 9.2 % respectively and represent mature stands where thinning intensity will pave the way for future lichen coverage.

Table 7. Area (ha) and stand count for key forest management classes, and their proportions relative to the total productive forest land within the study area.

Layer	Area (ha)	Share of total productive forest land (%)	Amount of stands	Share of total forest stands (%)
Management class 21	35,536	14.9	3,256	16.1
Management class 31	41,324	17.4	2,772	13.7
Management class 32	21,768	9.2	1,520	7.5
Total	98,628	41.7	7,548	37.2

2.3 Methods of analysis

2.3.1 ArcGIS Pro

Initially, the data serving as the basis for the analysis was imported into ArcGIS Pro. These include the vector layer over the entire study area and the lichen raster.

> *"GIS is a computer system that creates, manages, analyzes, and maps data that is attached to unique locations. It enables users to capture, store, manipulate, analyze, and present spatial or geographic data." (Bajjali 2023).*

GIS (Geographic Information System) is a tool that helps visualize patterns and relationships and allows its users to, through complex questions, analyze many features at once and then see the results on a map. To capture, store, query, analyze, display and present data are the six fundamental operations that a GIS performs. It is used all over the world to achieve various tasks such as managing the environment, and allows users to study virtually everything, such as land management, climate, natural resources etc. (Bajjali 2023).

In ArcGIS Pro, geoprocessing tools are used to perform spatial analysis and manage GIS data, and will in this case classify forest land based on aforementioned criteria. To streamline the process, ModelBuilder was used. ModelBuilder is a feature in ArcGIS Pro that can be used to create and manage geoprocessing models that automate different tools. These models combine sequences of geoprocessing tools, and works by directing outputs from one tool into other tools as inputs (Bajjali 2023). In this study, ModelBuilder was used to create workflows that classify areas based on the parameters of several layers of spatial data.

2.3.2 Workflow

A definition query was applied to the vector layer over the research area to select only forest land (land-use class 10, “AGOSLAG” in Table 2). This was then exported to create a new layer with this classification (Figure 2a). Before exporting, a new field was created in the attribute table of the layer. It was named “forest_id” and was calculated to equal the individual ID’s of every polygon. This was done by setting *forest_id* to equal the individual ID’s for each stand. By doing this, *forest_id* could be used to track the original polygons throughout the analysis, making sure the values of interesting parameters could always be linked to the same polygons.

The lichen raster, with a range of values between 0 and 70 was classified into four classes (Table 4). Each of the four new layers were converted into polygon format to facilitate spatial overlay. The vector layer classified as forest land was overlapped with each lichen intensity class layer, creating one overlapping layer for each lichen intensity class (Figure 2b). This was done with the intersect tool (Bajjali 2023).

After each intersection, the dissolve tool was used to preserve the original shape of the polygons from the vector layer over the research area (Bajjali 2023). Each layer was dissolved by “forest_id” in order to link each polygon from the intersected layers with the shapes and ID’s of the original forest stands. By doing this, each polygon from the overlap could be traced to the original forest stand which was crucial for the steps to come. ModelBuilder in ArcGIS Pro was used to streamline this multi-step process – including classification of the lichen raster into intensity classes, conversion to polygons, intersection with forest stand data, and dissolution by stand ID. This automation allowed the workflow to be executed efficiently without the need of completing each step individually.

For each of the four current layers, two new fields were added to the attribute table: “lichen_area” and “lichen_percent”. The field *lichen_area* represented the area (in hectares) covered by the corresponding lichen intensity class within each forest stand and was calculated using the calculate geometry tool (Bajjali 2023). *Lichen_percent* was derived by dividing *lichen_area* with the total area of the stand and multiplying by 100, yielding the percentage of lichen cover for each stand. Each layer was then further classified into three sublayers each based on lichen cover percentages (Figure 2c), following the coverage class thresholds defined in Table 5. This classification produced a total of 12 layers – three for each original layer – representing low, medium and high lichen cover classes.

Finally, each of the 12 lichen sublayers was further divided into three new layers based on management class 21, 31, and 32, (Table 6, Figure 2d). This process was intended to yield a total of 36 layers (12 x 3). However, due to the scarcity of stands meeting the criteria of high lichen intensity and coverage classes, several of these combinations produced extremely small or empty outputs. To maximize the quality of the analysis on structural characteristics across all combinations in the final prioritization output, these were excluded from the analysis. Ultimately, this resulted in a final output of 21 layers, and the combinations of lichen intensity, coverage, and management classes that were excluded are shown in Figure 4. The excluded data included three stands, two of which met the criteria of lichen intensity class 2 and coverage class C, and one stand that met the criteria for lichen intensity class 3 and coverage class B. The exclusion answered for a total of 13.9 ha of ground lichen cover, or 0.01 % of the total lichen cover on forest land. For the remaining combinations that were eliminated, zero stands met the criteria.

