



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.

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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 ($[\text{Band 5} - \text{Band 4}] / [\text{Band 5} + \text{Band 4}]$). 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 km² 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-Arctostaphyilion* 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/m² 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.

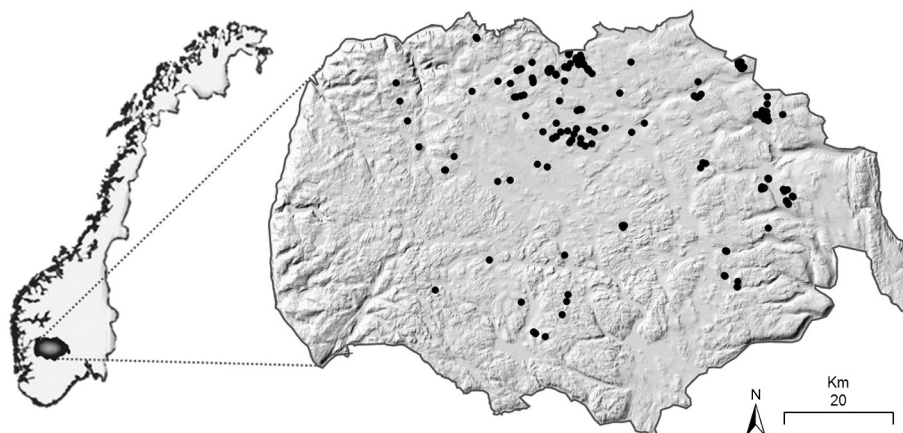


Fig. 1. Map of the study area, Hardangervidda, located in the southern part of the Norwegian mountain range (60°N, 7° 30' E). Black dots represent sample areas for measurements of lichen volume (n = 1345).

As preliminary analysis suggested severe over-sampling of areas with low lichen volumes, we used a binned sub-sampling design with 32 equidistant classes of lichen volume to achieve an even distribution of sample areas. Using a random draw of 10 sampling areas per bin, sample size was reduced to $n = 202$ as some of the bins contained less than ten sample areas. Within the sub-sample, lichen volume was equally distributed between 0 and $80 \text{ dm}^3/\text{m}^2$.

2.3. Image selection and preprocessing

Landsat images were obtained from USGS through Metria, Sweden, and orthorectified on WGS84 UTM 32N by Geodata senteret AS using ERDAS Imagine 8.7 (LEICA Geosystems, 2003) based on a digital elevation model (DEM) and ground control points. Ground control points were derived from a formerly corrected Landsat image (Landsat 5 TM; Path/row: 199/18; 9th Aug. 2003, Fig. 2) geo-referenced using Vexcel aerial photos, and a water mask obtained from a 1:50,000 topographical map. The image was the only available free of cloud coverage during the study period. Cubic convolution was preferred over the nearest neighbor resampling as spatial accuracy for possible later change detection is most critical and normalized differenced indices were used rather than reflectance values of single bands. The estimated root mean square error (RMS) of the orthorectified image fell between 13 and 14 m. Considered the limited resolution of the DEM (25 m), and the obtained RMS of ground control points (5–7 m), the total RMS could still be limited to less than half a pixel size.

Topographic normalization was used to control for relief induced differences in ground reflectance (Parlow, 1996). C-correction was preferred over alternatives (e.g. cosine) because, together with Minnaert-correction (see e.g. Blesius & Weirich, 2005), it performs best for illumination correction, and coefficients for c-correction are easier to obtain. C-correction uses a parametric model accounting for non-lambertian reflectance by introducing ground cover specific correction factors (c-factor; Civco, 1989; Meyer, Itten, Kellenberger, Sandmeier, & Sandmeier, 1993). C-factors were derived from the regression coefficients of the digital number against the sun incidence

angle as calculated from DEM (based on 30,000 random points). Bands with significant topography effect on reflectance were corrected (BANDS 2–5 and 7).

