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Quantifying winter forage resources for reindeer: Developing a method to estimate ground lichen cover and biomass at a local scale

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ABSTRACT

Boreal forests serve as the primary winter range for reindeer (*Rangifer tarandus*) in Sweden, where ground lichens constitute the main food source. Lichen-rich forests have declined drastically, and modern forest practices, along with other land uses, impact both the quantity and availability of lichen. The resulting reduction in lichen has serious consequences for reindeer and Sami reindeer husbandry. Consequently, robust methods for mapping and measuring lichen are highly sought after.

We developed and implemented a multistep method for objectively estimating lichen cover and biomass. We collected data at three study sites in lichen-rich pine forests in northern Sweden during July–August 2021. First, we collected data on NDVI and tree cover using a drone. These data informed a spatially balanced sampling approach to provide a distribution of plots for a representative field sample. Following this, we collected field data on lichen cover and height in these plots. In addition, we compared methods for assessing lichen cover in the field and found that visual estimates resulted in lower values than a point-intercept method. We recommend the point-intercept method for its objectivity and consistency between observers. By combining data from a literature review and fitting a linear regression on lichen volume (dm^3 m^{-2}) and biomass (kg dry weight m^{-2}) through the origin, we determined a slope of 0.0148 for estimating biomass from volume measures. Using this relationship with field data on lichen cover and height, we obtained statistically unbiased estimates of lichen cover and biomass. This approach reduces the time required compared to destructive methods involving lichen collection and weighing.

While our method provides lichen cover and biomass estimates, we also demonstrate how these biomass estimates can be linked to the number of reindeer grazing days an area can sustain each year, enhancing the usefulness of the results. Our estimates will be valuable in planning and management of reindeer husbandry, as well as for quantifying the loss of the ground lichen resource in forestry, energy and mining industries.

1. Introduction

Reindeer and caribou (*Rangifer tarandus* sp. hereafter referred to as reindeer) are recognized as a keystone species in the northern hemisphere and occupy 25% of the global land biome (Vors and Boyce, 2009). In Eurasia, many reindeer populations are domesticated and herded, and are vital to more than 20 indigenous cultures (Uboni et al., 2016). Reindeer have a unique adaptation to eat and digest lichens, and in winter, ground lichens such as *Cladonia* spp. and epiphytic pendulous lichens such as *Bryoria fuscescens* and *B. fremontii* may provide up to 80% of their winter diet (Heggberget et al., 2002). Lichens are thus crucial for reindeer survival in winter, and in many populations, lichen-rich boreal forests constitute the main winter range (Berg et al., 2008; Skarin et al., 2022). In Sweden, the boreal region has experienced significant changes due to human activities, especially from intensive forestry practices that have affected a large portion of the forest area (Östlund et al., 1997; Svensson et al., 2019). This has contributed to a long-term decline in lichen-rich forests (Sandström et al., 2016). Forestry, alongside other land uses like hydropower, wind power, mining, and infrastructure, impacts both the amount and availability of winter food for reindeer, as well as their ability to navigate the landscape (Kivinen et al., 2010; Axelsson-Linkowski et al., 2020; Horstkotte et al., 2022).

All reindeer in Sweden are owned and herded as a part of the Sami reindeer husbandry system and considered a cornerstone of Sami culture

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(Holand et al., 2022). Hence, mapping, and quantifying the declining availability of ground lichens is especially important. Robust methods of mapping and quantifying ground lichens are important not only for reindeer husbandry, but for other users of forested land including forestry, energy, and mining. Knowledge about where, and how much lichen can be found within specific areas is necessary for well-informed forest planning and management decisions, environmental impact assessments, and consultation processes.

Over time, various methods have been developed to map and quantify ground lichen cover and biomass. For methods that rely primarily on field data, allometric equations are commonly used to estimate biomass, minimizing the need for labor-intensive collection and weighing of lichens (Greuel et al., 2021). These equations relate either lichen cover alone (Thomas et al., 1996; Dunford et al., 2006; McMullin et al., 2011) or a combination of cover and height (Arseneault et al., 1997; Kumpula et al., 2000; Moen et al., 2007; Olofsson et al., 2011; Odland et al., 2014; Rosso et al., 2014; Greuel et al., 2021; Errington et al., 2022) to lichen biomass. Using volume (cover × height) provides more accurate results than using cover alone, particularly in regions impacted by reindeer grazing (Moen et al., 2007; Odland et al., 2014; Rosso et al., 2014). To date, no comprehensive comparison across studies has been conducted to assess the general applicability of these volume-to-biomass relationships.

In addition, most field studies rely on visual estimates to assess lichen cover. Although experienced observers can make accurate visual estimates, variability between observers is generally higher than when using frequency-based methods, such as point-intercept methods (Morrison, 2015). To choose the most suitable method, it is also necessary to understand the extent to which results produced by different methods for assessing lichen cover in the field differ from one another.

The methods described above that rely primarily on field data are mainly intended for fine-scale assessments focused on limited areas. At broader scales, from national to landscape levels, methods to map and quantify ground lichens involve building models that incorporate (objective) information from satellite imagery, along with field data for training and validation (Gilichinsky et al., 2011; Nelson et al., 2013; Falldorf et al., 2014; Hillman and Nielsen, 2020; Kennedy et al., 2020; Erlandsson et al., 2022; Horstkotte et al., 2023). The resulting models produce lichen maps with resolutions ranging from a few meters up to 30 m. At local or site-specific levels, when higher resolution is asked for, such model-based methods are not precise enough to be useful, and they often do not provide error estimates (Jansen et al., 2022). In recent years, drones have emerged as a tool to produce lichen cover maps with a resolution of a few centimeters. However, these maps have primarily served as training data for satellite image-based models and have predominantly focused on lichens with pale surfaces (Macander et al., 2020; He et al., 2021; Jozdani et al., 2021; Richardson et al., 2021; Fraser et al., 2022, 2023). Additionally, the accuracy of lichen cover predictions may decrease when the ground is not fully visible in drone imagery. Detailed mapping of ground vegetation using drones is limited by trees and other vegetation that can obscure significant portions of the ground and reducing the accuracy of cover predictions (Hernandez-Santin et al., 2019).

Advancements in remote sensing have not only enhanced lichen mapping but also created opportunities to employ new sampling methods that integrate land cover data into the sampling design (Grafström et al., 2014). Selecting a suitable sampling design is essential for precise estimates of population characteristics (Kermorvant et al., 2019). Spatially balanced survey designs, which allow for the selection of well-spread, representative samples across the population, is increasingly being used in biological and environmental management surveys (Grafström et al., 2014; Brown et al., 2015; Kermorvant et al., 2019).

The goal of our study was to develop and evaluate an objective method to accurately estimate ground lichen cover and biomass at the local scale. The method was designed to produce results that were both objective and easy to interpret, ensuring that all land users can trust the findings in situations when there are conflicting land use interests. To achieve this, we (i) developed a multi-step method that combined high-resolution remote sensing data to select sample plots where field data on lichen cover and height were collected, (ii) analyzed and compared three methods for measuring lichen cover in the field sample plots, and (iii) reviewed existing scientific studies regarding the relationship between lichen volume and biomass to derive biomass estimates from volume measurements. Additionally, we (iv) demonstrated how biomass estimates can be used to calculate the number of reindeer grazing days an area can sustainably support each year.