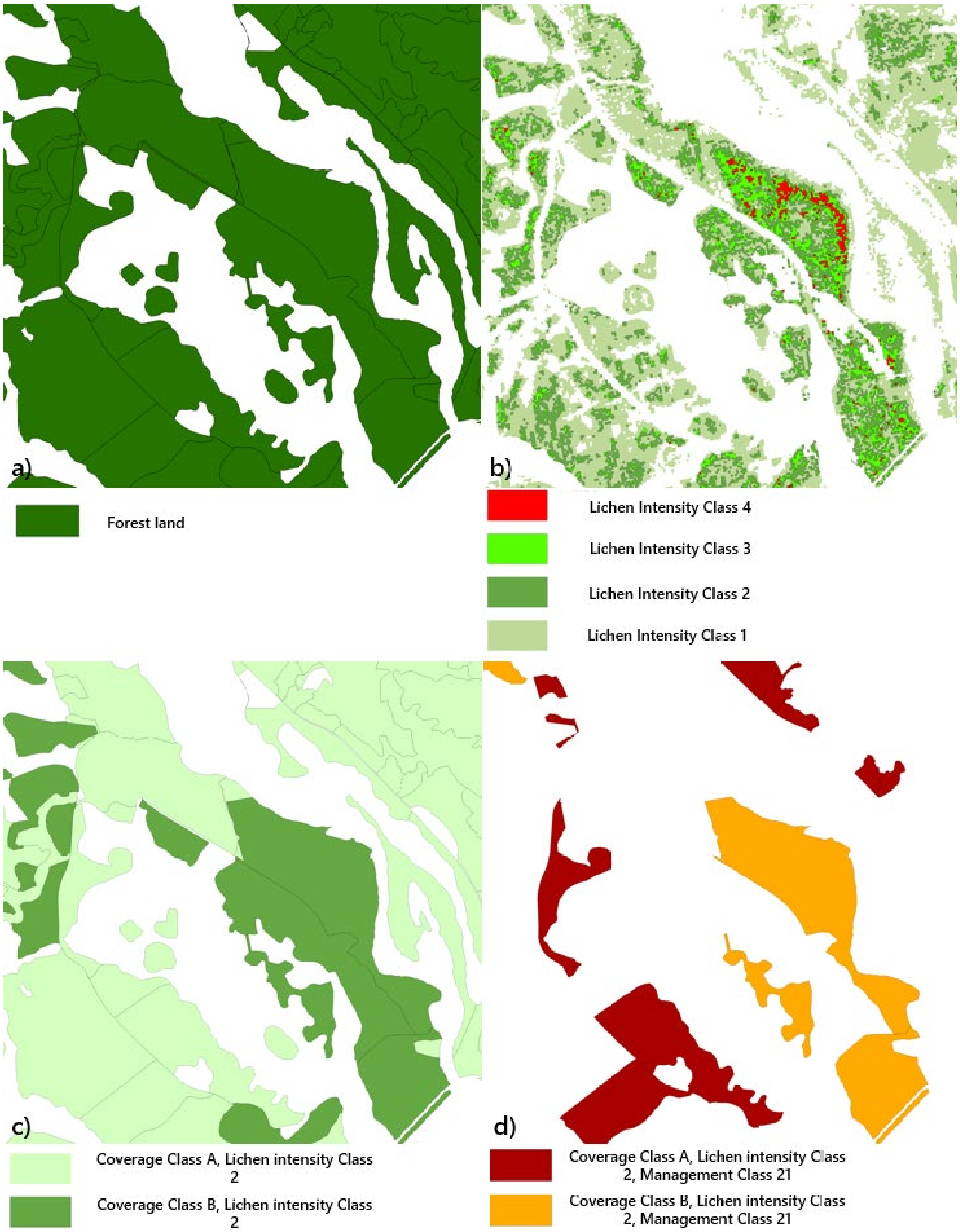

Figure 2. Visualization of the classification process used for a part of the study area. (a) Productive forest land based on stand data. (b) Lichen intensity classes 1-4 across productive forest land, derived from raster data. (c) Example of spatially grouped stands classified by lichen intensity and coverage class (coverage classes A and B for lichen intensity class 2). (d) Further classification of the same stands by management class (management class 21).

The layers were then analysed to assess the distribution of forestry-related parameters across the different combinations of lichen cover and management class. The parameters that were of highest relevance for the study were site index, age, basal area (m^2ha^{-1}) and stand density (stems ha^{-1}). Their changes across management classes and lichen intensity classes are illustrated in Table 10. This allowed for a comprehensive evaluation of lichen coverage patterns related to forest structure. In addition, the final output was used to describe the abundance of lichen cover in intensity classes 1-4 and their proportion of the total research area. Furthermore, through analysing this distribution across management classes, prioritization of stands for reindeer-adapted management was assessed based on the silvicultural stage of the forests in which the lichen was present.

Finally, the shapefile containing stands identified by the Sami villages as important was spatially overlaid with the final prioritization to evaluate how the prioritization established in the study aligned with a prioritization made by local Sami people.

The overall GIS workflow is summarized in Figure 3:

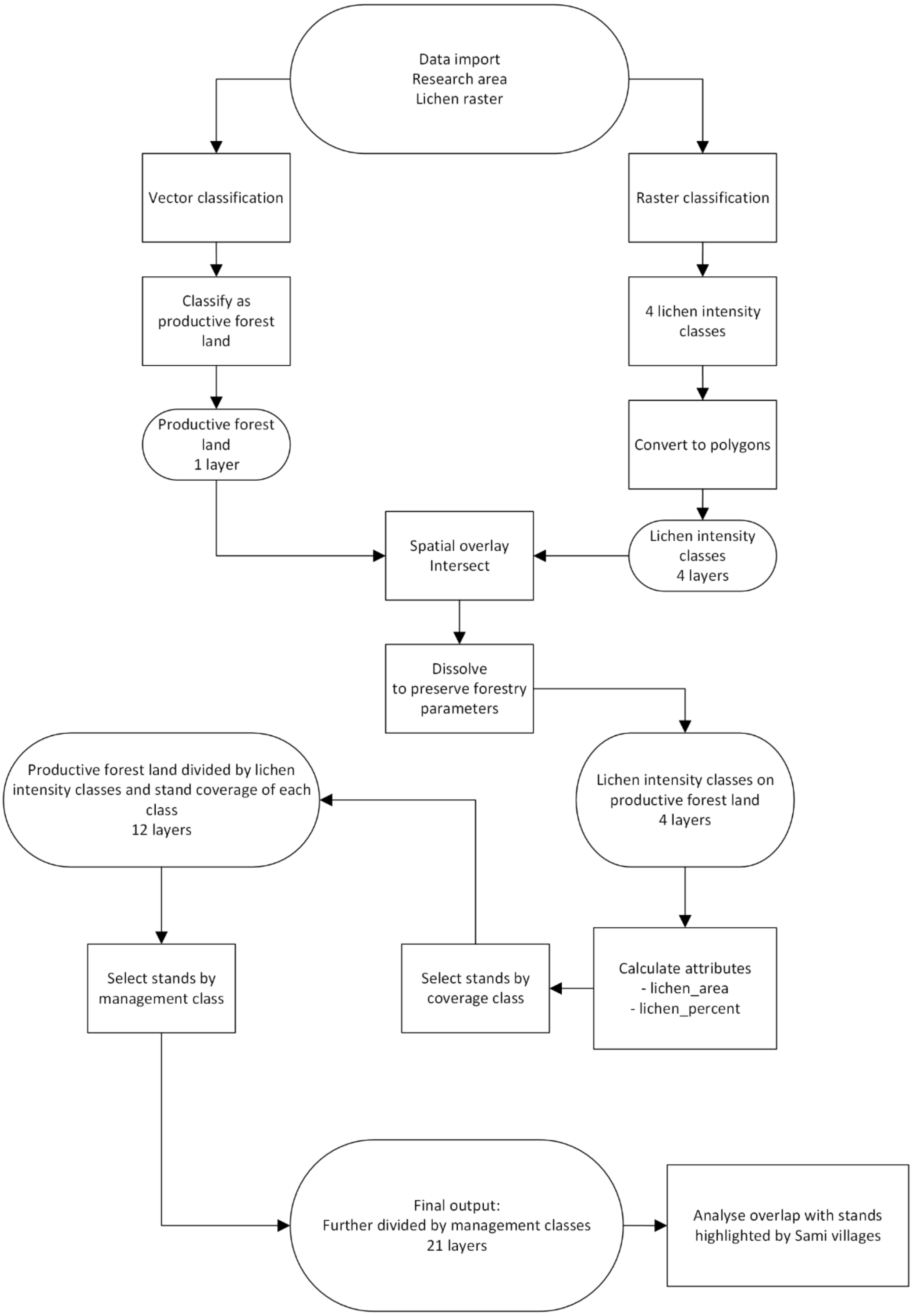

Figure 3. GIS Workflow for Forest Stand Classification. Spatial analysis steps used to classify forest stands into based on lichen cover and management class. Vector-based forest data and raster-based lichen data were intersected and classified into lichen

intensity and lichen coverage classes, which were later filtered by management class to produce a final set of 21 layers.

The final set of layers used in the analysis is summarized in Figure 4, which indicates inclusion or exclusion across lichen intensity class and cover thresholds, as well as forest management classes.

