LAND RECLAMATION BY REINDEER LICHENS

On the complexity of substrate and reindeer grazing on artificial Cladonia spp. dispersal

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Front cover: Hopukka quartzite heap, Kiruna, Northern Sweden.
Abstract
Reindeer lichens are on a dramatic decline in Sweden, with a 71% decrease in abundance over the last 60 years. Reindeer (Rangifer tarandus tarandus L.) management, undertaken by indigenous Sámi people, depend upon extensive winter grazing grounds with abundant reindeer lichen cover. The objective of this pilot study is to restore the ecosystem function of reindeer winter grazing in post-industrial environments, by developing an artificial dispersal program of reindeer lichen thalli. This study is performed in co-operation with the mining corp. of LKAB and in consultation with Laevas reindeer herding district. There are two components to this study: I) a comprehensive literature review of indigenous and scientific knowledge regarding reindeer winter grazing and artificial reindeer lichen dispersal; and II) a field assessment of relationships between fructiose lichen occurrence and environmental variables within a coarse grid overlapped on a mosaic of vegetation patches in various successional stages, which cover part of a 28-year old abandoned quartzite heap. My findings validate that a well-drained substrate with a thin humus layer or barren ground together with the occurrence of bryophytes (not Sphagnum spp.) had the highest abundance of fructiose lichens. In contrast, abundant organic soil layer, high soil moisture, and extensive cover of graminoids and herbs showed low abundance of fructiose lichens. I conclude that reindeer lichens are indeed present in a few findings but are still facing environmental and dispersal limitations to become abundant. These limitations can be understood in the light of moisture regimes, instability or compaction of substrate, and limitations within the colonization-pool, and are further discussed with suggested revegetation implementations.

Key words: Artificial dispersal Quartzite quarry, Reindeer lichens, Reindeer winter grazing, Substrate.
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1 Introduction

The abundance of mat-forming lichens is subjected to dramatic change in Fennoscandia, due to industrially intensified forestry (emphasizing soil scarification and fertilization) (e.g. Kivinen et al. 2010) coupled with fire oppression (Roturier et al. 2017), dust from mining extraction activities (Chen et al. 2017), and local examples of suboptimal reindeer (Rangifer tarandus tarandus L. 1758) grazing dynamics (Kumpula et al. 2014). It has been estimated that the area of lichen-rich forests in Sweden has declined by 71 % over the last 60 years (Sandström et al. 2016) together with a considerably impaired quality of the reindeer grazing grounds overall (Berg et al. 2007). Additionally, mat-forming lichens are expected to be challenged by the panarctic ‘greening’, as a consequence of climate warming coupled with prolonged growing season and increased nutrient availability (Cornelissen et al. 2001). Observations, including satellite imagery (Myers-Smith et al. 2019), ground measurements (Björkman et al. 2018), qualitative observations by Sámi herders (Horstkotte et al. 2017), and experimental findings, have confirmed that shrubs are highly responsive to changes in temperature (Walker et al. 2006), including northern Sweden (Johnsson et al. 2013).

Mat-forming lichens, commonly known as reindeer lichens (here referred to a functional group commonly grazed by reindeer, including Cladonia stellaris, C. arbuscula, C. rangiferina, C. mitis and C. uncialis, known as jeagil in Northern Sámi, see e.g. Nordin et al. 2018, Inga 2007 and Warenberg et al. 1997), constitute the principal (up to 80 %) winter forage for reindeer (e.g. Heggerberget et al. 2002). Reindeer lichens, coupled with snow conditions (Kumpula and Colpaert 2003; Rassa 2007; Riseth et al. 2011; Kuoljok and Blind 2012), therefore represent a critical bottleneck resource for reindeer management, undertaken by indigenous Sámi people in northern Fennoscandia (e.g. Inga 2007; for more information on the complexity of winter grazing see Supplementary index 1). Semi-domesticated reindeer has been identified as an ecological keystone species as well as a socioecological cornerstone of northern indigenous peoples (Forbes and Kumpula 2009). Sámi herders have, traditionally, used migration of reindeer as a mean to cope with unfavorable grazing conditions and disturbance. However, as a consequence of the local indigenous communities’ struggle with land-use changes and infrastructure exploitation in the past (e.g. hydropower development), their capacity to adapt to the present-day multiple changes is limited (Brännlund and Axelsson 2011).

The present-day environmental stressors that Sámi herders are facing are multifaceted and include both climate stressors (e.g. Moen 2008), such as summer extreme heat events (SMHia 2018), changes in wind speed and direction (Rees et al. 2008), microfungi ‘mold’ formation on reindeer lichens (Kumpula et al. 2000), increased frequency of icing events on i) the ground (Sirpa et al. 2018), ii) at reindeer lichens1, and iii) in the mid- and surface layer of the snow (Hansen et al. 2011), and non-climate stressors, such as impaired quality of grazing grounds from modern stand-oriented, even-aged, monoculture forestry (Kivinen et al. 2010), as well as, the ‘tyranny of small losses’ from infrastructure development and disturbance, such as traffic, power lines, snow mobile activity, dog-sledging, military activities, wind parks, hydropower and extraction activities. All these factors result in an increasingly fragmented landscape in northern Sweden, to the detriment of the reindeer herds and herders (e.g. Gallardo et al. 2017; Kivinen et al. 2012).

In the subarctic and Arctic, vegetation regeneration is often limited by low temperature, a short growing season, and slow rates of organic matter decomposition and, thus, nutrient turnover (Forbes and Jefferies 1999). This influences the time it takes for ecosystems to recover following disturbance. For example, the natural recovery time for a mesic Alaskan site following extraction activities has been estimated to be 600 to 800 years (Harper and Kershaw 1996). Yet, the natural recovery time also depends upon the severity of the

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disturbance and on landscape properties. A commonly used restoration method of disturbed areas in poor and well-drained northern sites is the introduction of vegetation by seeding or planting vascular plants, indigenous or otherwise (Reid and Naeth 2005). However, several years after these revegetation efforts, the process of succession is usually slow, and these sites can remain dominated by few species, often atypical of the surrounding landscape with low occurrence of natural early colonizers, such as bryophytes and lichens (Hugron et al. 2013).

Nearly all sites that are physically disturbed with removal of the organic insulating surface share common properties of coarse-texture soils, which are well drained, have low amounts of organic matter, but higher levels of mineral nutrients in surface layers including altered heat flux between the ground and the atmosphere (Forbes and Jeffries 1999). Lichens are naturally early colonizers of such barren soil in boreal regions, starting with crustose lichens and bryophyte species, followed by cup lichens, and then eventually fruticose lichens (such as reindeer lichens) become dominant in a later successional stage. In the group of reindeer lichens, Cladonia mitis is generally one of the first to establish after 30 to 50 years, followed by C. arbuscula, C. rangiferina, and lastly C. stellaris (Ahti and Oksanen 1990). Light is usually the limiting resource in competition among lichens, and given the appearance of C. stellaris, being quite ‘shrubby’, that particular species has the potential to shadow smaller lichens in a later successional stage and eventually become dominant (Helle and Aspi 1983). The optimal growth for reindeer lichens in a forested setting normally occurs at >40 % canopy openness (Jonsson Čabrajić 2009).

In the northern boreal zone, reindeer lichens are closely associated with edaphic conditions of sandy or rocky, low productive, and more open Pinus sylvestris-dominated stands (e.g. Ahti and Oksanen 1990). When modeling habitat preference for reindeer lichens, Uboni et al. (2019) found the ideal habitat to be a lichen-dominated forests dominated by P. sylvestris, with low basal area and low canopy cover, located in south- and west-facing areas with high summer precipitation, and low winter precipitation and temperature on gentle slopes. Since vascular plants are less tolerant of dry conditions, poorer sites function as a barrier to vascular plants favoring lichen establishment and growth (Ardelean et al. 2018).

Nevertheless, similar to vascular plants, lichens require water and light for photosynthesis activity. However, lichens are poikilohydric organisms (lacking structures to regulate water content) meaning that they can survive in a metabolically inactive state throughout periods of drought. Hence, their metabolic and photosynthetic activity, and thus growth rate, mainly depend on their water status and the irradiance received when wet (e.g. Gaio-Oliveira et al. 2006). Reindeer lichen growth can indeed be relatively high, with similar energy use efficiency to that of vascular plants, during optimum conditions in their active periods (Gaio-Oliveira et al. 2006). Yet, the periods when lichens are active are often sparse, resulting in generally low growth rate (a few mm annually). For C. stellaris in northern Finland, the growth rate more specifically corresponds to an annually increase of 8 to 17 % (den Herder et al. 2003).