2. Material and methods

2.1. Study areas

Sami reindeer husbandry can be carried out on the northern 55% of Sweden's land area (Fig. 1a). We established three study sites, each constituting an area of 1–1.5 ha (Table 1), within Ran reindeer herding community's winter grazing area, near the city of Umeå (Fig. 1b). At each site, we collected drone and field data.

We selected sites to cover the two most common types of lichen-rich forests within reindeer husbandry area in Sweden. The Haddingen (Had) site is located on pine heath forest on sandy soils, and Kummelsberget (Kum) and Sävar (Sav) are pine forests on rocky ground. Besides the dominating pine (*Pinus sylvestris*) the sparse tree cover in these two forest types contained some *Picea abies* and *Betula pendula*. Lichen dominated patches were mixed with patches dominated by dwarf shrubs, mainly *Vaccinium vitis-idaea, Calluna vulgaris, Empetrum nigrum* and *Vaccinium myrtillus*, as well as various species of moss. All sites were occasionally grazed by reindeer. We found the lichen species that reindeer consume (*Cladonia arbuscula, C. mitis, C. rangiferina, C. stellaris, C. uncialis, Cetraria islandica*, and *Stereocaulon paschale)* in at least one of the study sites. Hereafter referred to as lichen. At the time of our field data collection, grazing was evident in some parts of the Kum site with low lichen thalli as a result, while the other sites showed no obvious signs of recent grazing.

2.2. Overview of the method

Our method is outlined step-by-step in Fig. 2, with each step further detailed in the following sections.

2.3. Drone data collection

As a first step in our method development, we used a DJI Phantom 4 Multispectral quadcopter to collect high resolution images on August 16, 2021. The multispectral camera array covered blue, green, red, red edge, and near-infrared bands, all at 2 megapixels. Data were collected at 45 m above ground to get images with a ground resolution of about 2.5 cm pixel^{-1}. The drone was equipped with a RTK module connected to the Swedish national network of permanent reference stations, SWEPOS, for real time position correction. We set the drone to fly in parallel lines across the study areas to capture images with a front overlap of 90% and a side overlap of 80%. We collected data on days with overcast skies to minimize shadows in the images.

Drone images were processed using Agisoft Metashape Professional 1.7.1 (Agisoft, 2021). For each site, we exported a dense point cloud along with both RGB and multispectral orthomosaics. We used R 4.1.1 (R Core Team, 2021) for all the data processing and statistics. The point cloud from Metashape was used with the R package lidR (Roussel et al., 2020; Roussel and Auty, 2021) to produce a canopy height model with 0.5 m resolution using the 'pit-free' algorithm developed by Khosravipour et al. (2014). The orthomosaic was loaded into R with the terra package (Hijmans, 2021) and we calculated the normalized difference vegetation index (NDVI) from the near-infrared band, 840 nm ± 26 nm

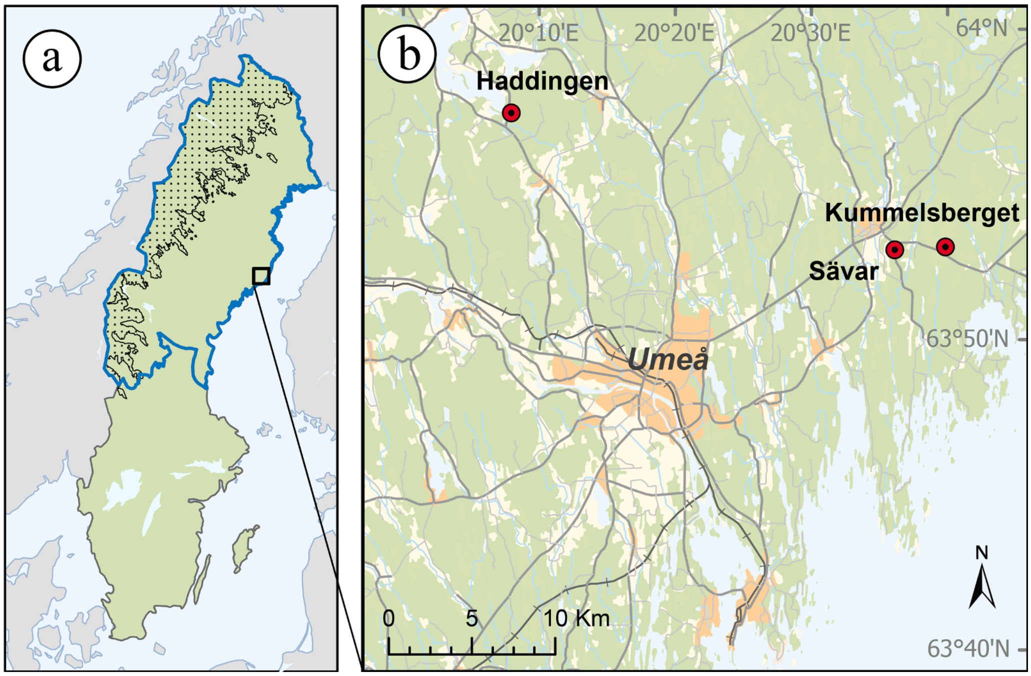

Fig. 1. Location of the study sites in northeastern Sweden where drone and field data were collected in August–September 2021. a) The blue border shows the Reindeer husbandry area in Sweden, where intensive forest practices are carried out on productive forestlands east of the Scandian mountain range (dotted). b) Locations of the three study sites—Haddingen (Had), Kummelsberget (Kum), and Sävar (Sav)—north of Umeå, Sweden.

Table 1
Summary statistics for the three study sites (Had, Kum, and Sav), including site area, tree cover and information on lichens found in the sample plots in northeastern Sweden, sampled in August - September 2021.

	Had	Kum	Sav
Area of study site (m^2)	14,489	14,676	11,109
Tree cover (visually estimated per site) (%)	35	40	20
Number of sample plots with lichen (out of 40)	32	32	28
Lichen cover (mean ± SE) (from point-intercept) (%)	28.4 ± 1.1	22.7 ± 0.9	27 ± 1.2
Lichen height (mean ± SE) (from point-intercept) (mm)	30.9 ± 1.3	23.5 ± 1.5	33.3 ± 1.4
Percent of total lichen cover (from point-intercept)			
Cladonia arbuscula + *C. mitis* + *C. rangiferina*	88.8	84.5	75.1
Cetraria islandica	0.3	1.7	19.9
Cladonia stellaris	10.2	0	4.3
Cladonia uncialis	0.7	12.1	0.7
Stereocaulon sp.	0	1.7	0

(NIR) and the red band, 650 nm ± 16 nm (red) using the formula: NDVI = NIR - red / NIR + red. The resulting image was resampled to a resolution of 0.5 m. The image resolution was chosen to match the 0.5 m × 0.5 m sample plots used for the field data collection, following the methodology described by Moen et al. (2007).

