



## Original Articles

# Modelling occurrence and status of mat-forming lichens in boreal forests to assess the past and current quality of reindeer winter pastures

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## ABSTRACT

Lichens play an essential role in northern ecosystems as important contributors to the water, nutrient and carbon cycles, as well as the main winter food resource for reindeer (*Rangifer tarandus*, also called caribou in North America), the most abundant herbivores in arctic and subarctic regions. Today, climate change and several types of land use are rapidly transforming northern ecosystems and challenging lichen growth. Since lichens are important indicators of ecosystem health and habitat suitability for reindeer, large-scale assessments are needed to estimate their past, present and future status. In our study, we aimed to develop models and equations that can be used by stakeholders to identify the occurrence of lichen-dominated boreal forests and to determine lichen conditions in those forests. Data were collected in Sweden and most input data are publicly available. We focused on mat-forming lichens belonging to the genera *Cladonia* and *Cetraria*, which are dominant species in the reindeer and caribou winter diet. Our models described lichen-dominated forests as being dominated by Scots pine (*Pinus sylvestris*), having low basal area and thin canopy cover, and being located in south- and west-facing areas with high summer precipitation, low winter precipitation and temperature, and on gentle slopes. Within those forests, lichen biomass was positively related to tree canopy cover and summer precipitation, while negatively and exponentially related to intensity of use of the area by reindeer. Forest, meteorological, topographic and soil data can be used as input in our models to determine lichen conditions without having to estimate lichen biomass through demanding and expensive fieldwork.

## 1. Introduction

Climate change and rapid landscape transformation are challenging northern ecosystems around the world. Lichens play an essential role in those ecosystems. They are important contributors to the carbon, water, and nutrient cycles (Cornelissen et al., 2007). Moreover, mat-forming lichens are an essential food resource in winter for an economically and ecologically important herbivore, the reindeer (*Rangifer tarandus*) (Heggberget et al., 2002). Despite their importance, lichens have suffered rapid declines in several parts of the world. The increase and mechanization of forestry activities, coupled in some regions with intense reindeer grazing, have strongly altered the abundance of mat-forming lichens. Examples come from Sweden (Sandström et al., 2006; Sandström et al., 2016), Finland (Kumpula et al., 2000; Uotila et al., 2005; Virtanen et al., 2003), Norway (Evans, 1996; Nygaard and Ødegaard, 1999; Virtanen et al., 2003), Alaska (Collins et al., 2011; Joly et al., 2007a; Joly et al., 2007b), Russia (Rees et al., 2003), some

parts of Northern Canada (Rickbeil et al., 2017), and to a lesser extent western Canada (Coxson and Marsh, 2001). On the contrary, forest management and fire have favored the expansion of lichen woodlands in eastern Canada, to the expense of the closed-crown boreal forest (Girard et al., 2008; Payette and Delwaide, 2003). Air pollution was the cause of the declines of forest and mountain heath lichens registered between 1973 and 1999 at the border between Norway and Russia (Aamlid et al., 2000; Tømmervik et al., 2003). Mat-forming lichens are expected to be additionally challenged worldwide by the foreseen expansion of vascular plants into arctic and subarctic regions, as a consequence of climate warming and increased nutrient availability (Cornelissen et al., 2001; Joly et al., 2009; Olthof and Pouliot, 2010).

Lichens are a symbiotic association between a fungus (the mycobiont) and an alga and/or cyanobacterium (the photobiont). *Cladonia arbuscula*, *C. mitis*, *C. rangiferina*, *C. stygia*, *C. stellaris*, and *Cetraria islandica* are the mat-forming lichen species preferred by reindeer in winter (Andreyev, 1954) and the most abundant in northern ecosystems. All six

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species have circumpolar arctic and boreal distribution and low growth rates (Sandström et al., 2006; Thomson, 1984). *Cladonia* spp. are characterized by a branched, fruticose growth form and are common on nutrient-poor soils in bogs, tundra, and boreal forests, while *Cetraria* spp. have a leaf-like shape and grow in dry or wet tundra and in old spruce forests (Thomson, 1984). Light exposure, humidity, and air temperature are the key factors determining lichen presence, abundance, and growth (Gaio-Oliveira et al., 2006; Jonsson Čabradič et al., 2010). Indeed, lichens are poikilohydric organisms that can survive in a metabolically inactive state throughout long dry periods and regain their metabolic and photosynthetic activity only when enough humidity is present. The amount of light that reaches them during this wet period determines their growth rate. In Swedish forests, mat-forming lichens grow primarily in Scots pine (*Pinus sylvestris*) heaths on dry oligotrophic soils (Ahti, 1961). In general, lichen cover decreases in old pine forests on dry sites, probably due to reduced light availability and to increased nutrient availability that promotes the expansion of mosses and shrubs which outcompete lichens (reviewed in Berg et al., 2008). *C. stellaris* and *C. islandica* reach growth peaks at intermediate light exposure and their growth rate is mainly determined by total irradiance they receive when wet, chlorophyll concentration, site openness, and is negatively correlated to air temperature (Čabradič Jonsson et al., 2010). Čabradič Jonsson et al. (2010) found that tree basal area ( $\text{m}^2 \text{ha}^{-1}$ ) can be used as a proxy for light exposure to determine potential lichen growth. Reindeer grazing can also limit lichen growth (den Herder et al., 2003; Moen and Danell, 2003), keeping mat-forming lichens at a height of few centimeters (Roturier and Roué, 2009). Similarly, reindeer trampling may damage lichens, especially when re-occurring frequently (reviewed in Crittenden, 2000). On the contrary, in some occasions trampling and grazing by reindeer can thin the lichen mats and thus promote recovery of the remaining lichen fragments (Gaio-Oliveira et al., 2006).