Lichens in general, and reindeer lichens in particular, often face dispersal constraints, since lichen thalli (loose fragments for asexual propagation) are typically dispersed within just one meter from the colony by wind, water, and animals (Heinken 1999). Artificial dispersal efforts of reindeer lichen (mainly C. stellaris) thalli, directly addressing the challenge of dispersal in Northern boreal landscapes, accelerated colonization and increased growth by 50 % over four years (Roturier et al. 2007), and resulted in a grazable reindeer mat in 10 years (Roturier et al. 2017), and an abundant cover of reindeer lichens in approximately 30 to 50 years (Duncan 2015; see supplementary index 3 for more details on artificial dispersal of reindeer lichen experiments). This could be compared to wild fires in a boreal setting, where reindeer lichens require approximately 40 to 60 years to recover to levels that are normally found in reindeer winter grazing lands (Russell et al. 2019; Roturier et al. 2017). However, a number of aspects are still to be examined before initiating large-scale revegetation efforts. Most notable is the question of substrate, that is, what substrate provides the best structure and micro-habitat success for lichen thalli establishment and growth.
1.1 Aim and predictions

Northern Sweden holds an expansive mining industry, with 98.5% of the value of the mineral extraction situated in present-day Swedish part of Sápmi (Lawrence and Åhrén 2016). Large scale infrastructure projects and extraction of natural resources in natural environments is often assumed to be an irreversible and permanent force of destruction (Larsen et al. 2018; Sámediggi 2017). Indeed, extraction operations and associated infrastructure tend to have far reaching effects on both the environment (e.g. Northey et al. 2017) and on indigenous community resilience (e.g. Nystad et al. 2014). Yet, land users utilizing the same landscape are increasingly recognizing that emerging techniques for revegetate critical winter reindeer habitat with lichens in disturbed areas have the prospect to reduce the destructive impact on reindeer management, and thus to a greater extent support the prerequisites for coexistence between mining and reindeer husbandry (e.g. Duncan 2015; Rapai et al. 2018; Roturier et al. 2017).

This pilot study searches to increase he body of knowledge on restoration of critical reindeer winter grazing habitat on post-industrial land, by developing an artificial dispersal program of reindeer lichen thalli. There are two components to this study: I) a literature assessment on what is known of reindeer winter grazing and artificial reindeer lichen dispersal, targeting substrate in particular; and II) a field assessment of plant community composition and environmental properties at quartzite heap and its transition zone to explore ecosystem responses to the disturbance and the recovery 28 years later. Here, I develop the hypothesis that in the absence of vascular plants, fructiose lichen (including reindeer lichens) will thrive on well-drained substrate, i.e. that a well-drained coarse substrate with occurrence of bryophytes (not Sphagnum spp.) and/or barren-ground and low soil water content will be favorable for fructiose lichen establishment. I test my predictions (see below) across a total of 80 systematically chosen 1 m² plots at Hopukka quartzite quarry 30 km southwest of Kiruna, Northern Sweden (figure 1). The study is performed in co-operation with Luossavaara-Kiirunavaara Aktiebolag (henceforth ‘LKAB’) and in consultation with Laevas reindeer herding district (for more information about LKAB and Laevas cooperation see supplementary index 2).

I will test the following hypotheses:

I. There will be a positive association between the abundance of fructiose lichens and the abundance of barren ground (mineral soil), bryophytes (except Sphagnum spp.), and grain size (well-drained substrate), at Hopukka quartzite heap and its transition zone.

II. There will be a negative association between the abundance of fructiose lichens and soil moisture, abundance of herbs, graminoids, and shrubs, at Hopukka quartzite heap and its transition zone.

2 Methods

2.1 Study site

Hopukka quartzite quarry (67°37’33.4” N, 20°59’33.6” E; 92 673 m² claimed area), is located in a northeast facing slope at an altitude of 490 m a. s. l., 30 km southwest from Kiruna in Northern Sweden. Including a 25 m high, small-scale quartzite heap (‘upplag’ in Swedish, 12 500 m² claimed area) located 175 m northeast from the quarry further down the slope. The volume of the quartzite heap is 22 252 m³ with a mass of 44 276 t (calculated on a density of 1.75 t/m³ and an extra 15 % weight due to compression). This relatively modest quartzite heap could be compared to the close by (12 km southeast) LKAB mine of Mertainen, where the annual in situ mine waste will be around 24 000 000 t. Hopukka is located in Aptavara Nature Reserve, a Natura 2000 Reserve characterized by old-growth boreal forest, mires, and low mountains (<600 m) (figure 1).
2.1.1 Climate and ecological setting

Over a 30-year period (1961 – 1990), the annual mean temperature has been -1.5 °C, ranging from -15.4 °C in January to +13.1 °C in July. For the same period, the mean annual precipitation has been 478.5 mm, ranging from 21.1 mm in February to 82.5 mm in July. The annual snow cover has lasted between 185 and 225 days, usually forming in late October and disappearing in early May (SMHIb 2018: data from the weather station of Veaikevárri/Svappavaara).

Hopukka quartzite heap has been resting the last 28 years (except a smaller outtake of 10 t, see LKAB 2011). The vegetation cover at the heap is still scarce with limited natural recovery covered by a mosaic of successional different vegetation types including patches of exposed quartzite mineral soil. The potential colonization pool of natural vegetation on the study site is mixed high-latitude boreal forest dominated by Norway spruce (*Picea abies*) on sandy moraine soil, with birch (*Betula pubescens*) occurring less frequently (figure 2). Shrub patches on the quartzite heap comprise mainly pioneer species such as *Salix* ssp. Other vegetation patches consist of ericaceous dwarf shrubs such as *Vaccinium myrtillus* and *V. vitis-idaea* or bryophytes (e.g. *Polytrichum piliferum*) and lichens (*Cladonia* spp., *Cetraria* spp. and *Bryoria* ssp.). From a Sámi herder perspective, the two most prominent feature of the landscape is the mires (potentially important in autumn-winter and winter-spring) and the old growth *P. abies* stands with an abundance of arboreal lichens².

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² Partapuoli, Hans-Göran. 2018. Sámi herder with reindeer part of a winter group in the study area, Hopukka, Laevas herding district. Telephone interview 2018-11-28
2.1.2 Historical and present land use

In consultation between LKAB and Laevas herding district, Hopukka quartzite has been selected for a pilot project regarding restoration of reindeer winter grazing, to increase LKAB’s knowledge leading up future large-scale revegetation efforts of reindeer lichens on borrowed land. Hopukka is today utilized for both extraction activities by Swerock Corp. and reindeer winter grazing for Laevas herding district. The quarry was operated by LKAB between 1973 – 1990. In the early days of the quarry, 270 000 t of quartzite was annually transported to the forges of Veaikevåri/Svappavaara, Kiruna and Malmberget (Nilsson 1974) and later in the process used as additives in iron ore pellets (LKAB 2011). Today, the quarry is managed by Swerock Corp. (with unknown extraction intensity), except the quartzite heap that is still managed by LKAB. In October 2018, reindeer and moose (Alces alces) droppings were frequently observed at the site as well as individuals of capercaillies (Tetrao urogallus).

Laevas is a mountain (i.e. not forest or concession) herding district with grazing lands ranging 300 km from the alpine summer lands west of Kebnekaise and Riksgården and the boreal winter lands in the east. Laevas winter lands are severe fragmented. There are 17 individual reindeer management businesses within Laevas managing around 7 000 reindeer, which is 1000 less than allowed for the herding district. In winter, Laevas is internally organized through family ties and traditional land use into smaller winter groups (siidat Northern Sámi), with approx. 1000 reindeer in each winter group. Throughout the winter season (Oct/Nov – April/May), Sámi herders manage their winter groups within a limited territory with limited grazing resources, and, thus, interact frequently with their reindeer (Gabna, Laevas and LKAB 2018). To this point, Sámi herders of Laevas have not been restrained to initiate extensive supplementary feeding operations during winter. Although, during the harsh winter of 2017/2018, with both icing events and deep snow, reindeer were held in the mountains, grazing the resource normally used for the calving period in May, which is not an ideal situation for either herders or reindeer (Gabna, Laevas and LKAB 2018;
for more information about winter grazing see Supplementary index 1).