2.4. Sampling - selection of sample plots

Spatially balanced sampling designs are often used to ensure samples are well spread geographically. However, they can also spread samples across multiple additional dimensions defined by auxiliary variables, such as wetness, slope, elevation, and vegetation indices, so that the distribution of these variables in the sample resembles that of the population (Grafström et al., 2012). Samples that are well-spread tend to improve estimates by reducing the variance, provided that the auxiliary variables used have explanatory power for the target variable (Grafström et al., 2014). We used the local pivotal method 1 (LPM 1) (Grafström et al., 2012) from the R package BalancedSampling (Grafström et al., 2024) for our sampling. We used NDVI, canopy height and the x and y coordinates as auxiliary information. NDVI is negatively correlated with increasing lichen cover (Nordberg and Allard, 2002; Erlandsson et al., 2023). The canopy height models were used to collect data from open areas, as well as from areas beneath trees of varying heights, reflecting the diversity in age structure. We included the x and y coordinates of each pixel in the Swedish reference frame 1999 (SWEREF 99) to ensure the sample was geographically distributed across the sites. All the auxiliary variables were standardized to have the same range. We sampled 40 pixels (0.5 m x 0.5 m) from each site, with each pixel representing a sample plot.

2.5. Field data collection – methods for lichen assessment

We collected field data between August 27 and September 9, 2021. We used the ArcGIS Field Maps app with an Emlid Reach RS2 multi-band RTK GNSS receiver, connected to SWEPOS for real-time position correction, to achieve centimeter-level precision locating sample plots. At each plot, we placed a 0.5 m × 0.5 m wooden frame aligned with north-south compass direction. The lichen cover and height within the frame were measured using methods from Moen et al. (2007). The frame was divided into 36 squares (Fig. 3). We measured the height of the lichen thalli to the nearest 0.5 cm by lowering a metal rod (3 mm diameter) to the base of the lichen at each of the 25 intersections created by the 36 squares, recording the measurement at the highest point where the lichen contacted the rod. The average of these measurements was then calculated to represent the lichen height for each plot. We measured percent lichen cover using three different methods, (i) percent of squares with presence of lichen (presence-absence), (ii) percent hits, out of 25, by the rod (point-intercept), and (iii) visual estimate of percent lichen (visual estimate). We measured lichen cover and height for each species separately (except for *Cladonia arbuscula, C. mitis*, and *C. rangiferina*, as it was difficult to distinguish between them when they had been grazed) and for all lichen species together as a group, and used the latter for the biomass estimations. All measurements were done a

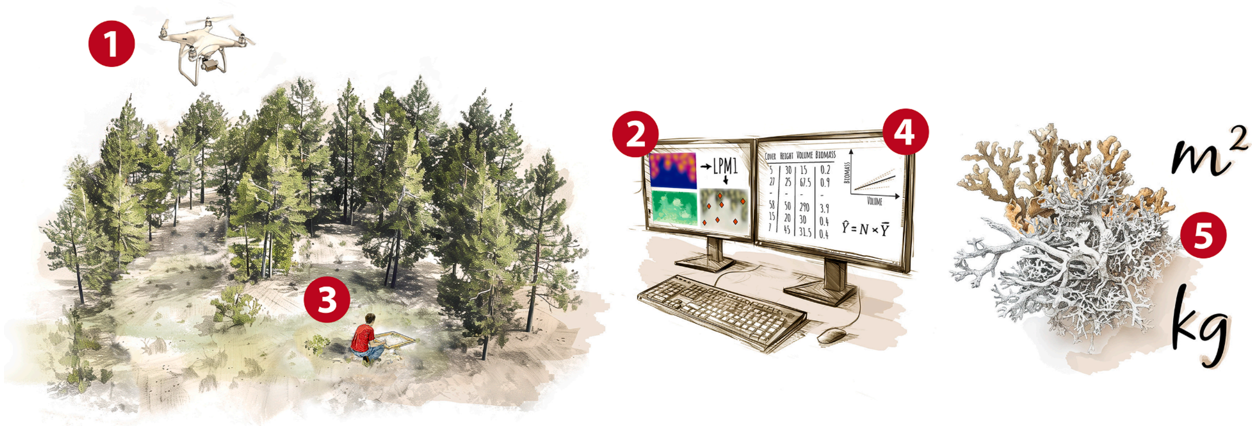

Fig. 2. Overview of the method developed for estimating ground lichen cover and biomass at a local scale. (1) **Drone data collection** - Multispectral images collected by a drone were used to acquire detailed and current information about the entire study site. (2**) Selection of sample plots** - By utilizing NDVI and canopy height data derived from the drone imagery we computed a spatially balanced sampling using the local pivotal method (Grafström et al., 2012), and achieved well-spread, objective, and reproducible sample plots. (3) **Field data collection** - Using these sample plots, we collected field data on lichen cover and height. (4) **Lichen biomass from volume** - We calculated biomass for each sample plot using a relationship between lichen volume (cover × height) and biomass derived from our literature review. (5) **Lichen cover and biomass estimations** - Finally, we computed statistically unbiased estimates of lichen cover and biomass for the entire site.

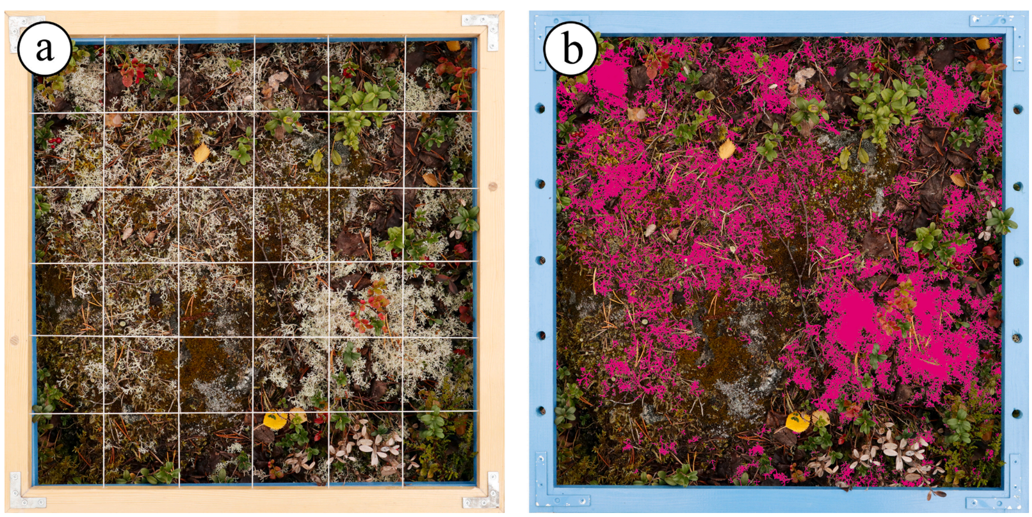

Fig. 3. Illustration of methods used for lichen cover assessment. a) Sample plot with a frame divided in 36 squares making 25 intersections. Lichen cover for this plot using each of the three methods: presence-absence: 97% (35 of 36 squares), point-intercept: 52% (13 of 25 intersections), visual estimate: 38%. b) Manual segmentation of lichen in photo of the same plot as reference: 22% cover.

few days after rainfall, placing the lichen in a state somewhere between moist and dry.