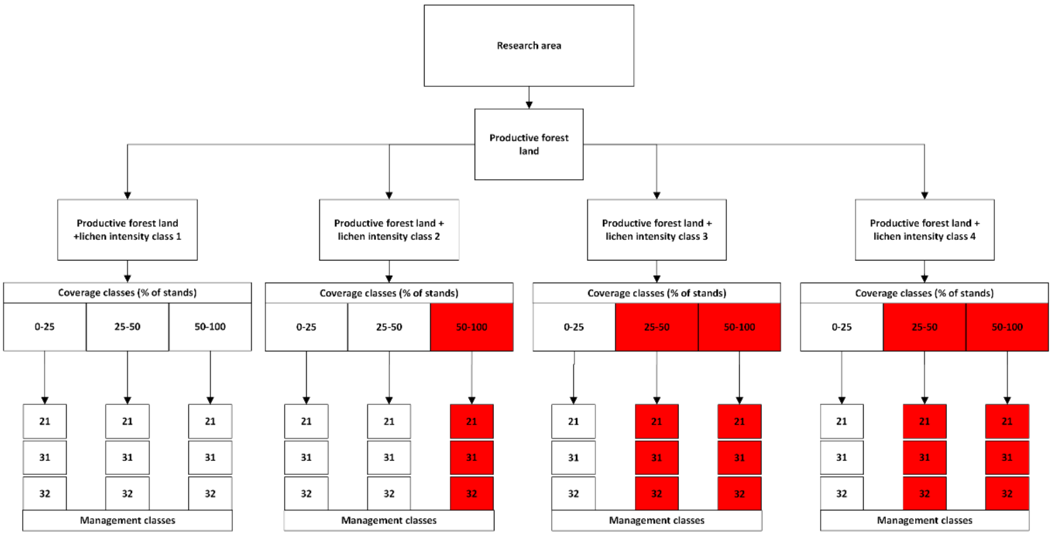

Figure 4. Illustration of how the initial research area was classified into subclasses based on lichen intensity and coverage of each lichen intensity. Red cells represent layers excluded due to small or empty outputs.

In order to visualize the output in a comprehensible way, each stand from each final layer was selected in the original shapefile. This way, the prioritized stands were visualized to their full extent. Since the final layers were the result of intersection with forest stands and lichen intensity classes, the polygons were only visible as the lichen coverage inside the forest stands, not the shape of the stands themselves. By doing this, the stands that were to be prioritized could be highlighted in a practical manner. Figure 5 shows an example of how prioritized stands can be visualized spatially in GIS. The example shows stands within coverage class B (>25-50 % lichen coverage), lichen intensity classes 1 (1-10 %) and 2 (>10-25 %) and across all three management classes. The upper half of the map displays only the lichen covered areas (10 x 10 m raster pixels) within prioritized stands, whereas the lower half shows the full spatial extent of each corresponding stand polygon. The same procedure can be applied to any combination of layers, facilitating planning of adapted management depending on objectives.

Figure 5. Spatial visualization of prioritized forest stands for reindeer-adapted management within Coverage Class B (>25-50 % lichen coverage), Lichen intensity Classes 1 (1-10 %) and 2 (>10-25 %), and across all three relevant management classes. The upper map shows the lichen covered areas within each stand, while the lower map displays the full stand polygons for the same area.

3. Results

3.1 Lichen cover distribution

Table 8 shows the extent and coverage percentage for each lichen intensity class overlapping with forest land. 10 x 10 m pixels with a lichen cover of 1-70 % were detected on 52.2 % of the forest land within the research area, but the vast majority of this fell into the lowest intensity class (1-10 %). Moderate to high lichen cover on forest land (classes 2-4) was very rare, making up 2.7, 0.4, and 0.05 % of the lichen map respectively. Total lichen raster area refers to the total area of lichen cover of 1-70 % on productive forest land.

Table 8. Total area (ha) and distribution of lichen intensity classes within productive forest land, regardless of management class, and their proportions relative to the total productive forest land in the research area.

Layer	Area (ha)	Share of total productive forest land (%)	Share of total lichen area (%)
Lichen Intensity Class 1 (1-10 %)	116,466	49.1	83.1
Lichen Intensity Class 2 (>10-25 %)	6,449	2.7	4.6
Lichen Intensity Class 3 (>25-50 %)	849	0.4	0.6
Lichen Intensity Class 4 (>50-70 %)	113	0.05	0.08
Lichen on productive forest land (1-70%)	123,877	52.2	88.4

The final output only included forest stands with management class 21, 31, or 32. These stands were in the context of the study considered to be subject to prioritization, and their distribution across lichen intensity classes and coverage classes is shown in Figures 6 and 7. This output produced a total of 7,518 unique stands, 98,634 ha of productive forest land and 51,038 ha of lichen cover in total, making up approximately 37 % of the total amount of forest stands, 42 % of the total productive forest area and 22 % of the total productive forest land respectively, as well as 41 % of the total lichen covered area.

Table 9 summarizes the lichen-covered area in the prioritized stands, expressed both in hectares and as proportions of total forest land, total lichen area, and total lichen area on forest land in the research area. The total area of the prioritized stands was 51,038 ha, with the largest share in lichen intensity class 1 and coverage class C. Management classes 21 and 31 each accounted for around 15 % of total lichen on forest land, while class 32 contributed roughly 10 %. Summing values across any of the three category types (lichen intensity class, management class, or coverage class) yields the total for the prioritized area.

Table 9. Number of stands, total lichen-covered area (ha), and their proportions relative to total lichen cover on productive forest land, total lichen raster area, and total productive forest land, for each category of management class, lichen intensity class, and lichen coverage class in prioritized stands.

Classification type	**Lichen area (ha)**	**Share of total lichen area on productive forest land (%)**	**Share of total lichen area (%)**	**Share of total productive forest land (%)**
By Lichen Intensity Class				
Lichen Intensity Class 1 (1-10 %)	47,912	38.7	34.2	20.2
Lichen Intensity Class 2 (>10-25 %)	2,751	2.2	2.0	1.2
Lichen Intensity Class 3 (>25-50 %)	337	0.3	0.2	0.1
Lichen Intensity Class 4 (>50-70 %)	38	0.03	0.03	0.02
By Management Class				
Management class 21	19,200	15.0	13.7	8.1
Management class 31	19,601	15.8	14.0	8.3
Management class 32	12,237	9.9	8.7	5.2
By Coverage Class				
Coverage Class A	5,500	4.4	3.9	2.3
Coverage Class B	11,805	9.5	8.4	5.0
Coverage Class C	33,733	27.2	24.1	14.2
Total (Prioritized stands)	51,038	41.2	36.4	21.5

Furthermore, areas pointed out as especially important for the reindeer herding community within the study area consisted of 158 stands and 3,461 ha in total. Among these, 105 stands and 2,554 ha were situated inside the final output. This demonstrates that the prioritization established in the study managed to capture 74 % of the stands defined by the Sami villages, and that this portion lies within management classes 21, 31, and 32.