### 2.2 Study design

The field work was carried out over a 5-day period in October 2018. Plots were systematically established along eight northeast facing transects (90 m each), 20 m apart, across the quartzite heap and transition zone covering successional different vegetation types. Along each transect, 10 plots (1 m² each) were placed 10 m apart, rendering a total of 80 plots (figure 3). The establishment of these plots were done using two 50-m measuring tapes and a compass. Smaller adjustments of the plots were made in the steeper parts of the quartzite heap, to avoid capture substrate slides initiated by trampling of the field team (figure 4).

Figure 3. Study design on a 3D-model over Hopukka quartzite heap. Locations of the plots (orange squares) are based on GPS-logged (Garmin eTrex® 10) positions.

As suggested by the FjällNILS-project (see Carlsson 2009 for a detailed method description), I estimated the cover (%) of substrate and vegetation of the ground, field, shrub, and tree layer. Additionally, I measured volumetric soil water content (%), collected soil samples for grain-size analysis, and measured humus layer depth (cm). Soil water content was measured with a HydroSence II handheld soil-water sensor paired with a CS658 portable soil-water probe (Campbell Scientific, Logan, Utah, USA) reaching to a depth of 11 cm. Within each plot, three random measurements were made and later averaged.

The soil samples were collected in the northeast corner from every 6th plot (rendering in 13 samples in total), 3 dl were collected in pre-marked plastic bags from a depth of 7 cm. In the majority of the plots, no soil was collected due to logistical constraint, instead an ocular estimation of grain size was done, resulting in notes on the three most common grain-sizes from every plot. For the humus layer depth, I used the same pit dug for grain-size estimation and measured (with a ruler in cm) the part between the above-ground living vegetation (e.g. bryophytes) and the start of the mineral soil. An obvious start and end of the humus layer was not always evident, but most plots did either have close to no humus layer or a quite deep layer (in more Sphagnum-dominated plots), and that difference is captured in the data set. In addition, every plot was documented with a photo.
The estimation of vegetation was done in layers (ground, field and tree) so each plot could exceed 100 % in cover. I estimated the cover (in %) of snow, water, boulders, mineral soil/barren ground, humus, solidified ground (Table 1). For the ground layer, I additionally estimated the cover of Sphagnum spp., other bryophytes, reindeer lichens (Cladonia arbuscula, C. rangiferina, C. mitis, C. stellaris and C. uncialis), fructiose lichens (e.g. Stereocaulon paschale), and foliose lichens (e.g. Peltigera aphthosa, Nephroma arcticum).

Table 1. Variables targeted for cover estimation, based on Carlsson (2009). Variables highlighted in grey were subjected for further analysis based on occurrence and relevance for the study.

<table>
<thead>
<tr>
<th>Snow</th>
<th>Sphagnum spp.</th>
<th>Herbs</th>
<th>Salix spp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Other bryophytes</td>
<td>Heath</td>
<td>Betula spp.</td>
</tr>
<tr>
<td>Boulders</td>
<td>Reindeer lichens</td>
<td>Graminoids</td>
<td>Deciduous trees</td>
</tr>
<tr>
<td>Barren ground</td>
<td>Fructiose lichens</td>
<td>Equisetum spp.</td>
<td>Coniferous trees</td>
</tr>
<tr>
<td>Humus</td>
<td>Foliose lichens</td>
<td>Lycopodium spp.</td>
<td></td>
</tr>
<tr>
<td>Solidified ground</td>
<td>Ferns</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Moreover, I estimated the height (in cm) of the highest individual of reindeer lichens in each quadrant of every plot, that is, four measurements in each plot. In the field layer, I estimated the abundance of: Ericaceae ssp., herbs, graminoids, ferns, Equisetum ssp., Lycopodiaceae and Salix herbacea together with S. reticulata. In the bush/tree layer, I estimated the abundance of Betula nana and Salix ssp., Betula pubescens and Sorbus aucuparia and Populus tremula, and lastly coniferous trees of the species P. sylvestris and P. abies.

2.3 Soil analysis
The procedure of determining the distribution of particle sizes was done in a grain-size analysis by sieving. First, to reduce the amount of organic matter and evaporate water, the soil samples were put in a kiln for 4 hours at 250 °C. The dried samples were then weighed, and a known mass was then poured into a column of progressively smaller mesh size (8 mm, 4 mm, 1 mm, 0.50 mm, 0.25 mm, 0.125 mm, 0.074 mm, and a bottom). The column was thereafter placed in a mechanical shaker on maximum speed, for 30 min. Each sample would then ripple through the columns and end up on the sieve corresponding to the relative
proportion of fractions. After the shaking was complete, the material on each sieve was weighed. The weight of the material on each sieve was then divided by the total weight to give a percentage for each grain size, to construct a distribution curve based on relative proportions of different grain sizes.

Thereafter, I classified the samples as either pebble (>40% of fractions 4 and 8 mm), sandy pebble (20 to 40% of fractions 1 and 4 mm), coarse sand (>40% of fractions 1 and 0.5 mm) or silty sand (20 to 40% of fractions 0.25, 0.125 and 0.074 mm) (Karlsson and Hansbo 1982). For inclusion in data models, I assigned the different classification categories a number from 1 – 5, where a low number represent finer material and a high a coarser material.

2.4 Pooling fructiose lichens
Reindeer lichens (Cladonia stellaris, C. arbuscula, C. rangiferina and C. uncialis) was quite rare at the site (few individuals occurred in 6 out of 80 plots; figure 5). Instead, the most abundant fructiose lichen observed at Hopukka quartzite heap was Stereocaulon paschale. (påskrislav in Swedish).

Figure 5. A) Spatial distribution of reindeer lichens and other fructiose lichens. B) Cladonia mitis and C) Stereocaulon paschale.

For reindeer, S. paschale is less preferred compared to reindeer lichens, yet still commonly grazed (Danell et al. 1994), more than expected to its relative occurrence (Eriksson et al. 1981). S. paschale and C. stellaris have clear habitat overlap with similar fundamental niches, with the exception of S. paschale being more tolerant to harsh environments such as submersion (Sadowsky et al. 2012). Hopukka is a quite dry place with coarse substrate and low probability of submersion. Therefore, I used fructiose lichens as a proxy for reindeer lichens. By combining fructiose- and reindeer lichens, the occurrence increased to 47 out of 80 plots.

2.5 Knowledge system
Reindeer management depends upon Sámi herders, that hold the ability to interpret and understand the landscape, individual reindeer, the herd, atmospheric and snow conditions, and the lifeforms grazed by reindeer (Kuoljok and Blind 2012). Sámi reindeer herders
possess knowledge that has been operatively tested and refined through generations by people dependent on herding expertise for survival. Integrating indigenous (ecological) knowledge (known as Árbediehtu in Northern Sámi) and scientific knowledge into ecosystem restoration and management is increasingly recognized as a valuable approach, as it adds a local-area dimension to point-based data (e.g. Tengö et al. 2014). Humans that directly depend on natural resources, per se, often notice changes in their local environment that show significant overlap with scientific data but still often are overseen by established scientific methods (Riseth et al. 2011).

The intensity of interaction between Sámi herders and their herd varies with seasons, and so does their observational-based knowledge on reindeer grazing. Sámi herders keep close contact to their herd during winter (Oct/Nov – Apr/May) and especially during period of calving (April-May) (Inga 2007). A characteristic for Sámi languages is an outstanding vocabulary describing different winter pasture and snow conditions (Rassa 2007), reflecting an in-depth understanding and know-how of interactions between pasture, snow, reindeer behavior, landscape, and weather (Riseth et al. 2011; Roturier and Roué 2009; Utsi 2009). An extensive body of research is adding to, and confirming, this indigenous knowledge. Therefore, this study aims at encompassing both scientific knowledge and indigenous knowledge from published and/or oral sources of Sámi herders. Árbediehtu is locally rooted, e.g. where and when my reindeer most likely cross a specific river (see e.g. Sámediggi’s policy for indigenous knowledge for more information). Statements based on indigenous knowledge captured in this report should be generalized with forethoughtfulness, considering that information from Northern Sámi herder might not be valid for another part of Sápmi, such as Idre herding district 1000 km south of Laevas. Moreover, some terms in this report are selectively translated into either Swedish or Northern Sámi, and such translations are based on the logic of either i) clarifying well-known words in Swedish with poor English translation such as 'sameby', or ii) using Sámi words when translations to either Swedish or English cannot capture the full meaning, such as ‘guohtum’.