To estimate how time consumption varied across methods, we recorded the time taken to assess the cover for all lichen species combined for each method on 15 sample plots, which were subjectively selected to capture the variation in lichen cover and distribution. Timing began at the start of each assessment and ended once the result was recorded. For the visual estimate and presence-absence methods, this involved recording a single value: percent cover for the visual estimate and the count of lichen-present squares for the presence-absence method. For the point-intercept method, we measured and recorded lichen height at each of the 25 intersections where lichen was hit by the rod.

2.6. Literature review – lichen biomass from volume

The process of collecting, cleaning, and weighing lichen samples to determine biomass is very time-consuming (Rosso et al., 2014). Therefore, we conducted a literature review on lichen biomass estimations to compare and potentially utilize data from earlier studies. We searched the major databases, i.e., Google scholar and Web of Science, using the search term ‘lichen biomass’ and widened the search using references in the articles found to identify as many relevant studies as possible. Through our search we found five articles (Appendix A) relating lichen volume to biomass, where data on lichen volume was accessible, either online or presented in graphs in the articles. Data on lichen cover in Rosso et al. (2014), were obtained through both visual estimates and point intercepts. To maintain consistency with the other studies where available data came solely from visual estimates, we used the data on visual estimates. Additionally, from the same study, we selected only data from the species groups found at our sites (*Cladina* and *Cetraria*). We collected data from graphs using the R package metaDigitise (Pick et al., 2019) and recalculated the data from all five articles to matching units (dm^3 m^{-2} for volume and kg m^{-2} for biomass).

To reduce the variation in volume range among the studies, we excluded the most extreme data points with volumes exceeding 80 dm^3

m^{-2} from the full dataset of 910 points, resulting in the removal of seven points. In addition, these values were much higher than the maximum lichen volume of 44 dm^3 m^{-2} observed at our study sites. Finally, we fitted linear regressions through the origin and quadratic regressions, with lichen biomass (kg dry weight m^{-2}) as the response variable and lichen volume (dm^3 m^{-2}) as the predictor variable, for each reviewed study and for all data combined.

2.7. Lichen cover and biomass estimations

For each of our 120 sample plots and for each method of assessing lichen cover (presence-absence, point-intercept, and visual estimate), we calculated lichen volume by multiplying lichen cover by mean lichen height. In six plots, lichen was present but no height was recorded as no lichen was hit by the rod using the point-intercept method. Instead, we used the mean height for the species in question across the entire site. To estimate lichen biomass for each sample plot we used lichen volume (cover × height) with the slope from the linear regression on the combined data from all studies in the literature review. We then estimated total lichen cover, volume and biomass for each study site using each cover assessment method by applying the unbiased Horvitz–Thompson estimator (HT) (Horvitz and Thompson, 1952) (eq (1)). Our goal was to estimate a total Y of the lichen variable with value y_i for unit i for a population with N units $Y = \sum_{i=1}^{N} y_i$. The total Y could then be estimated from the sample by HT, which in this case with equal inclusion probabilities, can be expressed as

$$\widehat{Y} = N * \overline{Y} \tag{1}$$

The variance was estimated using a local mean variance estimator suggested for spatially balanced samples selected with the local pivotal method (Grafström and Schelin, 2014):

$$\widehat{V}_{SB}(\widehat{Y}) = \sum_{i \in s} \frac{n_i^*}{n_i^* - 1} \left(\frac{y_i}{\pi_i} - \frac{1}{n_i^*} \sum_{j \in s_i^*} \frac{y_j}{\pi_j} \right)^2 \tag{2}$$

Where s_i^* is a coherent subset of s with n_i^* units. The coherent subset s_i^* includes unit i, and $j \in s_i^*$ if $j \in s_i^*$ and $d(i, j) = \min j \in s, k \neq i^{d(i,k)}$. We calculated the standard error for the estimator using $\widehat{SE}(\widehat{Y}) = N * \frac{s}{\sqrt{n}}$ and the relative standard error $RSE = \frac{\widehat{SE}}{Y} * 100$. Finally, we divided the estimates by the site area in hectares to yield comparable figures for lichen cover (m^2 ha^{-1}) and lichen biomass (kg ha^{-1}).

2.8. Reindeer grazing days

To demonstrate how our estimates of biomass can be more directly linked to reindeer grazing, we estimated the number of grazing days per hectare each study site could support each winter. For grazing to remain sustainable over time, we assumed that only the yearly growth can be consumed. In their literature review, McMullin and Rapai (2020) estimated a global average annual linear growth rate for reindeer lichens to be 4.9 mm $year^{-1}$. The conditions most similar to our sites were dry pine forests in northeastern Finland, where the growth rate for *Cladonia rangiferina* ranged from 3.9 to 4.3 mm $year^{-1}$ and for *Cladonia mitis* from 3.0 to 3.5 mm $year^{-1}$ (Helle et al., 1983). As a compromise and to keep the calculations simple, we used a growth rate of 4 mm $year^{-1}$. We used data from the point-intercept method and subtracted 4 mm from the mean lichen height in each sample plot and re-estimated lichen biomass to represent the biomass from the previous year. By subtracting this from our original estimate, we obtained the annual biomass increase.

In winter, daily dry matter intake for free-ranging reindeer in Norway has been estimated at 490–1800 g (Storeheier et al., 2003). For our calculations, we used an average intake of 1.5 kg lichen day^{-1}. Besides their actual intake, when reindeer are cratering, they remove additional lichen from the ground. Although these fragments contribute to regrowth within the craters, modeling suggest that 0.5 kg wastage per kg intake should be included to explain the reduction in lichen after winter grazing in Finland (Pekkarinen et al., 2017). Thus, we added 0.75 kg to the average daily intake of 1.5 kg, resulting in a daily consumption estimate of 2.25 kg per reindeer. The number of grazing days was then estimated using the estimated annual increase in lichen biomass divided by the average daily lichen consumption.

To estimate uncertainty in the estimations, we calculated the smallest annual biomass increase as the difference between the lowest biomass estimates from the 95% confidence interval (estimate − SE × 1.96) for both years, and the largest annual biomass increase as the difference between the highest biomass estimates (estimate + SE × 1.96). We then divided these values by the daily intake to determine the minimum and maximum grazing days. The uncertainty was defined as the difference between these extreme values and the grazing days calculated from the average annual biomass increase.

3. Results

3.1. Drone data

The drone survey took approximately 20 min to complete at each site, while the processing (mostly automated) and exporting of images (Fig. 4) required about two hours per site on a standard desktop PC equipped with an AMD Ryzen 7 5800 8-core processor, 64 GB of RAM, and an NVIDIA GeForce RTX 3070 graphics card.

Our data on canopy height showed a negative correlation with lichen cover at all sites: Had ($r = -0.45$, $p = 0.0035$), Kum ($r = -0.38$, $p = 0.014$), and Sav ($r = -0.34$, $p = 0.034$). For NDVI, there was also a negative correlation with lichen cover that was significant at the Kum ($r = -0.47$, $p = 0.0022$) and Sav ($r = -0.5$, $p = 0.0011$) sites, but not at the Had site ($r = -0.27$, $p = 0.088$).

3.2. Sampling - selection of sample plots

The sampling using the local pivotal method resulted in 40 selected pixels (Fig. 4c) for each study site, well spread in the auxiliary information (Fig. 5).