In coverage class A, where less than 25 % of each forest polygon was covered by any given lichen intensity class, a vast sample of stands were available across all management classes and lichen intensity classes. Out of all three coverage classes, this group represented the largest and most evenly distributed dataset. Coverage class B included stands where 25 % or more of each polygon were covered by any of the lichen intensity classes. Data availability was more limited in this class since the amount of stands in 3 and 4 were either none or extremely low. Coverage class C represented forest polygons where more than 50 % of the area was covered by any of the four lichen intensity classes. This class showed a further drop in data availability, as zero or an extremely low number of stands overlapped with lichen intensity classes 2-4, leading to the exclusion of these during classification.

Figure 6 illustrates the distribution of the final mapped lichen area across different combinations of management class, lichen coverage class and lichen intensity class. Coverage class C (>50 % coverage) contained the largest total lichen cover. Across all combinations, lichen intensity class 1 (1-10 %) dominated the total area. While representing almost half of the lichen covered area throughout coverage class A, lichen intensity classes 2-4 were mostly restricted to this coverage class and only accounted for a small fraction of the total lichen covered area.

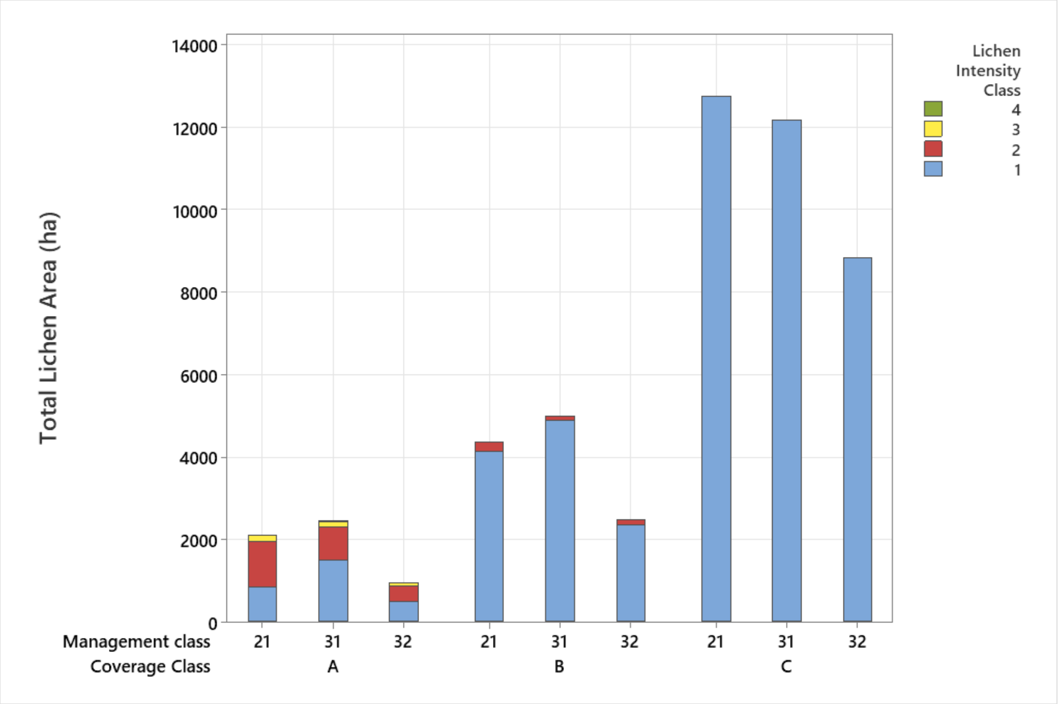

Figure 6. Total ground lichen area (ha) distributed by management class (21, 31, 32), lichen coverage class (A-C), and lichen intensity class (1-4). Each bar represents the distribution of lichen coverage (in hectares) for each lichen intensity class within a given management class. Management classes are grouped by lichen coverage class. Bars are stacked by lichen intensity class, showing the relative distribution of each intensity level.

Figure 7 presents the number of occurrences of stands within the different subclass combinations in the final output. Instead of unique stand counts, values indicate how many times stands appear across combinations of management class, coverage class, and lichen intensity class. Because a single stand could meet the criteria for more than one subclass, the total number of recorded occurrences (17,203) was higher than the total number of unique stands (7,518). This overlap occurred when a stand contained multiple lichen intensity and coverage class combinations, leading to its inclusion in several categories.

The pattern of distribution showed that the majority of observations fell within coverage class A (>1-25 % stand coverage), where higher lichen intensity classes (2-4) represented the largest amount of stands. Management class 21 consistently recorded the highest number of occurrences in each coverage class, particularly in coverage class 1. Across all management classes, the number of occurrences of stands, both in general and with higher lichen intensity, declined substantially from coverage class A to C, reflecting the scarcity of continuous high-coverage lichen areas.

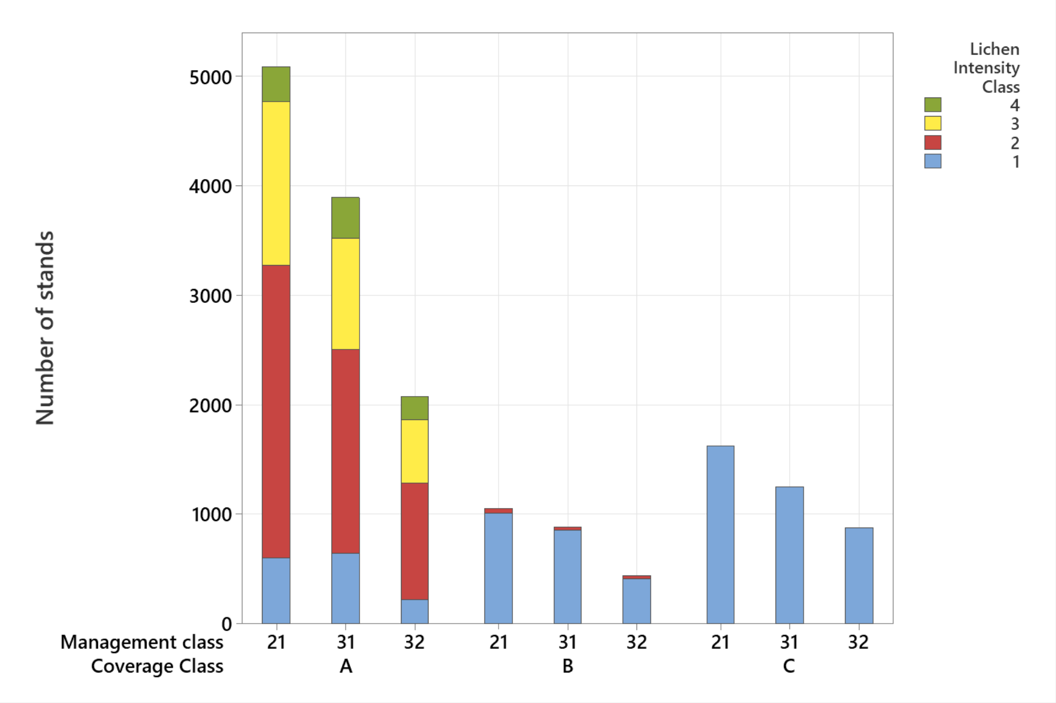

Figure 7. Number of occurrences of stands within different combinations of lichen intensity, coverage, and management classes. Bars represent how many times stands appear in each class combination (i.e., occurrences), not the number of unique stands. The patterns illustrate the distribution pattern of lichen intensity and spatial continuity across management and coverage classes.