2.4. Lichen volume estimation

In order to remove possible confounding reflectance values we masked out areas where lichens were not detected and we focused on areas with lichen dominated vegetation types (land cover class alpine heath; Falldorf et al., manuscript). Within each lichen dominated area we modeled lichen volumes as follows. First, we screened the data for possible correlations between the observed lichen volume and reflectance values of individual Landsat bands (scatterplots, linear/logistic regression). This revealed most promising results using Landsat bands 2, 4 and 5. Utilizing these findings, a modest negative correlation was found between NDLI and lichen volume with strongest sensitivity at intermediate values but poorer predictability for both very low and high lichen volumes. Also the Normalized Difference Moisture Index ($\text{NDMI} = [\text{Band } 4 - \text{Band } 5] / [\text{Band } 4 + \text{Band } 5]$) appeared to be a reasonable candidate for further analyses. NDMI contrasts the near-infrared band 4, which is sensitive to the reflectance of leaf chlorophyll content, to the mid-infrared band 5 – which is sensitive to the absorbance of leaf moisture (Wilson & Sader, 2002). Rees et al. (2004) showed that lichens of the species *Cladonia*, *Stereocaulon* and *Flavocetraria* are well separated from each other in the mid-infrared band 5 (TM), and Neta, Cheng, Bello, and Hu (2010) supported such findings also for wet samples of the same species. Preliminary data investigation suggested better results using multi-dimensional Gaussian curve estimates rather than single two dimensional linear regression models. The final regression model used to predict the observed lichen volume, i.e. the Lichen Volume Estimator (LVE), is:

$$\text{LVE}(\text{NDLI}, \text{NDMI}) = a \times \exp^{-0.5 \times \left(\left(\frac{\text{NDLI} - \text{NDLI}_{\text{mean}}}{b} \right)^2 + \left(\frac{\text{NDMI} - \text{NDMI}_{\text{mean}}}{c} \right)^2 \right)}, \quad (1)$$

where $\text{NDLI}_{\text{mean}}$ and $\text{NDMI}_{\text{mean}}$ are the NDLI and NDMI respectively, and a, b and c are the normal distribution parameters to be parameterized.

