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Estimating lichen volume and reindeer winter pasture quality from Landsat imagery[☆]

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ABSTRACT

Reindeer and caribou are keystone species in the circumpolar region, and rely on lichens as their main winter forage to survive in some of the most extreme environments on Earth. Lichen mats, however, can be heavily overgrazed at high deer densities, triggering area abandonment or population declines. Although the species' management and conservation require precise information on the quality of winter grazing areas, no reliable and cost-efficient methods are available to date to measure lichen volume across wide and remote areas. We developed a new Lichen Volume Estimator, LVE, using remote sensing and field measurements. We used a Landsat TM land cover mask to separate lichen heath communities from other vegetation types and, therein, we predicted lichen volume from a two dimensional Gaussian regression model using two indexes: the Normalized Difference Lichen Index, NDLI (Band 5 − Band 4 / Band 5 + Band 4), and the Normalized Difference Moisture Index, NDMI (Band 4 − Band 5 / Band 4 + Band 5). The model was parameterized using 202 ground measurements equally distributed across a gradient ranging from 0 to 80 lichen dm^3/m^2 ($R^2 = 0.74$ between predicted and observed ground measurements), and was validated with a ten-fold cross validation procedure ($R^2 = 0.67$), which also showed a high parameter stability. The LVE can be a valuable tool to predict the quality of winter pastures for reindeer and caribou and, thus, help to improve the species' management and conservation.

1. Introduction

Reindeer and caribou (*Rangifer tarandus*, L 1758) are keystone species in the circumpolar region for their ecological role in the sub- and high arctic trophic chains (Dale, Adams, & Bowyer, 1994; Mowat & Heard, 2006; Musiani et al., 2007; Soppela, Ruth, Åhman, & Riseth, 2002) and their important social, cultural and economic value to a large number of local communities and indigenous cultures (Hummel & Ray, 2008). The understanding of reindeer and caribou population dynamics and spatial behavior, and consequently the development of adequate management and conservation plans, depends to a large degree on a correct spatial and temporal quantification of their food resources (Crittenden, 2000). In winter caribou and reindeer feed mainly on lichens, which are slow-growing symbiotic organisms occurring in some of the most extreme environments on Earth (Boertje, 1990; Gaare & Skogland, 1975; Mathisen, Haga, Kaino, & Tyler, 2000). Ground lichens constitute a vital part of reindeer and caribou winter diet, and non-destructive estimation of lichen biomass or volume is crucial to support a sustainable management of winter grazing areas (Moen, Danell, & Holt, 2007). Lichen mats, however, can be heavily affected by overgrazing and trampling which, in high density populations, can cause substantial winter forage depletion and trigger large scale habitat shifts or population declines (Crittenden, 2000; Den Herdner, Kytoviita, & Niemela, 2003; Klein, 1987; Mansenau, Hout, & Crête, 1996).

As reindeer and caribou roam large, remote, and often inaccessible habitats, several attempts have been made to measure lichen biomass or volume using remote sensors (e.g. Colpaert, Kumpula, & Nieminen, 2003; Nordberg, 1998; Théau, Peddle, & Duguay, 2005). Lichens of the dominant genus in low tundra areas, *Cladonia*, are known to display strong absorption of ultraviolet energy and short-wavelength blue light, making it possible to separate the dominating lichen species from vascular plants (Petzold & Goward, 1988). Nordberg (1998) developed a Normalized Difference Lichen Index, NDLI, derived from Landsat TM spectral bands 4 and 5 ([Band 5 − Band 4] / [Band5 + Band 4]). Later Nordberg and Allard (2002) showed the Normalized Difference Vegetation Index, NDVI, to be a better predictor of lichen cover than NDLI. Dahlberg (2001), however, argued that NDVI might be more representative of land cover classes than lichen biomass and recommended topography or other ancillary data to be used together with

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NDLI or NDVI to achieve better estimates of lichen biomass. In addition to the NDLI also the NDMI (Normalized Difference Moisture Index) first introduced by Wilson and Sader (2002) contrasts the near- to mid-infrared band (band 4 to 5) and holds a potential for lichen biomass detection since lichens in the species groups *Cladonia*, *Stereocaulon* and *Flavocetraria* are well detected and separated in the mid-infrared bands of Landsat TM/ETM+ (Rees, Tutubalina, & Golubeva, 2004) and in Landsat 8.

Previous attempts to measure ground cover of lichens from satellite images relied on a variety of supervised and hybrid-supervised classification methods to distinguish among a few and rough classes of abundance (i.e. worn versus pristine pastures). Although such methods can yield a classification accuracy of more than 85% for the most lichen-dominated vegetation classes (Colpaert et al., 2003; Gilichinsky, Sandstrom, Reese, Kivinen, & Nilsson, 2011; Nordberg & Allard, 2002; Tømmervik, Høgda, & Solheim, 2003), they do not allow quantifying lichen volume or biomass directly from remote sensed data. To our knowledge no studies to date have established a direct relationship between satellite-derived vegetation indices and lichen volume or biomass.

The objective of this study was to develop a method allowing for a continuous estimation of lichen volume within lichen-dominated alpine heath communities and thereby to provide a valuable tool for *Rangifer* research, management and conservation.