3.3. Field data

On average, it took 20 min to complete field data collection at each sample plot. This included accurately locating the exact position, capturing photographs, and recording data for each method and species separately. Lichen species composition, height, and cover varied to some extent between the sites (Table 1). Most of the plots contained lichen, and the most common species across all sites were *Cladonia arbuscula, Cl. mitis* and *Cl. rangiferina*. Among the less common species, *Cetraria islandica, Cladonia unicialis*, and *Cl. stellaris* were each quite common on one of the three study sites, while *Stereocaulon* sp. only appeared in four sample plots at the Kum site. Compared to the Had and Sav sites, lichen height and cover at the Kum site was slightly lower.

3.4. Methods for lichen assessment

A comparison of the different methods showed that the point-intercept method yielded higher cover estimates than using visual estimates but lower cover than the presence-absence method (Fig. 3 and 6). Point-intercept and visual estimate were linearly correlated ($R^2 = 0.77$, slope = 0.70) and the plot shows that the error is relatively evenly spread around the regression line. The correlation between visual estimates and presence-absence was weaker ($R^2 = 0.48$, slope = 0.39). A plot with high cover according to presence-absence could have almost any value when visual estimation was used (Fig. 6c). The same was true when comparing point-intercept to presence-absence (Fig. 6b), even if the correlation was stronger between these two methods ($R^2 = 0.69$,

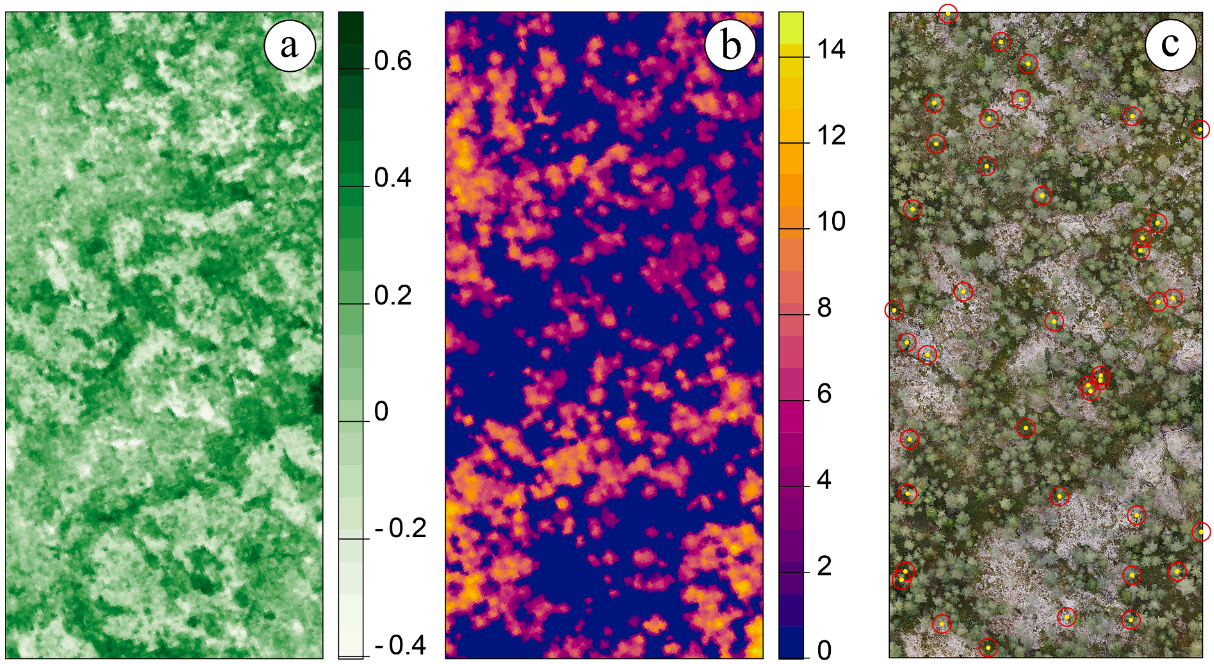

Fig. 4. Example from the site Sav in northeastern Sweden, showing data derived from drone images collected in August 2021 and sample plots selected during the sampling process.a) Normalized difference vegetation index (NDVI), and b) canopy height, both used as auxiliary data in the sampling, and c) RGB orthomosaic with sample plots indicated by a yellow dot surrounded by a red circle.

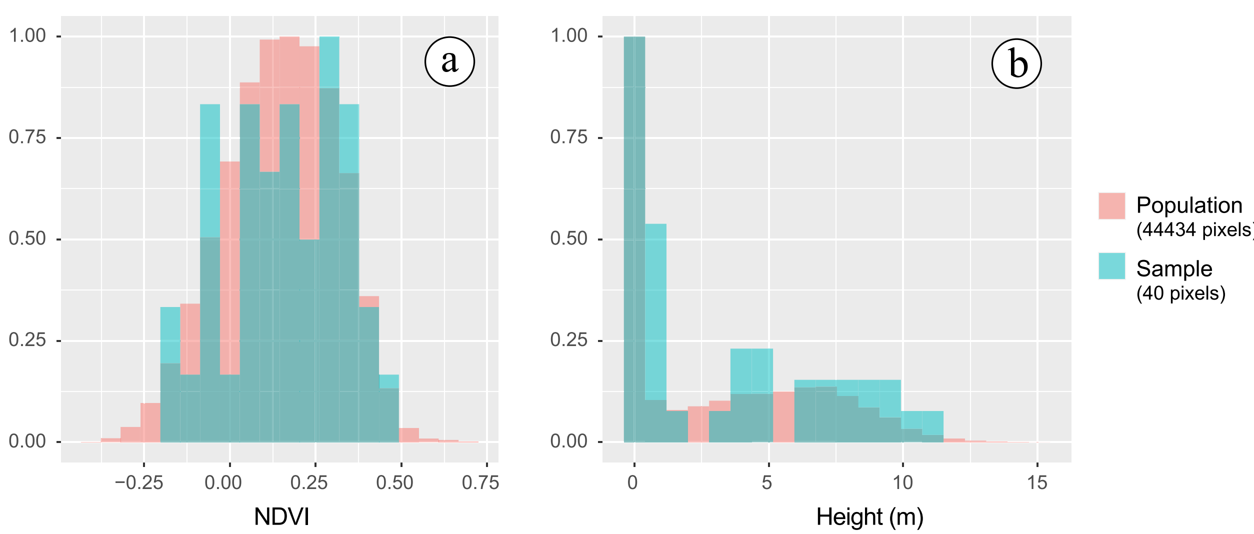

Fig. 5. Example of how the use of the local pivotal method 1 spreads the sample so that the distribution of the auxiliary information in the sample resembles that in the population. Histograms of the distribution of a) the NDVI and b) canopy height variables in the population (red) and sample (blue) for site Sav, when the sample was spread using all auxiliary information: NDVI, canopy height, x and y coordinates in SWEREF 99. The counts on the y-axis are scaled to a maximum of 1.

slope = 0.59) compared to the correlation between visual estimates and presence-absence.