Supplementary table 3 was constructed by assembling all experiments on artificial dispersal of fructiose lichen by searching for studies in Web of Science and in reference lists.

2.6 Data and statistical analysis
I performed a Non-Metric Multidimensional Scaling (henceforth ‘NMDS’) together with nonparametric correlation analysis to visualize and validate any negative or positive associations between reindeer lichen abundance and environmental variables. My data analysis and statistical analysis were performed with R Studio software v. 3.5.0 (R Core Team 2019) and JMP software v. 14.0 (JMP Corp. 2019). First, to gain understanding and interpret my dataset, with a variety of variables of hydrology, soil and vegetation properties, I collapsed my dataset into simpler dimensions by constructing a NMDS model based on vegetation composition using the meta-MDS function in the Vegan R package (Oksanen et al. 2018). MDS analysis is a robust method commonly used by community ecologists. NMDS uses rank orders and does not rely on Euclidean distances, as do e.g. Principal Coordinates Analysis (PCA). Reading a NMDS plot is quite straightforward: objects that are ordinated closer to one another are likely to be more similar than those further apart.

Since my dataset did not fulfil the test assumptions of normality and homoscedasticity and no linear relationships were present, I performed non-parametric Spearman’s Rank-Order Correlation Coefficient analysis to measure the strength and direction of associations, presented in a matrix. I tested for associations between fructiose lichen (incl. reindeer lichens) and the following 10 variables; abundance (% cover) of bryophytes (not Sphagnum ssp.), graminoids, heath, Salix spp., herbs, barren ground (mineral soil), humus cover, soil volumetric water content (%), organic soil depth (cm) and grain size. Spearman’s correlations measure the strength of monotonic (i.e. linear) relationship, that is, if the value of one variable increases, so does the value of the other variable, or if the value of one variable increases, the other variable value decreases. The closer the resulting Spearman’s Correlation
Coefficient ($\rho$) is to ±1, the stronger is the negative or positive monotonic relationship. However, as $\rho$ is a measure of a monotonic relationship, there could still be nonlinear relationships despite a 'very weak' value, but these were not tested in this study. In the nonparametric correlation analysis, only variables of direct relevance to the hypothesis were included, whereas additional variables are included in the NMDS ordination. Yet, variables occurring in 1 or less plots (i.e. *Lycopodium* ssp., *Equisetum* ssp., ferns, *Betula nana*, water shed cover, and snow cover) were excluded from the NMDS.

3 Results

After 28 year, fructiose lichens (mostly *S. paschale*) have naturally recovered on parts of the Hopukka quartzite heap and its transition zone, with occurrence in 47 out of 80 plots (figure 5). This colonization has not occurred in a random fashion, as fructiose lichen cover demonstrates close ordinations (figure 6) and significant positive associations (figure 7) with dry areas, coarse substrate (figure 8) and the absence of graminoids and herbs.

![Figure 6. NMDS ordination based on Hopukka composition of vegetation (highlighted in white) and abiotic variables (black arrows). The ranges are outlined per site; forest (green), transition zone (red) and quartzite heap (grey). Stress: Non-metric fit, $R^2=0.964$ and Linear fit, $R^2 = 0.814$.](image)

As indicated by the NMDS ordination (figure 6), the vegetation composition can be understood in the light of soil water content zonation and disturbance regime. Starting from the left in the forest zone (on the opposing side from fructiose and foliose lichens) with the highest percentage of soil moisture, there is *Sphagnum* ssp. and a deep organic layer (in plots with *Sphagnum* ssp., this deep organic layer is most likely more or less peat). Following the soil moisture gradient to the right in the forest zone, next growth form is heath (mostly *V. myrtillus*) and coniferous trees (*P. abies*).

In addition to the soil moisture gradient, the disturbance regime should be considered in interpretation of the Hopukka NMDS ordination. In old-growth spruce dominated landscapes, solidified or barren ground with mineral soil or a thin humus layer will most likely be a result of destructive disturbance within the past century. In the light of disturbance, it is evident why deciduous trees (e.g. >2 m high and often older *B. pubescens*...
individuals) are ordinated further away from the disturbance proxies (barren humus layer and solidified ground), compared to the more short-term disturbance favored growth forms of herbs, graminoids, *Salix* spp., and bryophytes (not *Sphagnum* spp.). All the same, both groups are ordinated in moderate soil moisture. Fructiose lichens, on the other hand, are ordinated in low soil moisture close to barren mineral soil cover, coarse grain size and other lichens at the quartzite heap zone close to the transition zone (figure 6). Based on these results and the intermediate disturbance hypothesis, the transition zone is probably the zone with highest species richness compared to the forest and quartzite heap, yet a ‘harsher’ environment with barren well drained substrate is more favorable for fructiose lichens. Regarding substrate fructiose lichen establishment, the NMDS ordination indicates a close ordination with coarse grain size and high mineral soil cover, rather than a high cover of bryophytes or a thin humus layer.

3.1 Fructiose lichen associations

As hypothesized (I), this study validates significant (*p* < 0.05) positive associations between the abundance of fructiose lichens and the abundance of barren-ground (*ρ* = 0.36 weak), bryophytes (except *Sphagnum* spp.) (*ρ* = 0.28 weak), and well drained substrate (*ρ* = 0.26 weak).

![Spearman’s Rank Matrix with Correlations on Fructiose Lichens Abundance](image)

*Figure 7. Green indicates positive Spearman’s rank correlation coefficient values and red negative. Significant values of *p* = <0.005 are indicated with *. In accordance with hypothesis II, significant negative associations were found between the abundance of fructiose lichens and soil moisture (*ρ* = -0.24 weak), abundance of herbs (*ρ* = -0.39 weak), graminoids (*ρ* = -0.48 weak), and heath (*ρ* = 0.756), or heath (*ρ* = -0.04 very weak; *p* = 0.998). The strongest negative associations (*ρ* = >35) were found for graminoids, organic layer depth, herbs, and mineral soil cover. Additionally, a significant negative association was found between fructiose lichen and organic layer depth (*ρ* = -0.41 moderate) (figure 7). These associations, revealed in the Spearman’s Rank Matrix, are further supported by a NMDS ordination (figure 6).*
3.2 Grain-size distribution
As shown in figure 8, the dominating soil fraction at Hopukka is coarse sand and sandy pebbles, with the exception of sample of 2B and 5B (green), sampled from forested sites uphill (southeast) from the quartzite heap. These two samples reveal inclusion of all soil fractions (including boulders), typical for moraine above the highest Scandinavian historical shoreline. This silty-sandy moraine is presumably the dominating soil type in undisturbed areas at the location. However, due to insufficient numbers of replicates from the natural environment this is yet to be ascertain. Three other samples are indicating abnormal distribution; 6J (brown), 3J (dark purple), and 5H (red); all sampled from the northwest side of the quartzite heap in, or just below, from a steep terrain slope (see figure 1C). These samples are most likely not representative for the majority of the heap, but rather a result of specific fractions sliding down the slope, due to physical properties and weather events. Please note that this grain-size analysis did not cover finer or coarser fraction such as clay or stones.

Figure 8. Grain-size distribution of the study area. Each line in the chart represent a sample. The yellow squares in the map represent every 6th plot from where the soil samples were collected.

3.3 Evidence base on artificial dispersal
Research focused on restoring terrestrial lichen communities has been completed on the following substrates; heath vegetation of forest and clear-cut (Roturier and Bergsten 2009), in a lichen-rich *P. sylvestris* heath on substrates of mineral soil, bark, moss, and twigs (Roturier et al. 2007), in post forest fire environments (Rapai et al. 2017; Roturier et al. 2017), in a reclaimed oil sand mine on substrates of moss, pine needles, and mineral soil (Duncan 2011), at sand and gravel quarries with mulch and peat (Hugron et al. 2013), in a reclaimed gold mine (Rapai et al. 2018), and at a smelting-slag quartzite heap (Rola and Osyczka 2017).
4 Discussion
Fructiose lichens in general, and reindeer lichens in particular, are considered late successional species (Ahti and Oksanen 1990). However, findings in this study confirm earlier observations regarding fructiose lichens as colonizers of harsh environments (e.g. Roturier et al. 2007). In addition, this study validates the general paradigm of fructiose lichens (in this study typically C. mitis and S. paschale) being positively associated to well-drained and coarse substrate with low soil water volume (e.g. Rapai et al. 2018). These environmental properties are available in abundance at Hopukka quartzite heap with the dominant soil fraction being coarse sand/pebble together with limited competition from other life forms. Yet, fructiose lichens in general occurred in 58 % of the plots and reindeer lichens occurrence in no more than 7.5 % of the plots, with an average cover of less than 5 % in those plots. In other words, although fructiose lichens are indeed present, there is no formation of a fructiose lichen mat that would sustain reindeer grazing. By understanding the reasons of establishment and growth constraints at the quartzite heap, this study has the potential to add insight to future large-scale artificial dispersal program. Here, I will discuss the limited natural recovery at Hopukka quartzite heap with arguments related to morphology (wind-exposed heap), landscape characteristics, colonization pool (old-growth P. abies forest), time (28 years recovery), and the relative structure, stability, and compaction of the substrate.