3.2 Structural characteristics of prioritized stands

Table 10 shows the mean values and standard deviations for site index, age, basal area and stem density across the 21 combinations of management class, lichen intensity class, and coverage class in the final prioritization output. A slight decrease in site index can be observed with increasing lichen intensity classes, and lichen intensity class 1 is generally found in stands with a lower age than lichen intensity classes 2, 3, and 4. Variations in site index are relatively stable across combinations, however, slighter higher standard deviations occur in lower lichen intensity classes. The opposite pattern can be observed for variation in age, where higher standard deviations generally are found in higher lichen intensity classes. For young forests (class 21), the stem density ranged between 4000 and 5000 stems ha^{-1}. Class 31 had not been thinned before and displayed slightly higher stems ha^{-1} than management class 32, between 1100 and 1700. Management class 32, which had been thinned before, had a stem count between 900 and 1200. Higher lichen intensity classes generally coincide with lower mean basal area and stem density. Standard deviations for stem density are comparatively large for management class 21 as opposed to classes 31 and 32, whereas basal area SDs are moderate across most combinations. For a summary of all analysed parameters across coverage classes A, B, and C, see Appendix.

Table 10. Mean site index (SI), mean stand age (years), mean basal area (m^2ha^{-1}) and mean stem density (stems ha^{-1}), with standard deviations (SD), for all combinations of management class, lichen intensity class, and lichen coverage class in prioritized stands (n = 17,203 observations; 7,518 unique stands).

	Management class																		
	21				**31**				**32**				**21**		**31**		**32**		**21**	**31**	**32**
Lichen intensity class	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**1**	**1**
Coverage class	**A**												**B**						**C**		
Mean Site Index (m)	18.2	18.5	18.4	18.2	19.5	19.0	18.7	18.3	20.9	20.2	20.0	19.9	18.6	18.2	19.5	17.2	20.5	17.9	18.5	18.8	20.1
Std. Dev	2.1	1.8	1.7	1.7	2.8	2.6	2.5	2.5	2.7	2.2	2.2	2.3	1.9	1.5	2.8	1.6	2.4	1.6	1.6	2.5	2.2
Mean Age (years)	17.4	16.8	17.4	18.2	47.7	52.9	53.9	56.5	52.5	57.9	58.7	58.6	16.4	25.7	51.2	64.1	56.2	64.4	17.7	55.3	59.4
Std. Dev	9.9	9.3	10.0	12.2	13.5	14.1	14.1	14.3	11.0	10.7	11.1	12.5	9.8	12.2	13.7	17.0	11.5	7.9	9.4	14.0	10.0
Mean Basal Area (m^2ha^{-1})	4.7	4.2	4.4	4.4	22.6	20.7	19.8	18.8	21.2	21.5	21.2	21.2	4.4	8.7	21.9	19.6	21.3	20.8	4.5	20.2	21.8
Std. Dev	8.4	6.0	6.1	6.3	8.0	7.1	6.9	6.5	4.7	3.8	3.8	4.7	6.2	9.1	7.1	10.0	3.8	2.3	5.9	6.5	3.8
Mean stem density (stems ha^{-1})	4629	4694	4505	4275	1667	1341	1264	1129	984	972	975	996	4964	4117	1473	1187	977	1059	4555	1225	958
Std. Dev	3593	3320	2997	2936	798	742	767	761	346	312	313	335	3777	2556	747	849	303	389	3203	706	297

4. Discussion

4.1 Results

One of the main objectives with the study was to develop methods to prioritize areas for reindeer-adapted management. The initial steps toward seeking out these areas was to filter areas based on lichen intensity and coverage. Further filtering based on management class was done to focus the analysis on stands with low, moderate and high lichen cover, that are within young and middle-aged forests that are subject to management, in order to seek out stands where lichen conditions can be improved in the short term. Stands with varying lichen abundance, within management classes 21, 31, and 32 were considered as prioritized stands for reindeer-adapted thinning. Since management classes were assigned to the stands by Sveaskog, they were considered operationally viable, due to them already being subject to thinning rotations, and in need of management, and therefore prioritized.

Across all management classes shown in Table 10, either stem density or basal area was above the suitable levels for ground lichen. In line with Jonsson Čabrajič et al. (2010), who stresses that canopy competition may still limit lichen growth despite stem density being relatively low, this indicates a need for intervention in order to maintain lichen. In addition, the negative correlation between higher lichen intensity and mean basal area, stems ha^{-1}, and site index (Table 10), validate the literature's delineations of ground lichen criteria (Eggers et al. 2024; Andersson & Persson 2023). This also suggests that the management classes are accurate and that they fit into the objective of the study.

Eggers et al. (2024) demonstrated that adapted management could increase lichen-abundant area by 22 % in a relatively short timeframe. In relation, this study found that a selection of stands in management classes 21, 31, and 32 are relevant to prioritize when planning adapted management, and represent key developmental stages where intervention has the potential of increasing and/or maintaining sufficient ground lichen cover.

As seen in Figure 6, the dominance of lichen intensity class 1 (1-10 %) across nearly all categories suggests that although total lichen area is high in this class, that area consists of low-intensity lichen cover which is considered low in grazing value. This is consistent with Roturier & Bergsten (2006), who noted tendencies for reindeer to avoid low-density lichen, and Widmark (2019), who stressed the importance of abundant lichen-rich areas. Coverage class C (>25-50 % stand coverage) exhibits the highest total lichen area overall (Figure 6), but considerably lower number of occurrences (Figure 7), suggesting that most of the lichen-covered area is present in large stands. This suggests that reindeer-adapted management of these stands can have a great impact on transforming low-value grazing areas (lichen intensity class 1) into valuable grazing lands (classes 2 and above). In contrast, coverage class A (>1-25 % stand coverage) showed lower overall lichen area but occurred at a greater frequency, and represented a greater proportion of higher-intensity classes (2-4) (Figures 6 and 7). This delineates that important grazing land is spread out and concentrated to small areas, as also noted in the Canadian lichen mapping by He et al. (2021).

These findings suggest that both large stands of low-intensity lichen (coverage class C) and small areas of high-intensity lichen (coverage class A) could be prioritized based on local needs. The former holds potential to restore continuous grazing-habitat and the latter can serve to maintain and increase patches with high grazing value. In comparison with Figure 6, observations in Figure 7 indicate that stands within management class 21 (young forests subject to pre-commercial thinning) represent the largest proportion of the prioritized stands, highlighting the potential value of these stands in enhancing lichen habitats from an early age.