Time consumption depended on the amount of lichen in the sample plots (Appendix B), particularly for the point-intercept method, where time steadily increased with lichen cover—from about one minute for the lowest cover to approximately five minutes as cover approached 100%. The time taken to record cover using the presence-absence and visual estimate methods was quite similar in most cases, typically requiring less than half a minute, with sample plots containing either little or abundant lichen being the quickest to complete. At our study sites where mean lichen cover was 20–30%, the time difference between the point-intercept method and the presence-absence and visual estimate methods was approximately two minutes per sample plot.

3.5. Literature review – lichen biomass from volume

In the regressions of lichen volume and biomass, based on the combined data from the five articles identified in our literature review, the quadratic regression curve and the linear regression line through the origin closely aligned across much of the range (Appendix C). Therefore, we used the simpler linear relationship, where the slopes allowed for easier comparisons between articles. The linear regressions through the origin for each article had slopes varying between 0.008 (Kumpula et al., 2000) and 0.0188 (Rosso et al., 2014) (Fig. 7). By combining data from all articles, we obtained a slope of 0.0148 that we used for our biomass estimations.

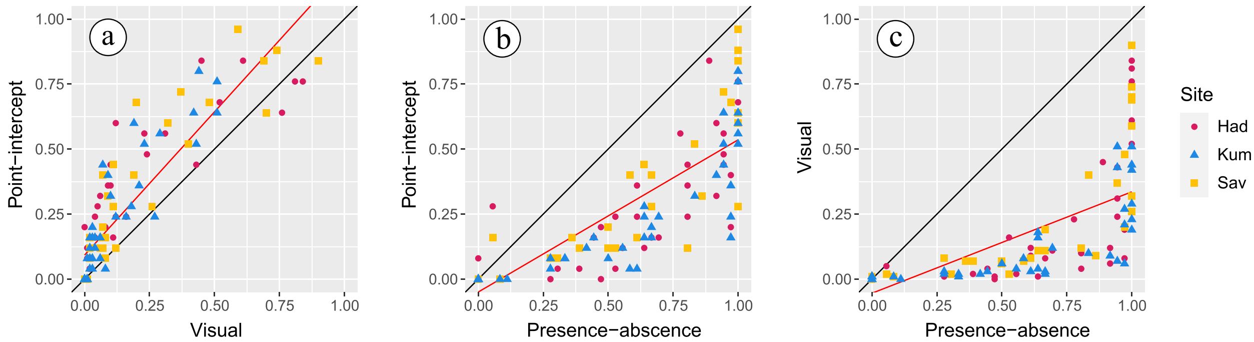

Fig. 6. Comparisons between the three different methods for estimating lichen cover: a) Point-intercept vs. Visual, b) Point-intercept vs. Presence-absence, and c) Visual vs. Presence-absence. The scale on both axes represents lichen cover, with 1 corresponding to 100% cover. Red lines depict the trend lines resulting from linear regressions, while black lines represent the 1:1 line, indicating a perfect match between the methods. Each data point corresponds to one of the 120 sample plots from the three study sites (Had, Kum, and Sav) in northeastern Sweden, sampled between August and September 2021.

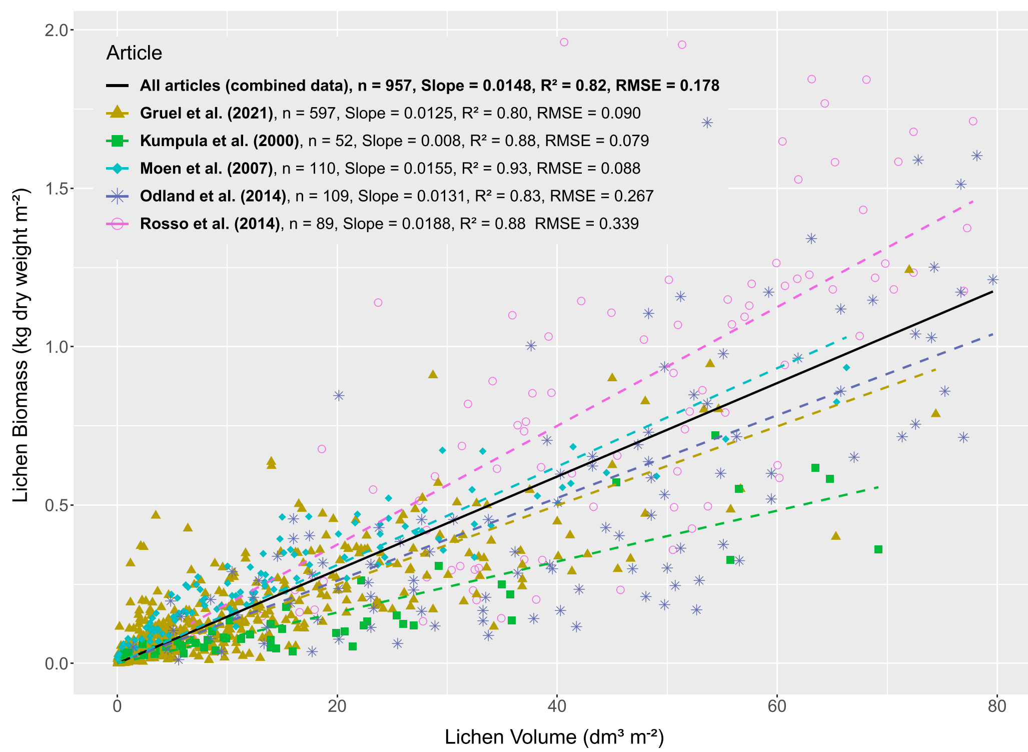

Fig. 7. Association between lichen volume (dm^3 m^{-2}) and biomass (kg dry weight m^{-2}). Linear regression through the origin for each article from our literature review (dashed lines) and for data from all articles combined (solid black line), with the number of points (n), slope, R-squared value (R^2) and root-mean-square error (RMSE).

3.6. Lichen cover and biomass estimations

Our estimates of lichen cover and biomass resulted in considerable differences, depending on the cover measurement method employed (Table 2). Cover estimates ranged from 1190 to 5736 m^2 ha^{-1}, and biomass estimates varied between 334 and 2318 kg ha^{-1}. As expected, the presence-absence method resulted in the highest cover estimates, followed by point-intercept and visual estimate, with consequent effect on biomass estimates. The use of the presence-absence method produced cover estimates, and consequently biomass estimates, that were approximately 2.5 to 5 times higher than those derived from visual estimates. The discrepancies between point-intercept and visual estimates were smaller, with the visual estimates being nearly half as large. In alignment with the estimates, the variance (Var) and standard error (SE) were highest for the presence-absence method, followed by point-intercept and then visual estimates, this pattern was inverted for the relative standard error (RSE). The RSE ranged from 8 to 13% for presence-absence, 13–16% for point-intercept, and 15–22% for visual estimates. The Kum site exhibited the lowest cover and biomass among the study sites. The relative difference in biomass compared to the other sites was clearly larger than the relative difference for cover: estimate cover from point-intercepts was 2270 m^2 ha^{-1} for Kum, versus 2840 and 2700 m^2 ha^{-1} for Had and Sav, respectively; and 649 kg ha^{-1} for Kum, compared to 1232 and 1221 kg ha^{-1} for Had and Sav.