In terms of wind exposure, barren mineral soil, and thin snow cover, the quartzite heap resembles more or less an alpine ridge, which is a quite extreme environment for most growth forms. Duncan (2011) has shown that lichen thalli on exposed sites (absence of forest

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Reference</th>
<th>Site</th>
<th>Thalli size</th>
<th>Duration</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bark</strong></td>
<td>Roturier et al. 2007</td>
<td>Conifer forest, Sweden</td>
<td>3 cm</td>
<td>36 months</td>
<td>40 % cover from 30 thalli</td>
</tr>
<tr>
<td><strong>Erosion blanket</strong></td>
<td>Rapai et al. 2018</td>
<td>Gold mine, Ontario</td>
<td>1 – 5 cm</td>
<td>23 months</td>
<td>18 % cover from 200 g matter</td>
</tr>
<tr>
<td><strong>Pinus needles</strong></td>
<td>Duncan 2011</td>
<td>Oil sand mine, Alberta</td>
<td>2 cm</td>
<td>14 months</td>
<td>19 % fragment retention</td>
</tr>
<tr>
<td><strong>Heath veg.</strong></td>
<td>Roturier et al. 2009</td>
<td>Conifer forest, Sweden</td>
<td>0.5 – 5 cm</td>
<td>69 months</td>
<td>46 % cover from 200 g dry matter</td>
</tr>
<tr>
<td><strong>Mineral soil</strong></td>
<td>Roturier et al. 2007</td>
<td>Conifer forest, Sweden</td>
<td>3 cm</td>
<td>36 months</td>
<td>53 % cover from 30 thalli</td>
</tr>
<tr>
<td></td>
<td>Duncan 2011</td>
<td>Oil sand mine, Alberta</td>
<td>2 cm</td>
<td>14 months</td>
<td>8 % fragment retention</td>
</tr>
<tr>
<td><strong>Moss</strong></td>
<td>Duncan 2011</td>
<td>Oil sand mine, Alberta</td>
<td>2 cm</td>
<td>14 months</td>
<td>19 % fragment retention</td>
</tr>
<tr>
<td></td>
<td>Roturier et al. 2007</td>
<td>Conifer forest, Sweden</td>
<td>3 cm</td>
<td>36 months</td>
<td>63 % cover from 30 thalli</td>
</tr>
<tr>
<td><strong>Mulch</strong></td>
<td>Hugron et al. 2013</td>
<td>Sand pit, Quebec</td>
<td>Unknown</td>
<td>29 months</td>
<td>3.7 % cover from 75 % thalli cover</td>
</tr>
<tr>
<td><strong>No mulch</strong></td>
<td>Hugron et al. 2013</td>
<td>Sand pit, Quebec</td>
<td>Unknown</td>
<td>29 months</td>
<td>22.6 % cover from 75 % thalli cover</td>
</tr>
<tr>
<td><strong>Peat</strong></td>
<td>Rapai et al. 2018</td>
<td>Gold mine, Ontario</td>
<td>1 – 5 cm</td>
<td>23 months</td>
<td>19 % cover from 200 g matter</td>
</tr>
<tr>
<td></td>
<td>Hugron et al. 2013</td>
<td>Sand pit, Quebec</td>
<td>Unknown</td>
<td>29 months</td>
<td>80.6 % cover from 75 % thalli cover</td>
</tr>
<tr>
<td><strong>Post forest fire</strong></td>
<td>Roturier et al. 2017</td>
<td>Clear-cut, scarified, sow</td>
<td>0.1 – 5 cm</td>
<td>84 months</td>
<td>3 thalli per 5 x 5 cm</td>
</tr>
<tr>
<td></td>
<td>Roturier et al. 2017</td>
<td>Clear- cut, planted</td>
<td>0.1 – 5 cm</td>
<td>84 months</td>
<td>9 thalli per 5 x 5 cm</td>
</tr>
<tr>
<td></td>
<td>Roturier et al. 2017</td>
<td>Untouched, set aside</td>
<td>0.1 – 5 cm</td>
<td>84 months</td>
<td>20 thalli per 5 x 5 cm</td>
</tr>
<tr>
<td></td>
<td>Rapai et al. 2017</td>
<td>Coarse, well-drained soil</td>
<td>2 – 7 cm</td>
<td>Unknown</td>
<td>Yet to be evaluated</td>
</tr>
<tr>
<td><strong>Slag substrate</strong></td>
<td>Rola et al. 2017</td>
<td>Smelting dumps, Kraków</td>
<td>Powdered</td>
<td>18 months</td>
<td>24 % from 6 g (with melt solution)</td>
</tr>
<tr>
<td><strong>Twigs</strong></td>
<td>Roturier et al. 2007</td>
<td>Conifer forest, Sweden</td>
<td>3 cm</td>
<td>36 months</td>
<td>72 % from 30 thalli</td>
</tr>
<tr>
<td><strong>Wood chips</strong></td>
<td>Rapai et al. 2018</td>
<td>Gold mine, Ontario</td>
<td>1 – 5 cm</td>
<td>23 months</td>
<td>25 % from 200 g matter</td>
</tr>
</tbody>
</table>
canopy cover) are increasingly prone to be displaced by wind and water. Even if fructiose lichens might be able to establish on an alpine ridge, there are likely to be growth constraints due to low air humidity as a consequence of wind and light exposure. Fructiose lichens are indeed favored, directly, by well-drained substrate as they need periods of drought to avoid destructive microfungi (Kumpula et al. 2000), and, indirectly, by limited competition from less drought-resistant growth forms. The growth rate, however, mainly depends on their water status and the irradiance they receive when wet. These contradictory aspects of lichen ecology are part of the challenges that revegetation projects are facing, that is, to generate a critical range of humidity that not only ensures establishment and survival, but also provides enough humidity for productivity and growth.

Reindeer lichens are seemingly more environmental and/or dispersal limited than fructiose lichens, as I found reindeer lichen only in the transition zone (figure 4). Possibly, reindeer lichens (here C. mitis) quite recently established in the transition zone of the heap, since C. mitis in generally could be expected to appear at a disturbed site after 30 – 50 years, in an earlier successional stage than other reindeer lichens (Ahti and Oksanen 1990), leaving the argument of limitations intact. On the other hand, reindeer droppings were observed on the quartzite heap, and based on this and available information it is hard to tell if this absence of reindeer lichens on the heap partly is due to destructive grazing and/or trampling of reindeer, or solely a result of environmental and dispersal constraints.

Additionally, the lichen colonization pool has presumably been limiting for the recovery of the heap, as the intact surroundings of Hopukka quartzite quarry is low in fructiose lichen (figure 2). Even if there would have been fructiose lichens in abundance, they grow and disperse at a slow rate, and in an event of dispersal, the thalli typically disperse within 1 m from its source and in a hit-or-miss fashion end up wherever the wind, water, or animal takes it (Heinken 1999). Local Sámi herders stress the importance of mires (potential important in early winter and late winter) and old-growth spruce forest with arboreal lichens (see figure 1B and note the numerous mires and lakes in the region) as sources of colonizing lichens. To values the possibility to restore a disturbed site to its natural state, landscape characteristics and its natural colonization pool have to be considered. That is, if the aim with the restoration effort is to minimize the destructive impact of a disturbance and bring it back to ‘business as usual’. For this project, however, the aim was to enhance the function of reindeer winter grazing on mat-forming lichens in a P. abies-dominated landscape to compensate Laevas reindeer herding district for LKAB claimed land and disturbance. Given the landscape properties of arboreal lichen rich old-growth P. abies forest, the most obvious restoration action would be to plant P. abies on the claimed land and let the wind disperse arboreal lichens from neighboring forests to the successively growing P. abies individuals. However, as the substrate at the site is well-drained coarse sand/pebble quartzite, with an estimated future cover of approx. 1.7 m (if 22 252 m³ material are flattened out of the area of 12 500² claimed land), the site will be too dry for P. abies to thrive.