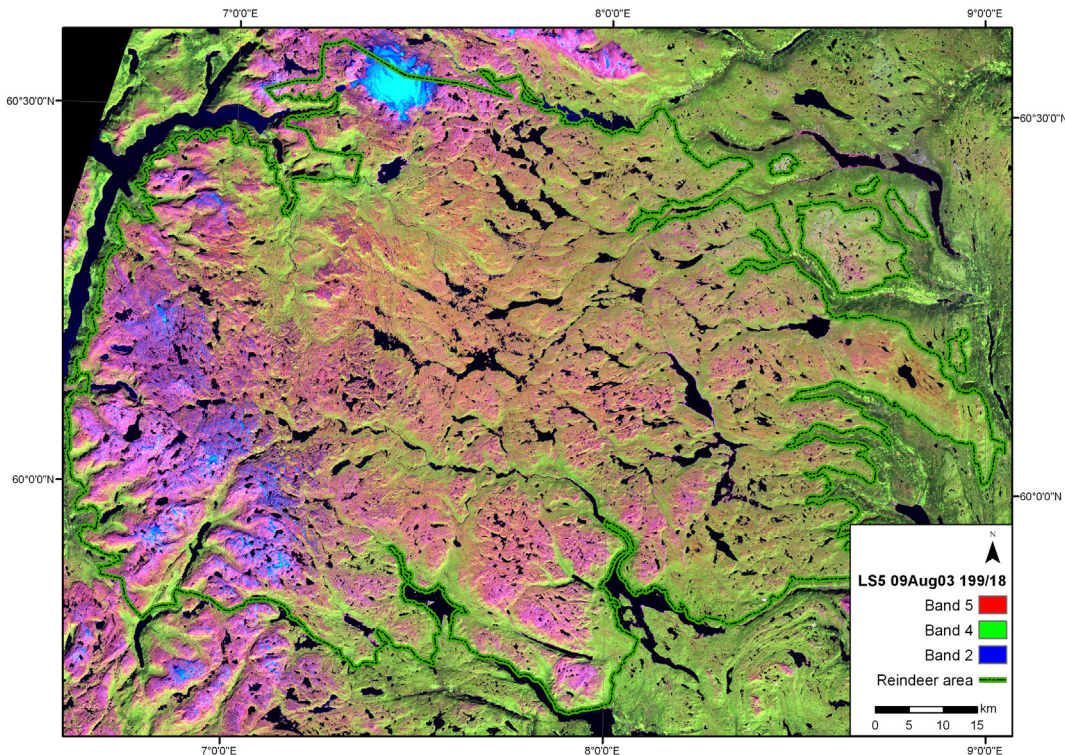


Fig. 2. Lichen biomass (Unit: dm^3/m^2) was estimated in Hardangervidda based on Landsat 5 TM; Path/row: 199/18; 9th Aug. 2003.

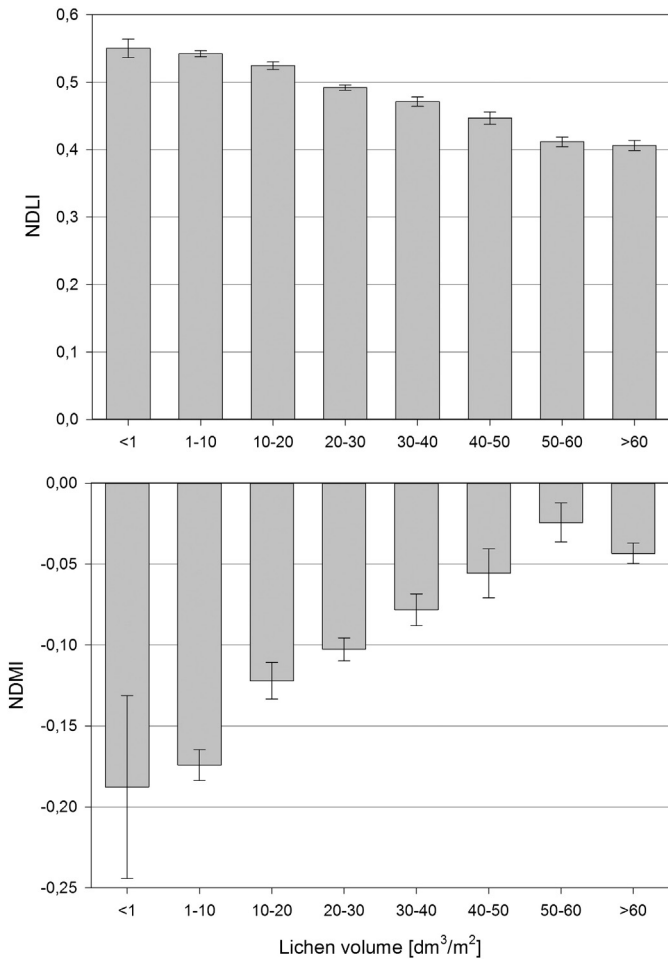


Fig. 3. Upper histogram: Normalized Difference Lichen Index (NDLI = Landsat TM (band 5 – band 4 / band 5 + band 4)) and observed average lichen volume, in dm^3/m^2 . Lower histogram: Normalized Difference Moisture Index (NDMI = Landsat TM (band 4 – band 5 / band 4 + band 5)) and observed average lichen volume.

Model building and parameter estimation was done using SigmaPlot 2000. Due to limited sample size, the model was validated using a tenfold cross-validation procedure (Boyce, Vernier, Nielsen, & Schmiegelow, 2002).

3. Results

A strong positive correlation was found between lichen volume and NDMI with a steady increase between 10 and 60 dm^3 of lichen per m^2 . While NDMI performed better than NDLI in separating among lichen volume classes below $60 \text{ dm}^3/\text{m}^2$, for lichen volumes higher than $60 \text{ dm}^3/\text{m}^2$ little or no difference between the two methods could be detected (Fig. 3). The lichen volume model with both NDLI and NDMI as simultaneous predictors (Eq. (1)) was successful in correctly classifying the observed lichen volume classes (adjusted R^2 : 0.70, $df = 4/201$, $F = 120.5$, $p < 0.001$). Univariate logistic regression models using NDLI or NDMI indicated significantly lower accuracies (NDLI: $R^2 = 0.61$; NDMI: $R^2 = 0.37$, respectively; Figs. 3 and 4). All estimated parameters were highly significant ($p < 0.001$) and no severe violations of regression assumptions (normal distribution of residuals, constant variance between residuals, absence of autocorrelation, no co-linearity between predictors) were detected.