The comparison between the study's prioritization output and areas prioritized by the Sami villages served as a practical validation of the method's credibility. Although this comparison was based on a relatively small dataset , the overlap was meaningful, and the fact that more than half of the stands prioritized by Sami villages corresponded to the prioritization made in this study suggests that the method manages to capture important values for grazing grounds. The 53 stands situated outside the prioritized areas might be explained by discrepancies in management class data; stands highlighted by Sami villages may not have been classified similarly in Sveaskog's stand register, potentially excluding them from the analysis. In addition, the study may have failed to capture values that need local Sami insights. The results of this comparison highlights the potential of the method developed in the study, as well as the importance of assessing local knowledge, a key aspect emphasized by Roos et al. (2022).

4.2 Data evaluation

This section evaluates the input data used in the analysis, discussing the limitations in data and how it shaped the choice of methods for the study.

The lichen raster from Sametinget (2022) provided the only landscape-scale dataset available for estimating ground-lichen cover within the study area and was therefore central to this analysis. While it enabled a consistent, large-scale assessment, its model-based nature also introduces uncertainty. The raster represents predicted lichen cover derived from field plots and remote sensing data rather than direct measurements of continuous lichen cover, meaning local variability and small-scale patches may be under- or overrepresented. This is particularly relevant for areas with high lichen cover, where earlier versions of the map showed underestimation. Although the updated version used in this study incorporated additional plot data from Sami villages and showed improved accuracy at higher cover levels, some misclassification is still expected. These limitations should be considered when interpreting the spatial extent of lichen-rich areas identified in the prioritization process. However, the strong correspondence reported by Sametinget (2022) between reindeer GPS positions and areas of high predicted lichen cover supports the utility of the raster as a decision-support tool for identifying grazing habitats at a broad scale.

It is important to acknowledge that the lichen data and the derived classification used in the study did not represent true lichen coverage. Instead, the classes served as estimates for local lichen density and, in addition, spatial extents of those densities, and was used to provide an overview of areas with sufficient grazing values for reindeer. This approach aimed to predict areas containing high lichen cover with the data provided to locate suitable grazing land, aligning with findings by Roturier & Bergsten (2006), who identified tendencies for reindeer to graze at sites with higher lichen cover.

A limitation in this study was the uncertainty surrounding stem density. It was one of the more uncertain variables, and its credibility depended on age of the forest as well as previous management. For stands that were previously thinned or pre-commercially thinned, stem density was likely to be closer to the truth than the stem density in an unmanaged stand where the parameters had been projected to today. According to Sveaskog, current stem density was usually based on initial planting density, and to project such a variable into the future based on a general development model is bound to result in uncertainty. For stands that have been managed, however, the parameter seems to be more reliable since it was redefined after said management. Stem density closely relates to canopy openness and therefore ground-layer light availability, a key factor for ground lichen growth (Andersson & Persson 2023). Therefore, this uncertainty in data resulted in challenges for precise classification of the lichen suitability of forest stands.

Initially, dense, young forest was a term used to describe the type of forest that the study would focus on. Upon choosing management classes as a classification tool, however, it was realized that referring to “young forest” may be slightly misleading since the forests subject to thinning generally were between 50 and 60 years old. The research area spanned over a large area with relatively varied climatic conditions, resulting in large fluctuations in productivity. In addition, stand density was one of the less trustworthy parameters in the dataset. Because of this, the type of forest used in the study needed to be defined by something other than age and stand density alone. By selecting stands by previous and planned management, forests with a need of future thinning or pre-commercial thinning were the subset of data used in the study. To mitigate confusion, these are to be considered young to middle aged dense forests, and are characterized by their need of intervention rather than parameters such as age and stand density alone.

Sample controls to evaluate Sveaskog stand data were planned, but were excluded from the study due to lack of time. Since multiple categories of data were of varying quality, such controls could have strengthened confidence in the dataset and helped calibrate interpretation of uncertain variables such as stem density, as well as enabling a more in-depth discussion of the results.

4.3 Methodological evaluation

4.3.1 Data constraints and choice of method

An initial approach aimed to define areas suitable for ground lichen by defining thresholds based on literature, and classifying the land based on them, with the ambition of mapping all or most of the land that would host considerable amounts of lichen. In addition, this type of classification sought to prioritize stands based on their density by using stand parameter values assigned to each stand. However, due to the data being displayed in mean values across stands, the method failed to capture within-stand heterogeneity, leading to large areas with lichen presence being excluded from the selection. Furthermore, the previously discussed stem density and its inconsistency resulted in complications for prioritizing stands for adapted management.

The limitations in data resulted in an alternative method that was ultimately used in the study sought. This method sought the same purpose; prioritizing stands for adapted management. However, it was based on their developmental stage as opposed to using stand characteristics alone. Because of the uncertainty of previously discussed forest parameters, the use of management classes was considered more accurate in determining the developmental stage of the forest. This classification was assumed to relatively accurately reflect denser forest, and was the best alternative that was found. Management classes were thus used with the assumption that this classification would succeed in identifying stands where management was needed in order to keep lichen cover from decreasing. Upon analysing the final outputs of the classification, it was discovered that the defined stands generally were dense based on either stem density or basal area. However, as previously stated, the parameters, especially stem density, were relatively uncertain. With better data on the density of stands, a more comprehensive prioritization could have been made with regards to lichen-habitats. In spite of this, the final selection of stands exhibited consistent patterns when grouped by management class. However, given the limitations discussed, conclusions drawn from them should be approached with this in mind.

It is important to note that the structural parameter means presented in Table 10 are based on the full set of 17,203 combinations of lichen intensity class, management class, and coverage class in the final output, rather than on the 7,518 unique stands. Consequently, stands that occurred in multiple combinations contributed their parameter values more than once, leading to a proportional overrepresentation of these stands in the mean values. The results should therefore be interpreted as representative of the characteristics of the selected stand-class combinations, rather than of unique stands.

4.3.2 Methodological and classification strengths

The method has proved useful for localizing forest stands that are subject to intervention in the near future, and in combination with varying levels of lichen abundance, highlighting areas that could be prioritized for the purpose of further integrating the needs of reindeer husbandry with forestry. Furthermore, as shown in Figure 5, these selections can be visualized in GIS for further assessments. For example, this could be used to analyze the spatial distribution of stands with higher lichen abundance within a certain management class, and to further assess clustering of stands that fit the criteria. The latter is something that was planned for the study but was excluded due to time constraints. The stands that previously have been targeted as important sites for the reindeer husbandry could have been assigned a higher prioritization, especially the stands that fell inside the prioritization defined by the study.

A core strength of the method was the combined use of both lichen intensity classes and lichen coverage classes, which captured both grazing quality and its spatial distribution. In GIS, this allowed assessments of how widespread sufficient grazing land is, as well as its position inside individual stands. The approach addressed the limitation of relying on a single metric for interpreting lichen cover: for instance, a stand with high lichen intensity but small overall coverage may not provide meaningful grazing opportunities, just as a stand with broad lichen coverage but low lichen intensity may also have a limited value. Therefore, the integrated classification allowed for a more meaningful evaluation of grazing potential, capturing both local density and spatial extent of lichen within forest stands.