3.7. Reindeer grazing days

The Had and Sav sites, with similar estimated biomass, supported 67 and 64 annual reindeer grazing days per hectare, respectively (Table 3). The Kum site, with biomass just over half that of the other sites,

Table 2
Summary of lichen cover and biomass estimates across the study sites (Had, Kum, Sav) in northeastern Sweden, sampled in August - September 2021, assessed using the presence-absence, point-intercept, and visual estimate methods. Lichen cover (m^2 ha^{-1}) and biomass (kg ha^{-1}) estimated using the unbiased Horvitz–Thompson estimator (eq (1)), along with variance, standard error (SE), and relative standard error (RSE), calculated using eq (2).

	Site	Method	Estimate	Var	SE	RSE (%)
Cover	Had	Presence-absence	5736	302,188	550	10
(m^2 ha^{-1})		Point-intercept	2840	147,767	384	14
		Visual estimate	1665	110,946	333	20
	Kum	Presence-absence	5493	217,179	466	8
		Point-intercept	2270	88,008	297	13
		Visual estimate	1190	33,362	183	15
	Sav	Presence-absence	4660	311,069	558	12
		Point-intercept	2700	169,633	412	15
		Visual estimate	1715	85,297	292	17
Biomass	Had	Presence-absence	2318	68,366	261	11
(kg ha^{-1})		Point-intercept	1232	41,011	203	16
		Visual estimate	717	24,668	157	22
	Kum	Presence-absence	1602	23,774	154	10
		Point-intercept	649	7727	88	14
		Visual estimate	334	3394	58	17
	Sav	Presence-absence	2065	75,429	275	13
		Point-intercept	1221	39,396	198	16
		Visual estimate	784	22,483	150	19

Table 3
Annual sustainable reindeer grazing days per hectare for each of the study sites in northeastern Sweden, calculated based on the estimated biomass, an annual lichen growth rate of 4 mm, and an average daily consumption of 2.25 kg of lichen per reindeer. The table includes the estimated biomass with standard error (SE), annual lichen growth, and reindeer grazing days, with uncertainties derived from the differences between years using the lower and upper bounds of the 95% confidence intervals for the estimates.

Site	Biomass estimate (±SE) (kg/ha)	Biomass estimate previous year (±SE) (kg/ha)	Annual lichen biomass increase (kg)	Reindeer grazing days
Had	1232 ± 203	1080 ± 183	152 ± 38	67 ± 17
Kum	649 ± 88	527 ± 74	121 ± 28	54 ± 12
Sav	1221 ± 198	1077 ± 178	144 ± 41	64 ± 18

supported 54 annual grazing days per hectare, a difference notably smaller than the difference in biomass.

4. Discussion

Effective and reliable methods for quantifying lichen are crucial for the sustainable management of winter forage resources for reindeer. We have demonstrated that our method, which integrates drone-derived site information into the sampling design and incorporates field measurements of ground lichen cover and height, offers a robust and objective approach for estimating ground lichen cover and biomass at the local scale. Furthermore, we identified significant differences in lichen cover between different field methods, leading to difference in biomass estimations. In addition to the lichen assessment method, the slope used to relate lichen volume to biomass is also crucial for the accuracy of these estimates. From our literature review, we derived and applied a slope of 0.0148. The lichen biomass estimates calculated using this slope and the point-intercept method had RSE of approximately 15%. The estimation of the number of reindeer grazing days at our respective field sites, were relatively consistent across sites due to similar lichen cover.

4.1. Sampling - selection of sample plots

The use of spatially balanced sampling can improve the selection of sample plots if units that are close in the auxiliary space have similar values on the variable of interest (Grafström et al., 2012). This means that a smaller sample size could suffice to achieve the desired level of precision, possibly also reducing the overall cost of the sampling process (Kermorvant et al., 2019). We found that both NDVI and canopy height demonstrated negative correlations with lichen cover at our study sites, thus proving to be pertinent auxiliary data for the sampling. Depending on the study area and whether relevant information is already available or easy to collect, additional auxiliary data with explanatory value for lichen presence, beyond NDVI and canopy height, could be integrated. However, incorporating additional auxiliary variables might make the sample less well spread in the other variables.

A primary focus in developing our method was to enhance objectivity and transparency, thereby ensuring that the outcomes will be accepted and trusted among diverse land users. Besides its potential to reduce variance in estimates, spatially balanced sampling also ensures representative samples and provides an objective approach for distributing sample plots, in contrast to subjective placements, which can be more susceptible to questioning.

4.2. Methods for lichen assessment

Our findings highlight the impact that the choice of method for cover assessment can have on the lichen cover and biomass estimates. Compared to the point-intercept method, we found that visual estimates resulted in lower lichen cover values, whereas the use of the presence-absence method led to higher values of lichen cover (Fig. 7). Out of our 120 sample plots, 18 were recorded as having 100% cover using the presence-absence method, while the coverage according to the other methods was lower. The point-intercept method may also generally overestimate cover, but to a lesser extent than the presence-absence method. Dividing the sample plot into smaller squares or employing more points could enhance the accuracy of both these methods, yet this would extend the time needed for data collection. Point-intercept methods are known to be impractical when the cover is low, as a very large number of points are needed to achieve accurate results (Drezner and Drezner, 2021). However, our method is primarily intended for areas with reindeer winter grazing, which typically have abundant lichen. Additionally, single sample plots with very low cover will have a marginal impact on the overall estimates. To improve consistency between observers, precision in the measurements and time consumption, it is advisable to explore alternative methods. A recent study demonstrated the successful application of image segmentation using a U-Net in measuring cover of reindeer lichens (Lovitt et al., 2022). The use of a Convolutional Neural Network has also been explored for differentiating various *Cladonia* species (Galanty et al., 2021). The automated method used by Lovitt et al. (2022) predicted less lichen cover compared to visual estimates, which was also indicated by our manual segmentation example (Fig. 3).

While the point-intercept method offers greater objectivity and generally reduces variation between users compared to visual estimates (Morrison, 2015), it is notably more time-consuming (Appendix B). However, as both cover and height measurements can be taken simultaneously when the rod is lowered to the ground, time is saved compared to other methods. In cases like ours, where the goal was to collect data for all lichen species combined and only one measurement per point is required, the time difference between the visual estimate and the point-intercept method was no more than about two minutes per sample plot, which is relatively small compared to the total time required for fieldwork.

In contrast to the methodology employed for cover assessment, height measurements often receive less attention. In our literature review, we found that the studies using height measurements taken at twenty-five systematically distributed points throughout the plot (Moen et al., 2007; Rosso et al., 2014) had the steepest slopes (Fig. 7), demonstrating sharper changes in biomass for increases in volume compared to other studies that measured height at a few subjectively selected points considered representative (Appendix A). While no definitive conclusions can be drawn from this, it suggests that the methods used for height measurement may yield differing results, deserving further study.