The maximum estimable lichen volume was approximately $60 \text{ dm}^3/\text{m}^2$ (indicating lichen mats of ca. 6 cm and 100% coverage), and corresponded to NDLI values of 0.4 and NDMI values of 0.05, respectively (Figs. 3 and 4). The cross validation procedure indicated a relatively high accuracy of the predictive model (average adjusted R^2 : 0.67, $SD = 0.115$, Table 1). All ten cross validation models were highly significant and all estimated model parameters remained significant through the cross validation procedure; coefficient estimates were also stable among groups (Table 1). Further examinations of the 10 different cross validation models did not indicate any severe violations of assumptions for the regression models. Although band 5 was used in both NDLI and NDMI, the correlation between the two indices was still considered modest (Pearson's 2-tailed correlation index: -0.58), and the hypothesis of co-linearity was thus rejected. Analysis of residuals indicated constant variances between sub-groups, and the hypothesis of autocorrelation could thus also be rejected.

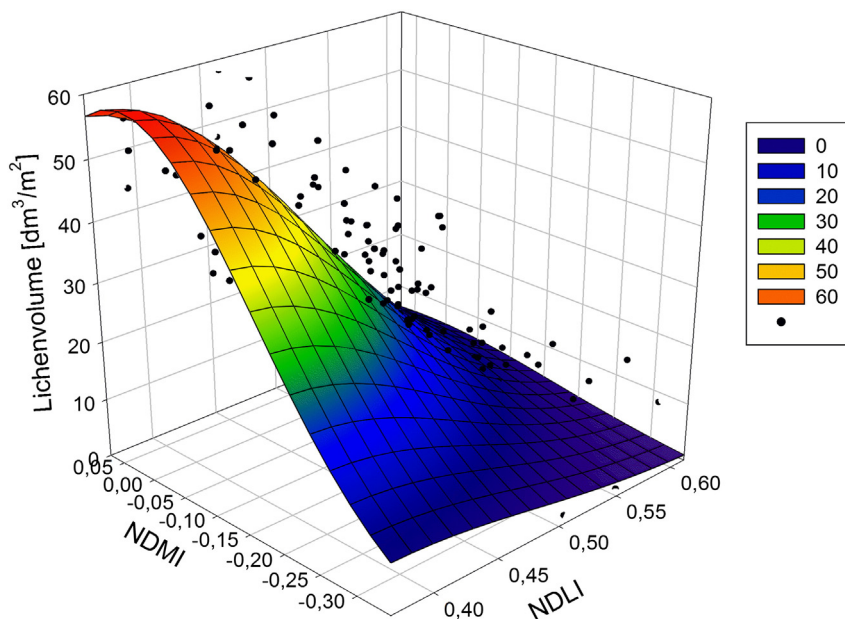


Fig. 4. Surface plot from a two dimensional Gaussian regression showing the relationship between the observed lichen volume, the Normalized Difference Lichen Index (NDLI = (Landsat TM (band 5 – band 4 / band 5 + band 4))), and the Normalized Difference Moisture Index (Landsat TM 5: (band 4 – band 5 / band 4 + band 5)).

Table 1

Summary of the tenfold cross-validation of the two dimensional Gaussian regression to predict lichen volume in dm^3/m^2 , based on the Normalized Difference Lichen Index, NDLI (Landsat TM: (band 5 – band 4 / band 5 + band 4)), and on the Normalized Difference Moisture Index, NDMI (Landsat TM: (band 4 – band 5 / band 4 + band 5)), following Eq. (1).