The purpose of implementing management classes was mainly to facilitate prioritization of stands for reindeer-adapted management, but also to better understand patterns in forest structure related to lichen cover. While the stand parameters of the dataset did not allow for precise classification of areas in need of intervention, the chosen method using management classes provided a workaround using the data at hand, i.e., management classes were used as a proxy for forest development stage. This facilitated post-classification assessment of structural characteristics, enabling both validation of the management classes and analysis of association between stand parameters and lichen abundance.

4.3.3 Limitations

The method in the study used the combination of lichen density and cover as well as management classes as a way to measure lichen potential and developmental stage of the forest. The management classes also served as a proxy for stand density. However, the framework for prioritizing stands for reindeer-adapted management could be improved by considering more factors relevant to the needs of reindeer husbandry. For example, reindeer husbandry systems are dependent on a landscape that can enable reindeer movement within and between seasonal grazing lands (Sandström et al. 2016). This highlights the need of spatial considerations regarding where adapted management could contribute to more value for reindeer. By using the GIS workflow developed in this study, the spatial distribution of stands with high potential could be assessed with this in mind, but the method itself did not use geography as a classification step. Doing so could improve the assessments regarding where adapted management could have greater impacts on reindeer husbandry. Another important factor for ground lichen is soil moisture, where dry or mesic soils are considered a basic criterion (Eggers et al. 2024). The selection was not based on this, but rather on actual lichen coverage as a way to determine habitat suitability of ground lichen. In other words, the method used in this study was built on the assumption that areas containing lichen likely meet criteria such as soil moisture and site productivity. An alternative method could be to classify stands based on their parameters, but as described earlier, this was constrained due to limitations in data.

4.4 Practical applications

This study provides a method for identifying and prioritizing forest stands based on potential for future lichen abundance and need of management. By assessing the proportion of land where intervention is needed or likely combined with ground lichen potential, areas where reindeer-adapted forestry could be focused are highlighted. Consequently, this also brings attention to areas where intensive forestry can continue with less detriment to grazing areas. For instance, areas with higher lichen cover could be targeted for reindeer-adapted management while areas with lower lichen abundance and limited potential could be prioritized for timber production.

The practical applications are best interpreted in GIS, where the user can filter stands based on different combinations of lichen intensity, lichen cover and management class. The selection can be assessed in relation to local requests from reindeer herders in terms of, for example, geographical location or spatial distribution. This way, the method can be used as a tool for decision-making tailored to different needs and preferences. Figure 5 demonstrates how such a selection can be visualized spatially, assisting decision-makers in identifying stands that fit certain criteria within certain regions or clusters. This can be particularly useful if certain areas are emphasized by Sami villages as more important for grazing. The integration of lichen intensity and its coverage within individual stands facilitates targeted planning and supports flexible decision-making. Adapted management practices can be applied either within targeted portions of a stand or across entire stands, depending on site-specific conditions such as soil moisture.

4.5 Future research

This study relied on modeled or remotely sensed lichen data. To improve credibility and to evaluate lichen-cover predictions, field validation and/or high-resolution drone imagery could be used to assess the accuracy and applicability of lichen-classifications defined in the study, relating to the assessments made by He et al. (2021). In addition, the fact that stand data was uncertain in the cases of select parameters such as stem density, and that forest properties were mean values for the stands suggest that the variation inside forest stands are suppressed, highlighting a need for more detailed data in future studies on the subject.

To further aid decision-making, growth modeling tools such as Heureka could be used to explore economic implications of adapted management, and to assess trade-offs between production-focused forestry and reindeer-adapted management. By integrating economic simulation into the framework, future research could enhance prioritization and decision-making, as well as supplement previous studies, such as Eggers et al. (2024). Furthermore, while this study focused on lichen coverage and silvicultural stage of the forest as the main drivers for prioritization, a key improvement point could also be to implement a broader ecological classification through for example soil type, soil moisture and topography.

Although spatial clustering is visually possible with the current method, incorporating spatial connectivity as a driver for prioritization serves as a key improvement area. Additionally, scaling the method across larger areas within the RHA could increase its utility for broader decision-making, and comparing it with existing planning strategies currently used could help evaluate its practical effectiveness. Finally, while future studies could incorporate aspects from this study such as the prioritization methodology, comprehensibility and simplicity serve as key improvement points. For example, key indicators such as high lichen intensity and coverage could be incorporated into a more dynamic classification where less steps are needed. Thus, by refining the prioritization system, key areas for reindeer-adapted management could be defined without needing the same extent of subclassification as this study.

4.6 Conclusions

This study demonstrates the distribution of lichen cover, both with regards to local intensity but also spatial continuity. It was found that the majority of lichen cover in the study area is characterized by low local abundance and is mostly exclusive to low coverage classes. This suggests that most ground lichen-covered areas likely provide low grazing values, and that lichen cover sufficient for reindeer is concentrated to small, spatially fragmented areas.

The results also indicate that the stands identified in the final selection hold significant potential for increased lichen cover if exposed to reindeer-adapted management. This relates to previous research on adapted forest management, indicating that such management over time could improve future grazing conditions for reindeer in the study area.

The methodology developed in the study provides a practical framework for identifying and prioritizing forest stands based on different combinations of lichen cover and forest developmental stage. The workflow serves as a tool for decision-support that can help forest planners and Sami villages in integrating forestry with reindeer herding by identifying areas with both a potential for improved lichen growth and a need for adapted management.

Constraints related to the applicability of the workflow as a decision-support tool largely stem from limitations in data quality, particularly in forest structure parameters. With more reliable data on factors influencing light-availability — such as stem density — or future incorporation of direct measures on canopy closure, the classification and prioritization of areas with high potential or urgent need for adapted management could be made more robust and definitive.

The study also concluded that forest structure strongly influences lichen abundance, especially through basal area, site index and stem density. These findings support the literature in terms of lichen criteria and validate the utility of the dataset for similar studies.

Future research should focus on validating the assessments made through analysis of forest stand data and lichen cover data. In addition, addressing the long-term economic effects of reindeer-adapted management would provide further insights into the trade-offs between production-oriented forest management and management focusing on the benefit of reindeer husbandry, and the viability of implementing adapted management at a large scale.

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Popular science summary

In northern Sweden, large parts of the forest land overlap between the forest industry and reindeer herding communities. However, the needs and prioritizations do not always align. Because reindeer rely on ground lichen as food during the winter months, the densification of forests have become an important subject since it limits their growth.

To make decision-making easier, this study developed a method for choosing stands where the potential of increasing or maintaining ground lichen cover is higher, in order to better balance the needs of timber with reindeer herding. By using lichen maps and forest data from Sveaskog, young and middle-aged forest stands with high potential for adapted forest management were identified.

The results prove that areas with high lichen cover grows in forests with low productivity and scarce canopies, and throughout the study, a GIS workflow to highlight which forest stands that should be managed differently was created. This tool can help forest planners and reindeer herders cooperate to balance their economic and ecological needs, serving as a step toward a more sustainable land-use in northern Sweden.