Based on field observations, an important aspect of fructiose lichen establishment at the quartzite heap seems to be the relative stability of the substrate, because plots in seemingly less stable substrate occasionally had occurrence of graminoids or herbs, but seldom fructiose lichens (figure 4). The stability of the substrate is usually due to terrain slope and soil fraction. In general, terrain slope has been shown to be a favorable and an important abiotic variable in determining lichen species composition and richness, as steeper sites are more prone to reduce water retention and more likely to display barren ground and rock outcrops, which in turn favors the establishment of lichens to the detriment of vascular plants and bryophytes (Ardelean et al. 2018). Nevertheless, since reindeer lichens lack below-ground anchoring systems (compared to e.g. graminoids with an extensive root system), their establishment depends on soil surface characteristics and relative stability of ground substrate. For example, sand and gravel tend to be less stable than finer or coarser fractions (Brady and Weil 2004), implying that steep terrain slopes at Hopukka quartzite heap are
likely to be unfavorable for lichen establishment.

Despite a number of studies that have explored substrate-reindeer lichen dynamics (see table 2), there is still uncertainty as to what determines the successional patterns of forage lichens, primarily as they relate to the extent of reindeer grazing. The evidence base is still weak and scattered. Mostly due to short duration of experiments, a lack of common research protocols and a variety in different experimental designs. Most studies target different species of Cladonia and are set up on different substrates during more or less short time periods. Many studies exploring substrate-reindeer lichen dynamics have focused on *P. sylvestris*-dominated stands. Although it is convenient to extrapolate those results and associated conservation guidelines to Hopukka, such approaches may be misguided. It is clear, nonetheless, that some kind of substrate with enough structure to enable lichen thalli to stick is needed for lichen establishment and growth. However, no particular type of substrate stands out as better than other. Instead, *any* substrate that does not entail twigs and branches that hinder reindeer from reaching the lichen, and a lack of supportive structure (e.g. compacted and/or fine-grained mineral soil) seems suitable for lichen establishment.

On Hopukka quartzite heap, positive associations were found between the cover (%) of bryophytes and fructiose lichens. Whereas this outcome is consistent with previous studies (Roturier *et al.* 2007), it contradicts the expected positive association between fructiose lichens and barren mineral soil (Duncan 2011). A possible explanation could be that the typical plot where fructiose lichen were found was covered by both bryophytes (e.g. *Polytrichum piliferum*) and barren mineral soil, and, therefore, it might be the co-occurrence of these factors that is favorable for fructiose thalli establishment and not the mineral soil alone. In other words, there is enough bryophyte abundance for favorable structure and microhabitat for lichen thalli establishment, but still enough mineral soil to minimize competition from vascular plants. Also, the surface of extensive parts of the quartzite heap constituted out of small stones with a radius up to 30 mm. Beneath the surface (>40 mm) the quartzite heap composed out of more sandy sediment, these fine sediments have presumably been eroded away from the surface by water and wind. I would argue that the microlief has enough structure for thalli establishment, compared to the more homogenous surface structure of mineral soils from previous studies, such as in Duncan *et al.* (2011).

The success of a program with artificial dispersal of reindeer lichens should not be evaluated in terms of just reindeer lichen abundance, but also in terms of accessibility for reindeer to reach the forage (see supplementary index 1 for more information). This distinction must be made clear, especially if the aim is to restore reindeer winter grazing habitat, because flat and open areas tend to have a deeper and harder snow cover with lower lichen diversity where snow cover is deep. Rassa (2009) speaks of how hilly landscape, with ‘bumps’ more exposed to wind, tend to be more heterogenous regarding snow cover and therefore more likely to offer snow conditions that are favorable for both lichen abundance and reindeer accessibility. This is aligned with Kuoljok and Blind’s (2009) conversations with Sámi herders, were the saying “the hillier, the better” is stated in the context of winter reindeer grazing. To date, these aspects of Sámi knowledge are infrequently studied.

### 4.1 Management implications

When deciding what source of reindeer lichen thalli and substrate to use in revegetation efforts, sustainable harvesting has to be carefully considered. For Sámi herders, harvesting and storage reindeer lichen for supplementary feeding is an old practice, however, this knowledge is infrequently recaptured in literature. Nevertheless, Roturier *et al.* (2017) report how Sámi traditionally have frozen down dry lichens stored in well-ventilated bags. Yet, since this is done for feeding and not for revegetation purpose, it might not be applicable for artificial dispersal efforts. However, the commercial infrastructure of reindeer lichens is already present, as harvest of reindeer lichen in Fennoscandia has been practiced since the beginning of the 20th century, with an annually export of 3000 t of *C. stellaris* for decoration.
purposes in the 1970s (Kauppi 1979). When harvesting C. stellaris, no more than approx. 20% of a reindeer lichen mat should be harvest every 5th to 6th year, to safeguard a sustainable regrowth (Kauppi 1979). The storage of lichen pre-dispersal is a critical step, as lichens might mold or die off under poor storage conditions. The survival of algal photobionts of lichens when stored in room temperature, have shown to be three years. In freezing conditions (-20 °C), however, lichens stay intact and viable up to 13 years (Honegger 2003). Glaholt et al. (1997) observed that S. paschale and C. nivalis could be stored without a significant loss in photosynthetic capacity for 135 days with air drying and dry storage in a cool basement or spread outside on a plastic sheet.

There are also technical uncertainties, such as what density of lichen thalli should be dispersed, at what water content and to what extent the lichen should be fragmented (Krekula 2006). Krekula (2006) occasionally had problems with the dispersal if the water content exceeded 69%, as the lichens got stuck in the outlet pipe. Yet, dry lichens are more prone to fracture, or even pulverize, to progressively smaller thallus fragments, which are more prone to get influenced by wind and are less likely to attach to the intended substrate.

Fragment size (1 cm or 3 cm in length) affects the ability of thallus fragments to stay in place on a P. sylvestris clear-cut, as 1 cm fragments to a higher degree were captured by the wind and relocated (Roturier et al. 2007). Moreover, Roturier et al. (2017) found a higher establishment success with reindeer lichen thalli dispersal late summer compared to late winter. Roturier and Bergsten (2009) compared scattered dispersal (all over the plot) and more concentrated dispersal of reindeer lichen thalli in intact boreal vegetation dominated by Vaccinium vitis-idaea. Each plot received the same amount of reindeer lichen thalli. Thalli dispersed more concentrated responded with more growth the first two years compared to the scattered thalli, but reindeer grazing equalized the effect by grazing more intense on the concentrated patches. Consequently, no difference could be observed six years later.

In planning for large scale artificial dispersal efforts, landscape properties should be considered to find an optimal reclamation scheme with the highest connectivity between grazing lands. Reindeer show strong preference for different grazing land (Skarin and Åhman 2014). For instance, Vistnes et al. (2001) found 71% more abundant reindeer lichen within <4 km from anthropogenic structures compared to further away, despite low levels of human activity at the distant sites. For Hopukka specifically, a dialogue with Swerock Corp. should be established, regarding disturbance from potential extraction activities during the winter grazing period from the quarry 75 uphill from the quartzite heap. To date, Swerock activity at the quarry is unknown for the author. Reindeer are habitual and tend to return to (or avoid) the same migration paths and grazing areas annually (Kuoljok and Blind 2012; Rassa 2007; Utsi 2008), and since the aim with the revegetation efforts at Hopukka is to enhance and restore winter grazing land, disturbance should be avoided in the nearest area. Moreover, Kiruna is the center of iron ore mining in Europe, and fine dust deposition from mining activities has shown to negatively affect reindeer lichens (Chen et al. 2017). Local Sámi herders have actualized a number of aspects connected to dust deposition: 1) how dust-on-snow prevent reindeer from smelling reindeer lichen under the snow, 2) how dusty (darker) snow gets harder by thawing in the sun then melt during night, and 3) how dust deposition might affect lichen abundance (Gaba, Laevas and LKAB 2018). Before initiating a large-scale lichen dispersal program, this aspect should be considered.