Cross val. sub-group	Adjusted R-square	Coefficients				
		X_0	Y_0	a	b	c
0	0.588	0.343	0.031	62.47	0.133	0.207
1	0.412	0.355	0.021	59.63	0.126	0.197
2	0.762	0.367	0.018	58.70	0.116	0.192
3	0.642	0.374	0.008	58.45	0.111	0.175
4	0.630	0.372	0.011	58.75	0.113	0.169
5	0.676	0.375	0.017	59.35	0.110	0.175
6	0.800	0.363	0.033	61.71	0.116	0.194
7	0.713	0.363	0.018	59.04	0.119	0.172
8	0.796	0.341	0.009	61.55	0.129	0.188
9	0.695	0.363	0.013	57.78	0.116	0.179
Average	0.671	0.362	0.018	59.74	0.119	0.185
Std. dev.	0.115	0.012	0.008	1.59	0.008	0.012

4. Discussion

We developed a novel Lichen Volume Estimator, which we used for obtaining a continuous prediction of lichen volume on a wide and remote area based on two previously developed indices derived from Landsat TM: NDLI and NDMI. Overall, our results for lichen volume prediction were promising, and suggest that LVE can become an important tool supporting *Rangifer* research, management and conservation (Fig. 5).

To our knowledge, LVE performs better than any other prediction model developed to date for quantify lichen abundance, and by establishing a direct relationship between remotely sensed images and lichen volume it allows overcoming the need to complement remote sensing data with topography or other ancillary data (e.g.

Dahlberg, 2001), and the issue of obtaining only a few rough predictive classes of lichen volume (Colpaert et al., 2003; Nordberg & Allard, 2002; Tømmervik et al., 2003). Hence, once the relationship between the observed lichen volume and the model formula is established, LVE can be used to monitor in the long term or even back in time spatial and temporal changes in lichen volume, provided that Landsat images are available.

NDLI and NDMI were insensitive to increases in lichen volume beyond an upper limit of approximately 6 cm in lichen height. This seems plausible, as lichen mats should yield a theoretical thickness threshold beyond which further increases in height do not affect their reflection characteristics. However, note that lichen thicknesses of >6 cm are rather scarce in the central part of the study area. The average lichen volume within alpine heaths was predicted to be approximately $15.4 \text{ dm}^3/\text{m}^2$, though we detected marked spatial differences. Such spatial differences are likely due to spatial differences in potential lichen volumes caused by factors such as elevation, climate, soil, and to spatial differences in reindeer grazing pressure, caused by natural habitat features and possibly human disturbance (Dale, Reimers, & Colemann, 2008; Nellemann, Vistnes, Jordhøy, & Strand, 2001) in some grazing areas.

Within the study area light-colored lichen species of the species *Cladonia*, *Flavocetraria* and *Stereocaulon* are more widespread than dark-colored species such as *Cetraria ericetorum*, *Cetraria islandica* and *Cladonia crispata* (Gaare et al., 2005; Hesjedal, 1975a,b). Thus, it may be argued that LVE primarily relies on changes in reflectance of light-colored species as their volume in-/decreases. We recommend performing experiments in visible-wavelength radiation under different proportions of light- and dark-colored lichens to assess the reliability of LVE in areas where dark-colored lichens dominate, and to assess its sensitivity to the ratio between light- and dark-colored lichens.

The method we developed allows predicting lichen volume, which can be used as a proxy for lichen biomass, reflecting the quality of reindeer winter pastures. Although we did not directly assess the