2. Methods

2.1. Study area

Hardangervidda is an 8000 km^2 mountain plateau above the tree line in the southern part of the Norwegian mountain range (60°N, 7° 30′ E), located about 50 km from the coast (Fig. 1). The plateau extends between 780 and 1300 m a.s.l.; although there are some peaks above 1800 m in the northern and south-western part of the plateau, most of the topography is fairly flat, with height differences in the range of 100–400 m. The substratum consists mainly of gneissic bedrock of the Precambrian Baltic shield (Sonesson, Wielgolaski, & Kallio, 1974). Gaare, Tømmervik, and Hoem (2005) reported that approximately 30% of the total area has no or very scarce vegetation. The western and southern parts of the plateau are subjected to more oceanic influences, with an annual precipitation of 1200–1800 mm, while the central, eastern and northern parts are more continental, (600–800 mm/year); here lichen-dominated vegetation prevails (Gaare et al., 2005). The distribution of land cover classes within Hardangervidda has been described by Hesjedal (1975a,b), Wielgolaski (1975) and Gaare et al. (2005). Note however that the land cover map used in the present work has been specifically developed by the authors (Falldorf et al., *manuscript*).

Most lichen heaths in Hardangervidda are oligotrophic and occur in localities where the snow cover usually is less than 50–60 cm (Lye, 1975). Because of the thin snow cover, winter temperatures may drop below −15 °C in the upper vegetation layers. This, together with the often extreme dry summer conditions (2–5% soil moisture) and high soil-surface temperatures (40–50 °C; Wielgolaski, 1975), strongly limits the number of vascular plant species on exposed heaths and ridges, which is represented by a few grasses such as *Festuca ovina*, and some dwarf shrubs such as *Empetrum hermaphroditum*, *Vaccinium vitis-idaea* and *Arctostaphylos alpina*. Lichen heaths are best developed in the central and eastern parts of Hardangervidda, which is also considered the best winter grazing habitats for reindeer (Gaare et al., 2005). These vegetation types (*Loiseleurio-Arctostaphylion* alliance) cover about 10% of the area (Hesjedal, 1975a,b; Gaare et al., 2005) and have been used by reindeer for 80–100% of the total grazing time during winter (Østbye et al., 1975; Skogland, 1984). In the central part of the Hardangervidda plateau lichens are often dominated by *Flavocetraria nivalis*, and their biomass has been quantified in the range of 200–400 g/m^2 dry weight by Wielgolaski (1975); we do not expect substantial deviations from such values in present times.

2.2. Field data and lichen measurements

Lichen coverage and height were recorded during late-July/August 2000–2005 (n = 1345 sampling areas), with highest sampling intensity between 2003 and 2005. The sampling areas were placed following a design stratified by geographical distribution (east–west/north–south gradient) and by elevation within the land-cover class "alpine heath", which covers app 26% of the total study area (Fig. 1). Sampling areas were separated by an average distance of 34.8 ± 18.6 km.

Each sampling area consisted of a 50 × 50 m square (whenever this was not possible, the size was reduced to 30 × 30 m), to reduce mixed pixel problems in the image analysis. Within each sampling area we randomly selected one sampling point close to its center, and four additional sampling points at 10 m distance from the central point in the four cardinal directions. Within a radius of 2 m around the center of each sampling point we placed a 0.5 × 0.5 m grid, consisting of 25 10 × 10 cm squares, within which we measured the percentage area covered with lichen as well as the lichen height. Individual grid locations were geo-referenced using GPS, and 95% of the measurements fell within an 11 m radius around each center (95% Circular Error Probable). The high GPS accuracy was made possible by the favorable topography, as the study area is a mountain plateau. For each sampling area all five measurements of lichen coverage and height were averaged, and used to calculate lichen volumes.

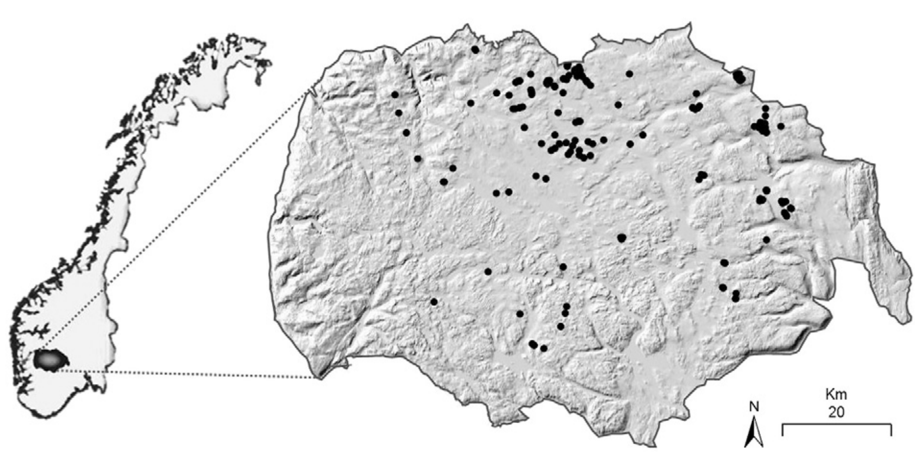

Fig. 1. Map of the study area, Hardangervidda, located in the southern part of the Norwegian mountain range (60°N, 7° 30′ E). Black dots represent sample areas for measurements of lichen volume (n = 1345).