For artificial dispersal efforts on post-forest fires, Roturier et al. (2017) suggest a time lag of at least two years to let the pH of the ash reduce as well as letting the substrate stabilize. It is advantageous if microorganism, moss, and crustose lichens have established before reindeer lichen thalli are dispersed. In Kuoljok and Blind (2012), Sámi herders discuss the relative exposure of reindeer lichens to reindeer grazing depending on substrate and vegetation composition. According to the informants, reindeer lichens on ‘hard’ barren substrate are often loosely attached and more exposed for destructive grazing from bottom to top. Whereas, reindeer lichen positioned in-between moss or heath, to a greater extent get to keep
their basal part attached when grazed and then given the potential to grow back (Roturier and Roué 2009). Mosses and decaying organic materials likely provide good substrates as they enable the stabilization of dispersed thallus fragments required for continued growth and prolong the active metabolic period of the lichens by retaining moisture (e.g. Duncan 2015; Roturier and Bergsten 2009). Roturier et al. (2007) found the highest establishment and growth rate of lichen thalli on moss in comparison between bark, mineral soil and twigs. Further, Duncan (2015) highlights benefits of incorporating organic amendments with terrestrial lichen fragments: I) securing lichen fragments to the substrate, and II) provide increased moisture-holding capacity at the substrate surface. Bark as a substrate has not been shown to increase establishment and growth to same extent as moss (Roturier et al. 2007). However, there is no long-term studies on artificial reindeer lichen dispersal (see supplementary index 3), and I would argue that a substrate of bark has the potential to hinder vascular plants to colonize the site and outcompete the lichens in the long term. Tree cover is another aspect to be considered as studies have found an open tree cover to be the best influential predictor of lichen volume and cover (Russell et al. 2019; Roturier et al. 2017).

Using radioactive tracers, researchers have found that nutrients are not taken up by reindeer lichens from the soil, but rather translocated from old and dead tissues to new lichen tissues (Ellis et al. 2004). Lichen preference for nutrient poor and low pH soils is likely for the same reason as for coarse and well-drained soils; lower vascular plant competition. Adding nutrients or nutrient rich soil to Hopukka quartzite heap, may in best case have no effect on reindeer lichens (Hugron et al. 2013), or, in worst case, increase negative influences of competition on the lichens. However, spraying nutrient-enriched water directly on the lichens with regular intervals potentially increases their growth, but would probably be costly, complicated, and associated with a risk of the nutrients leaking down to the soil and thereafter favor competitors (Gordon et al. 2001). In a potential situation where an artificial hilly site would be prepared for e.g. an effort of artificial dispersal of reindeer lichens, one should carefully identify depleted areas to delineate areas prone to flooding, even temporarily flooding, as excessive water can be detrimental to reindeer lichen thalli (Rapai et al. 2017; Duncan 2011). Redirection of excess water could be considered in order to avoid damage caused by shallow surface flooding. Meeting this requirement may be transformed into an opportunity to increase site heterogeneity and biodiversity by creating areas where water pools temporarily or permanently, thus providing habitat for a variety of plants and fauna that would not otherwise colonize the site (Campeau 2013). Roturier et al. (2017) point out how some sites might not be economically justifiable for revegetation efforts of reindeer lichens due to their environmental properties such as moisture regime. Hopukka, however, has considerable potential.

4.2 Conclusion
In summary, active restoration efforts are necessary to secure the successional process of lichens at Hopukka. Here, I suggest an adaptive management approach for Hopukka quartzite heap. I suggest LKAB to flatten out Hopukka quartzite heap, but still keep it ‘hilly’ to avoid a flat ledge appearance, and let the reconstruction follow the natural slope to avoid excess water in depleted depressions during snowmelt. Compaction of the material should be avoided and depending on how compacted the quartzite material will be after reconstruction, some extra coarse material (though, no nutrient rich or fine material) might be added to the surface to ensure high permeability. Ideally, the site should then be left resting for at least two years to let the substrate stabilize and give crustose lichen and moss the opportunity to colonize the bare substrate, which would be beneficial for reindeer lichen thalli establishment later on. Grasses, herbs, and deciduous shrubs (e.g. Salix spp.) should be removed from the site, as they would outcompete reindeer lichens. Hence, to actively transplant Salix spp. to the south-east part of the heap, as stated in an informal management plan for Hopukka quartzite heap, is likely not a good idea. Also, I suggest dividing the study site into six parts to be able to test different treatments on artificial reindeer lichen thalli dispersal. I suggest the
elements of the treatments to be; i) transplanted *P. sylvestris* seedlings, ii) moss, and iii) *P. sylvestris* bark. The dispersal should be performed in late summer, just before the first snow arrives, to ensure thalli establishment, and at the same time minimizing disturbance from reindeer management disturbance. The reindeer lichens should be divided to thalli parts with a diameter of approx. 3 cm, not smaller, and should be wettened before dispersal. Lastly, a monitoring plan should be established, including a standardized protocol to evaluate the progress. Potential destructive grazing by reindeer (reindeer lichens) and moose (*P. sylvestris* seedlings) should be evaluated with an established dialogue with Laevas about the potential to install a fence around the study area, until *P. sylvestris* and the reindeer lichens have established.

Figure 10. A schematic scheme of an adaptive learning system with six different treatments and one control with the components of; *Pinus sylvestris* seedling transplantation (P), *P. sylvestris* bark (B), dispersal of *Cladonia stellaris* thalli (C) and moss (M).
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Supplementary index 1: Reindeer winter grazing

From October to April/May, lichen in general and reindeer lichens in particular, are of outstanding importance for reindeer vigor and survival, often comprising > 80% of the diet (e.g. Heggberget et al. 2002; Kumpula and Colpaert 2003; Inga 2007). Under natural conditions, one reindeer consumes about 5 kg (dry weight) of lichen per day (Virtala 1992). Sámi herders have observed a general preference for the lichen species of Cladonia stellaris, C. rangiferina and C. arbuscula, yet stresses individual differences within a herd were some reindeer might prefer e.g. arboreal Bryoria fuscecaens (Kuoljok and Blind 2012; Inga 2007). To examine reindeer winter diet preference, a ‘cafeeteria’ experiment apportioned reindeer nine species (commonly grazed in winter). The findings indicate indeed a significant preference for: 1) reindeer lichens (C. stellaris C. rangifera, C. arbuscola) and 2) arboreal lichen (Bryoria sp.), followed by 3) evergreen grass (Deschampsia flexuosa), and 4) the fructoio lichen Stereocaulon paschale (Danell et al. 1994).

Other known species grazed by reindeer from Oct – May are e.g. mushroom (protein-rich, grazed to Dec), Equisetum fluviatile (grazed late winter/early spring close by mires), sitnu (Northern Sámi for evergreen graminoids such as Deschampsia flexuosa, D. alpina, Festuca ovina and Poa alpina), and the early-spring, protein-rich plant Eriophorum vaginatum (grazed late winter/early spring) (Blind et al. 2015; Inga and Daniell 2008; Inga 2007; Warenberg et al. 1997). When diet preference of Canadian caribou was studied using DNA analysis of droppings and video recordings from collars, more than 75 species were found to be included in their winter diet (Newmaster et al. 2013). Somewhat unexpectedly, Linneaus (Carl von Linné) was informed by Sámi herders that reindeer occasionally snatches Norway lemmings (Lemmus lemmus) (Linneaus 2003 [1732]), information aligned with more recent observations (Kuoljok and Blind 2012). Further, it has been suggested that, on occasion, reindeer also feed on fish such as Arctic char (Salvelinus alpinus) and bird eggs (pers. comment Johan Olofsson). Indicating that reindeer are partly opportunistic and might adjust their diet to food availability.

Yet, species composition an abundance of winter forage is irrelevant if the resource cannot be accessed by reindeer. When Sámi herders are asked to define a vegetation type with ideal winter grazing conditions, a vegetation type with abundant reindeer lichen cover is indeed preferred (Inga 2007). However, an abundant reindeer lichen cover might indicate that reindeer have not been able to utilize that particular resource due to a deep snow cover (>50 cm) with harsh digging conditions previous winters. Thus, since snow is not distributed evenly in the boreal landscape, such sites may not be considered ideal. Such is the nature of the ‘ideal grazing site’; multifaced and varies with time and space (e.g. Kuoljok and Blind 2012; Routier and Roué 2009; Rassa 2009).