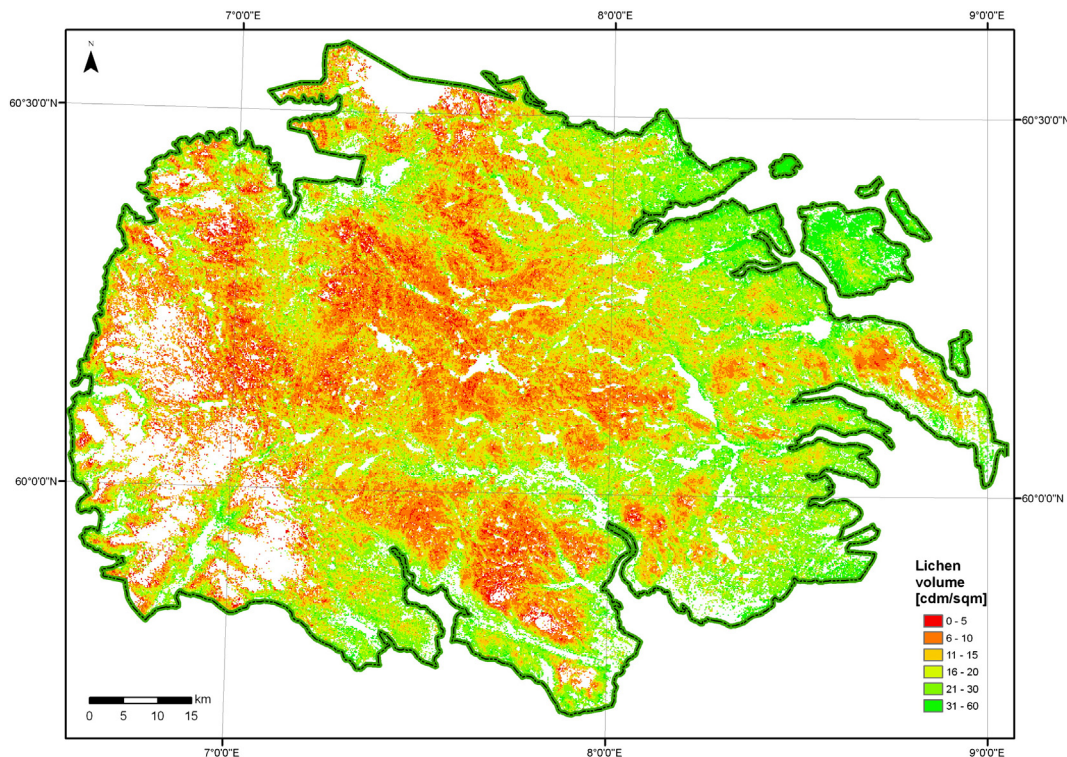


Fig. 5. Lichen volume (dm^3/m^2) in Hardangervidda, estimated by applying the Lichen Volume Estimator to the Landsat 5 TM image from August 2003.

relationship between LVE and lichen biomass, several authors previously assessed the strength of the relationship between the volume and the biomass of the lichen standing crop (Colpaert & Kumpula, 2012; Kumpula, Colpaert, & Nieminen, 2000; Tømmervik, Bjerke, Gaare, Johansen, & Thannheiser, 2012). Kumpula et al. (2000) and Moen et al. (2007), for example, obtained correlation coefficients of $R^2 = 0.78$ and $R^2 = 0.81$, respectively. However, if growth rates and productivity estimates are needed, it will be necessary to calculate LVE independently for species with different growth rates, which depends on chlorophyll content and distribution (Moen et al., 2007; Palmqvist & Sundberg, 2000). Indeed, we suggest future studies to discriminate between dominant lichen species on alpine heaths by using high resolution satellite sensors (e.g. SPOT 5 and Sentinel 2). This may be done for example using three categories: (i) *Cladonia stellaris* dominant ridge/heath, (ii) *Cladonia arbuscula* and *Cladonia rangiferina/stygia* dominant heaths, and (iii) *Flavocetraria nivalis* dominant ridge/heath. Furthermore, although the predicted lichen volumes were reliable in our study area, we recommend performing field tests before adopting LVE in other areas, since both the relative proportion and the height of lichens and vascular vegetation might change and alter the reflectance values. Note, however, that the collection of field data required for the first model parameterization is time consuming, although the model can thereafter be used in the same area multiple times. Finally, note that the applicability of the proposed model is limited to alpine heaths dominated by lichen heath communities.

The approach we proposed reliably predicted lichen volume in the Hardangervidda plateau. As several studies highlighted a strong correlation between lichen volume and biomass, the approach we proposed can be reliably used to predict the quality of reindeer winter grazing areas and, ultimately, to facilitate and improve *Rangifer* habitat and population management. On a more general perspective, if appropriate field tests are performed our approach can be adopted across the circumpolar range of *Rangifer* to aid adaptive management for the species.

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