Appendix

Appendix includes summary tables (Tables 1, 2 and 3) for the final selection of stands, illustrated in Figure 4. Apart from stem density, basal area, site index and age, they include several additional forest stand metrics such as mean diameter, mean height and proportion of pine and spruce, as well as mean lichen area, mean lichen coverage per stand (%) across the different combinations of lichen intensity class, lichen coverage class and management class. These tables provide a more in depth look at stand properties for the stands that were assessed in the study.

Table 1. Summary of forest structure by lichen intensity class and management class for coverage class A (0-25 % lichen cover)

	Management class											
	21				**31**				**32**			
Lichen intensity class	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Total forest area (ha)	5 825	31 526	21 062	5 364	10 020	33 119	20 697	9 396	2 910	17 800	10 882	4 497
Number of stands (no.)	603	2 673	1 495	320	643	1 868	1 014	370	219	1 068	580	207
Mean stand area (ha)	9,7	11,8	14,1	16,8	15,6	17,7	20,4	25,4	13,3	16,7	18,8	21,7
Std. dev	10,2	11,1	12,2	13,5	19,1	17,9	19,1	21,9	14,1	13,9	15,4	16,3
Total Lichen area	834	1 116	138	15	1 494	812	128	15	485	384	71	8
Mean lichen area (ha)	1,4	0,4	0,1	0,05	2,3	0,4	0,1	0,04	2,2	0,4	0,1	0,04
Std. dev	1,8	0,8	0,4	0,2	3,1	1,2	0,3	0,07	2,7	0,8	0,8	0,08
Mean lichen proportion of stand (%)	14,1	3,7	0,8	0,4	14,2	2,5	0,8	0,2	15,8	2,6	0,8	0,3
Std. dev	6,9	4,5	1,7	1,2	6,6	4,1	1,7	0,3	6,2	4,1	1,9	0,6
	Properties											
Mean basal area (m^2ha^{-1})	4,7	4,2	4,4	4,4	22,6	20,7	19,8	18,8	21,2	21,5	21,2	21,2
Std. dev	8,4	6,0	6,1	6,3	7,9	7,1	6,9	6,5	4,7	3,8	3,8	4,7
Mean diameter (cm)	3,4	3,3	3,4	3,5	15,2	16,5	16,6	17,1	18,9	18,9	18,8	18,5
Std. dev	3,4	3,4	3,6	4,1	3,8	3,8	3,7	3,5	2,4	2,6	2,6	2,5
Mean height (m)	3,5	3,1	3,2	3,3	12,9	13,1	12,9	12,9	15,4	15,8	15,8	15,4
Std. dev	2,9	2,3	2,5	2,8	2,8	2,4	2,2	2,1	1,9	1,9	1,9	1,6
Mean stems ha-1	4 629	4 694	4 506	4 276	1 668	1 342	1 265	1 129	984	972	976	996
Std. dev	3 593	3 320	2 997	2 936	798	743	767	762	347	312	313	336
Mean age (years)	17,4	16,8	17,4	18,2	47,7	52,9	53,9	56,5	52,5	57,9	58,7	58,6
Std. dev	9,9	9,3	10,0	12,2	13,5	14,1	14,1	14,3	10,9	10,7	11,1	12,5
Mean site index (m)	18,2	18,5	18,4	18,2	19,5	19,0	18,7	18,3	20,9	20,2	19,9	19,9
Std. dev	2,1	1,8	1,7	1,7	2,8	2,6	2,5	2,5	2,7	2,2	2,2	2,3
Proportion pine	37,6	79,7	88,2	89,1	65,2	88,2	93,4	93,5	76,7	95,8	97,8	95,2
Proportion spruce	62,4	20,2	11,8	10,9	32,2	11	5,6	5,7	21,9	4,2	2,2	4,3

Table 2. Summary of forest structure by lichen intensity class and management class for coverage class B (>25-50 % lichen cover)

	Management class					
	21		**31**		**32**	
Lichen intensity class	**1**	**2**	**1**	**2**	**1**	**2**
Total forest area (ha)	10 649,1	724,7	12 901,7	320,5	6 083,7	340,0
Number of stands (no.)	1 011,0	45,0	859,0	24,0	416,0	27,0
Mean stand area (ha)	10,5	16,1	15,0	13,4	14,6	12,6
Std. dev	10,5	13,8	15,8	16,1	14,2	20,7
Total Lichen area	4 130	225	4 885	100	2 351	114
Mean lichen area (ha)	4,1	5,0	5,7	4,2	5,7	4,2
Std. dev	4,4	4,4	6,1	4,6	5,7	7,2
Mean lichen proportion of stand (%)	38,4	31,1	38,2	33,5	38,4	32,9
Std. dev	7,2	5,7	7,4	6,1	7,1	5,6
			Properties			
Mean basal area (m^2ha^{-1})	4,4	8,7	21,9	19,6	21,3	20,8
Std. dev	6,2	9,1	7,1	10,0	3,8	2,3
Mean diameter (cm)	3,3	6,1	16,3	17,0	19,1	18,0
Std. dev	3,5	4,0	3,7	4,0	2,7	2,8
Mean height (m)	3,2	4,8	13,2	12,8	15,7	15,6
Std. dev	2,4	2,7	2,6	1,9	1,9	2,0
Mean stems ha-1	4 964	4 118	1 473	1 187	977	1 060
Std. dev	3 778	2 556	747	849	304	389
Mean age (years)	16,4	25,7	51,2	64,1	56,2	64,4
Std. dev	9,8	12,2	13,7	17,0	11,5	7,9
Mean site index (m)	18,6	18,2	19,5	17,2	20,5	17,9
Std. dev	1,9	1,5	2,8	1,6	2,4	1,6
Proportion pine	69,1	100,0	79,6	100,0	89,4	100,0
Proportion spruce	30,7	0,0	19,3	0,0	10,3	0,0

Table 3. Summary of forest structure by lichen intensity class and management class for coverage class C (50-100 % lichen cover)

	Management class		
	21	**31**	**32**
Lichen intensity class	**1**	**1**	**1**
Total forest area (ha)	19 070,8	18 397,1	12 774,2
Number of stands (no.)	1 625,0	1 255,0	881,0
Mean stand area (ha)	11,7	14,7	14,5
Std. dev	11,2	16,1	12,8
Total Lichen area	12 742	12 167	8 824
Mean lichen area (ha)	7,8	9,7	10,0
Std. dev	7,6	10,8	8,7
Mean lichen proportion of stand (%)	66,9	67,5	70,7
Std. dev	10,7	10,8	11,6
Properties			
Mean basal area (m^2ha^{-1})	4,5	20,2	21,8
Std. dev	5,9	6,5	3,8
Mean diameter (cm)	3,5	17,1	19,2
Std. dev	3,5	3,7	2,6
Mean height (m)	3,3	13,3	16,1
Std. dev	2,3	2,3	1,9
Mean stems ha-1	4 556	1 226	958
Std. dev	3 204	707	297
Mean age (years)	17,7	55,3	59,4
Std. dev	9,4	14,0	10,0
Mean site index (m)	18,5	18,8	20,1
Std. dev	1,6	2,5	2,2
Proportion pine	90,3	93,4	96,3
Proportion spruce	9,7	6,1	3,7

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