Consequently, the actual accessibility to pasture, rather than lichen abundance alone, is central from a herding perspective. This is reflected in the term ‘guohtum’ (figure 11), a Northern Sámi term, which alludes to the English verb ‘grazing’, incorporating different levels of forest structure, landscape morphology, reindeer behavior, lichen quality, and the microstructure, stratigraphy, and depth of the snowpack; all these variables vary continuously in response to weather and among sites (e.g. Turunen et al. 2016; Riseth et al. 2011; Routier and Roué 2009). In general, ideal winter conditions, in a specific place in time, appear when barren ground freeze in the autumn and sort of ‘dry’ snow accumulates above resulting in ‘clean’ and dry reindeer lichen and sia beneath. Then, it is ‘litnaguothum’ or ‘gtnaguothum’ at a ‘guohttos sadje’, i.e. fine pasture at a fine grazing location (Kuoljok and Blind 2012; Rassa 2007). snow depth, the ground, what is on the ground, if there is lichen; the idea is that reindeer can get their food: guohtum. The reindeer guohtum: the reindeer eat, the reindeer ... graze.”. Sámi herder G. Kuhmnunen defines guohtum in an interview with
Roturier and Roué (2009) as; “Guohtun means, in fact, that the reindeer get the food. Therefore, it includes the snow conditions,

![Diagram of reindeer migration](image)

Figure 1.1. Thematic scheme of reindeer migration between summer and winter land for a typically mountain herding district in Sweden and a graphic illustration of the complex nature of Guohtum; grazing reindeer.

To access forage under the snow, reindeer dig using their hooves as shovels, resulting in a patchy grazing pressure with a variety of non-grazed and grazed patches (due to digging constraints or compacted snow by trampling), leaving remnant lichen communities intact (Sandström et al. 2016). Digging conditions are often getting harder later in winter, with increased rain-on-snow events and/or snowmelt (thaw) forming ice crusts in different layers of the snow cover (Turunen et al. 2016). In harder snow conditions, reindeer spend more energy digging, and therefore as a functional response to less accessible reindeer lichens, tend to increase their intake of less palatable vegetation in their grazing pit, such as *Vaccinium* ssp. (Kuoljok and Blind 2012).

Arboreal lichens (e.g. *Bryoria* ssp.) are an important complement to ground reindeer lichens, or, in some examples, even more important (Inga 20017; Kumpula and Colpaert 2003). Old-growth forest with abundant accessible arboreal lichens increases the resilience in events of ice-locked pasture. The most immediate reaction of a winter reindeer group to insufficient availability to forage is dispersal (Turunen et al. 2016). This risk is especially notorious during late winter/early spring (Mars–May), prior to “green-up” due to increased frequency of thawing and freezing events (Rassa 2007). As a herder, to avoid scattered herds and starvation, supplementary feeding might be used to compensate forage-loss and regain group control. However, supplementary feeding intensifies the use of specific sites, might change reindeer behavior, has the potential to (unintentional) disperse graminoid seeds (on the determine of reindeer lichens), and requires more financial resources and a heavier workload from Sámi herders (Turunen et al. 2016). Besides, Hanssen et al. (2018) have shown that winter supplementary feeding (compared to free ranging lichen diet) increases greenhouse gas emissions (methane) from rumen microbial fermentation by 50%.

A diversity of snow conditions derived from a heterogenous forest age structure and morphology is key for an effective winter ‘guohtum’ system. In contrast, large open areas in the forest, such as a clear-cut or a quartzite quarry, alters the depth and compaction of the snowpack, which is perceived as an impediment to reindeer grazing (Hansen et al. 2018;
Turunen et al. 2016; Routier and Roué 2009). At worst, an open area might scatter a herd, as most reindeer avoid open spaces in winter. Occasionally, whereas older clear-cuts can be favorable, as they are more exposed to wind and might dry up earlier in the spring, more recent clear-cuts have the potential to offer accessible vegetation, such as sia, in late winter/early spring (Kuoljok and Blind 2012). In an interview by Routier and Roué (2009), Sámi herder N.-J. Utsi states that: “When a forest is clear-cut, there is no more protection, the pasture is locked down. The snow locks it in, with snowdrifts, like in the mountains. Even if there is something to graze, the reindeer cannot dig through the snow. The snow is too deep and hard in the clear-cut. (...) Reindeer avoid clear-cut areas until the pines have grown through the snow cover again.”.

Supplementary index 2: Extraction industry and reindeer management

Sámi rights, such as rights to self-determination, have been strengthened successively since late 19th century. Yet, researchers have pointed out that the landscape today is shaped primarily by the aims and principles of non-Sámi interests, without Sámi ownership rights to land or formal mechanisms for consent and revenue sharing (e.g. Larsen et al. 2018; Brännström 2017; Gallardo et al. 2017; Haikola and Anshelm 2016; Ojala and Nordin 2015; Horstkotte et al. 2014). Sweden has received repeated critique from United Nations and European Union bodies for non-recognition of Sámi rights in land-use planning (e.g. UNHRC 2016). These power asymmetries can be understood against the background of historical events, such as the colonization that was initiated in the 17th century and intensified in the 18th. During the 18th and 19th centuries, governmental policies established the Swedish state as the primary owner of land and resources in Swedish part of Sápmi and supported discrimination and theories of cultural standings (Persson et al. 2017; Ojala and Nordin 2015; Lehtola 2004).

The extraction industry is one example of an industry that alters disturbance on reindeer management, both by fragmenting the landscape by claiming extensive areas for extraction activities and by acting as driver behind development of associated infrastructure, such as roads, power lines, and settlements (Haikola and Anshelm 2016). Consequently, mining Sápmi is a controversial and polarized topic. However, large-scale infrastructure projects and extraction of natural resources are often beneficial from an economical growth perspective at the national, regional, or global scales (Ojala and Nordin 2015). Sweden is the largest mining economy in the European Union, owing to extensive iron ores and the 100 % Swedish state-owned mining company LKAB. During the period 2006–2016, the Swedish share of iron ore production of the EU28 countries has been in the range of 88–91% (Geological Survey of Sweden 2016). LKAB is a backbone in Swedish economy and has seen the creation of a pro-mining policy regime with rapid expansion in the last two decades (Larsen et al. 2018). LKAB’s most profitable iron ore is mined in Gironvärri/Kiirunavaara in Giron/Kiruna, located within Gabna and Laevas Sámi reindeer herding districts (sameby in Swedish).

A leading opportunity for the mining sector to acknowledge Sámi rights is to develop participatory governance systems to integrate views, knowledge, and values of local communities into land-use planning and increase the circulation of information, transparency, and accountability (Landauer and Komendantova 2018). This opportunity is increasingly being recognized by LKAB. Founded 1890 in Giron/Kiruna in the central parts of the reindeer herding districts of Laevas and Gabna they, 123 years later in June 2013, signed a historical cooperative agreement (samverkansavtal in Swedish) with Gabna and Laevas to ensure participatory governance and a mutual trustfully and respectfully cooperation (Lauritz et al. 2016). The agreement has resulted in, among other things, two cooperative in-depth risk-assessment documents, regarding LKAB’s mining operations and its direct and cumulative consequences for reindeer management (Gabna, Laevas and LKAB 2018; 2015).

The following paragraph contain personal comments from the author on a non-public document, here reproduced with the permission of the publishers. Leavas’ effective area
available for reindeer grazing is today highly limited (figure 12). The risk assessment from 2018 describes the colonial historical relations between LKAB and the local Sámi community, LKAB mining activities, Gabna and Laevas management activities, the direct consequences of LKAB’s mining activities on reindeer management, and an assessment of cumulative social and cultural aspects. The risk assessment is partly based on traditional knowledge, obtained by informal group discussion in Northern Sámi among members of Laevas and Gabna.

In the risk assessment from 2018, Laevas report that 61% (287 600 ha) of their grazing lands (of total 472 500 ha) are subjected to disturbance, mainly from extraction activities (27%), snow mobile activity (20%) and road infrastructure (18%). Due to historical and present disturbances, Laevas states that “the reduced winter pasture means that every location, even small locations, is of great importance for us”. Partly based on the participatory governance work within the cooperative agreement, Gabna, Laevas and LKAB have agreed to initiate this pilot project to investigate the prospect to restore the function of winter grazing at disturbed sites (LKAB 2011).