Despite the essential role that lichens play in boreal forests, large-scale tools to monitor their status are rare. Some national inventories collect information on lichen horizontal extent, usually quantified in terms of percent lichen cover. One example is the Swedish National Forest Inventory (NFI, Anonymous, 2015). However, the thickness of the lichen mats, which is strictly correlated to lichen biomass (Moen et al., 2007; Olofsson et al., 2011), is rarely monitored on a large scale. Such monitoring is essential to quantify total lichen biomass and to predict how climate change and human disturbances will affect lichens, ecosystem functioning, and reindeer survival in the future. Reindeer herders, practitioners and conservationists would greatly benefit from tools to estimate the past conditions of mat-forming lichens and to detect current lichen hotspots. The purpose of this study was therefore to develop regression models that can be translated into equations which allow the assessment of lichen conditions when forest, meteorological, topographic and soil characteristics of a certain area are known. We first developed a model describing the occurrence of forests dominated by mat-forming lichens. Secondly, we developed models describing lichen biomass, height (i.e., lichen vertical growth), and cover (i.e., lichen horizontal extension) in those forests in which the ground layer is dominated by mat-forming lichens (Fig. 1). We hypothesized those forests to be dominated by Scots pine and characterized by dry soils (Ahti, 1961). We also hypothesized that lichen biomass would be favored by low basal area and thin canopy cover (Berg et al., 2008; Gaio-Oliveira et al., 2006; Jonsson Čabradič et al., 2010). Lastly, we hypothesized reindeer grazing to negatively affect lichen height (den Herder et al., 2003; Holt et al., 2008; Moen and Danell, 2003), while positively affecting lichen cover (Gaio-Oliveira et al., 2006).

## 2. Methods

### 2.1 Predicting the occurrence of lichen-dominated forests

#### 2.1.1. Input open data

Since the 1920s, each year the NFI has been recording data on the

Swedish forests in circular temporary plots (<http://www.slu.se/nfi>). Since 1953 the plots, with a 10 m radius, have been organized in clusters, distributed over a grid covering the whole country. Each cluster has a squared shape and three to four plots per edge, the length of which can vary between 1 and 2 km (Fridman et al., 2014). The distance between clusters varies between northern and southern Sweden, with clusters in the south being closer to each other than in the north. We selected all forest plots ( $n = 48267$ ) which were sampled by the NFI between 1983 and 2014, and were located within the reindeer herding husbandry area of northern Sweden, i.e. in the counties of Jämtland, Västerbotten, and Norrbotten. We assigned a unique code to each annual cluster of plots, hereafter referred to as *Cluster*. The NFI classifies each forest plot based on the vegetation group dominating the ground layer, differentiating among dry mosses, wet mosses, and mat-forming lichens. Based on the NFI classification, we divided the plots into two categories: moss-dominated and lichen-dominated. We defined as lichen-dominated those plots classified by the NFI as either “lichen dominant” (> 50% lichen cover), “lichen moderate/Sphagnum type” (25–50% lichen cover), or “lichen moderate” (25–50% lichen cover) (Anonymous, 2015). We defined all other plots as moss-dominated. The NFI also records several forest characteristics at each plot, e.g. basal area, tree canopy cover, forest type, forest age, and tree height.

We obtained data on monthly average air temperature and monthly total precipitation from the Swedish Meteorological and Hydrological Institute (SMHI). Data were provided as monthly maps covering the whole country and divided by year (2005–2014). We averaged the monthly temperature data and summed monthly precipitation data by season (winter: December–February; spring: March–May; summer: June–August; fall: September–November). The temperature map for June 2009 was missing, so we did not develop a temperature map for summer 2009. Similarly, we did not develop temperature and precipitation maps for winter 2005 because maps for December 2004 were not available. A preliminary analysis revealed that meteorological data averaged over a 5-year period (2010–2014) were highly correlated to data averaged over a 10-year period (2005–2014). Therefore, we assumed that data averaged over the 10-year period could confidently represent the spatial variability in climatic conditions among plots in our study area. Similar patterns were suggested by Jonsson Čabradič et al. (2010). This assumption allowed us to test the importance of meteorological conditions in determining lichen dominance even for those years for which meteorological data were not available in map format (i.e. 1983–2004).

We derived topographic data from DEM maps with 50 m resolution downloaded from the Lantmateriet website (accessed on April 28, 2016: <http://www.lantmateriet.se/sv/Kartor-och-geografisk-information/Hojddata/>). For those areas where a 50 m resolution map was not available, we used maps with 2 m resolution. In ArcGIS 10.2.1 (ESRI, 2014), we derived slope and aspect maps from the DEMs. We obtained soil data, i.e. a map describing the percentage of sand content and a map of Available Water Capacity (AWC) in the topsoil, from the European Soil Data Centre, <http://eusoiils.jrc.ec.europa.eu/content/topsoil-physical-properties-europe-based-lucas-topsoil-data> (Ballabio et al., 2016). Lastly, we extracted information from the meteorological, topographic and soil maps for each plot.

#### 2.1.2. Model development

We developed a quasibinomial mixed-effect regression model in which lichen dominance was the response variable, taking the value 1 for lichen-dominated plots and the value 0 for moss-dominated plots. A quasibinomial model was necessary because the corresponding binomial model suffered of overdispersion. The candidate predictor variables were basal area, tree canopy cover, forest type, forest age, spring, summer and winter precipitation, summer and winter temperature, slope, aspect, sand percentage in the soil (*sand*) and AWC. We did not include spring and fall temperature as candidate predictor variables because they were highly correlated with winter temperature

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