4.3. Literature review – lichen biomass from volume

For our method to be practically useful, a predefined relationship between volume and biomass is essential, offering a more efficient alternative to the highly time-consuming process of collecting and weighing lichen. By fitting a linear regression to all data from our review studies, we obtained a slope of 0.0148. Visual estimates of cover were used in these five studies. Based on our method comparison, it is reasonable to assume that using cover measurements from the point-intercept method, combined with a relationship based on visual estimates, may result in a somewhat inflated biomass estimation, as the point-intercept method yielded higher lichen cover values than visual estimates. However, the results from Moen et al. (2007) and Rosso et al. (2014) suggested smaller differences between these methods compared to our study. The conditions at our study sites were also similar to those in Moen et al. (2007), where visual estimates of cover yielded a slope of 0.0155 in our comparison. Additionally, the linear relationship from Finland reported by Kumpula et al. (2006)—which we did not use due to the unavailability of volume data—was closely aligned with that of Moen et al. (2007). This supports our decision to use the slope of 0.0148 that we derived from the combined dataset. This dataset also offered data points across a wider range of volumes making the resulting relationship more applicable and robust, also beyond our study sites. Still, in environments with significantly different conditions or species compositions, or when using methods like image segmentation that can yield substantially lower estimates of lichen cover, it may be necessary to establish a new volume-to-biomass relationship.

Our comparison helped clarify the extent to which the relationships between lichen volume and biomass differed across studies, but pinpointing specific causes was not possible with the available information. Methodological differences and variations between observers in the assessment of lichen cover and height likely contributed, as well as inconsistencies in the cleaning and removal of dead parts from the collected lichen (Appendix A). Differences in species composition and environments are other factors that likely played a role. Among species, *Cladonia stellaris* and *Cetraria islandica* is noted to have a higher density (weight per volume) compared to *Cladonia rangiferina* and *Cladonia arbuscula* with density differences ranging from 1.2 to 2 times higher (Andrejev, 1971; Fleischman, 1990; Moen et al., 2007; Akujärvi et al., 2014). *Stereocaulon paschale* has been identified as having the highest density among the species present in our study (Andrejev, 1971; Fleischman, 1990; Akujärvi et al., 2014) but was only present in small amounts at one of our sites and absent in the studies reviewed. Additionally, the moisture level of lichen during measurement should be considered. Both Kumpula et al. (2006) and Olofsson et al. (2011) observed that dry lichen of *Cladonia* species is shorter than wet and moist lichen. Kumpula et al. (2006) found that dry lichen was 16.8% shorter than wet lichen. Environmental factors might also affect the growth forms of the lichen and thereby the density. However, Errington et al. (2022) found that equations relating volume to biomass for the *Cladonia* subgenus *Cladina* varied only slightly across topographical or climatic gradients. Similarly, differences among landcover types in Rosso et al. (2014) and among ecoprovinces in Greuel et al. (2021) were small, indicating that volume-to-biomass relationships are relatively unaffected by environmental preconditions.

4.4. Lichen cover and biomass estimations

Our study highlights the importance of considering both cover and height for biomass estimations. We calculated lichen biomass for each sample plot from volume, determined by multiplying cover by height. The fact that both lichen cover and height were lower at the Kum site compared to the other sites explains why the relative difference between sites in estimated biomass was larger than the relative difference in estimated cover, underscoring the importance of using volume rather than cover alone. Given that the RSE for our estimates from data obtained via the point-intercept method was approximately 15%, our selection of 40 samples was in this case a good balance between fieldwork effort and the precision of the estimate. The low RSE resulting from our method also makes it suitable for monitoring over time, enabling early detection of changes in the environment. Our design-based estimations rely solely on the data collected from the sample plots. This makes it straightforward and interpretable compared to the often-used model-based estimations, which sometimes rely on complex models.

4.5. Reindeer grazing days

Our approach to estimate reindeer grazing days offers valuable insights for planning and assessing the impact on reindeer herding in real-world scenarios. Our results of 54 to 67 reindeer grazing days per hectare across the study sites align with the models of Tahvonen et al. (2014), where one hectare, with biomass levels similar to those of our study sites, supported about 60–70 grazing days per year. The relatively small difference in estimated reindeer grazing days for the Kum site compared to the other sites—despite the larger difference in biomass estimates—illustrates that cover rather than biomass determines grazing days in our calculations. Even if the cover, and therefore the theoretical annual grazing days, is similar across areas, less cratering and lower energy consumption are required to access the same amount of lichen in areas with taller lichen and higher biomass. This makes such areas less vulnerable to overgrazing.

4.6. Method application and limitations

Land use by industrial forestry along with the increased demand for natural resources in northern Sweden poses a significant threat to traditional reindeer husbandry based on natural pastures (Harnesk, 2022; Horstkotte et al., 2022). The decline, loss of access to, and destruction of lichen-rich areas increases the need for winter feeding of reindeer (Rautiainen, 2024). When assessing the impact on reindeer husbandry from the often piecemeal development of competing land uses, local-scale information on lichen resources is essential. However, it is important to integrate such information with reindeer herders' traditional knowledge of reindeer landscape use. A narrow focus on isolated lichen patches could inadvertently enable other land users to exploit areas not recognized as lichen-rich, potentially compromising the overall use of the landscape and the availability of grazing lands.

Our method offers a new and efficient way to collect detailed data on lichen biomass and cover. Although it is designed for a local scale, it is applicable to considerably larger areas than those of our study sites. When working with larger areas our method can be effectively combined with other methods utilizing satellite data. This enables the identification of lichen rich areas in the landscape where in-depth assessments of cover and biomass are most needed, optimally applying our method. Providing data on both biomass and cover not only quantifies the amount of lichen present but also indicates how it is distributed. Additionally, the high-resolution orthomosaics derived from drone images make it possible to visually identify the lichen distribution across the study area. Together, this provides a comprehensive understanding of the amount and distribution of lichen to be used in planning and management by both herders and other land users.

The appropriate number of sample plots needed for accurate biomass estimation largely depends on the variability of the study area. Areas with less variability require fewer sample plots, and vice versa. The total area covered by the 40 sample plots in this study ranged from 0.2% to 0.4% of each site. For larger sites, it is advisable to increase the number of sample plots and exclude large, continuous biotopes or vegetation types where lichens are absent. While it took us 20 min to complete each sample plot, in practical applications aimed at estimating the total food resource for reindeer, only one method is used to assess the cover and height for all lichen species combined. This reduces the time required to complete a sample plot by at least half. However, the time needed to locate and navigate between plots may increase with the size of the site and depends on the terrain.

Comprehensive documentation, including access to photos and all data from each sample plot enables anyone to verify the reasonableness of the data used for cover and height in the estimates. All our calculations and estimates were performed using the open-source software R, and the code that we used is freely available. To make the method even more accessible, a vegetation index based on RGB images can be used as auxiliary data in the sampling process instead of NDVI, avoiding the need for a multispectral camera. Additionally, drone image processing can be done using open-source software such as OpenDroneMap (OpenDroneMap Authors, 2020). Methods that directly map lichens from remote sensing images typically focus on pale lichens with distinct spectral signatures. Our method does not require lichens to be identifiable in the images, making it effective for more lichen species important as food for reindeer, such as *Cetraria islandica*. Additionally, when using our method, other resources correlated with the auxiliary variables can be concurrently quantified, further enhancing its overall usability.

5. Conclusions

Using both original and literature data we present a robust and objective method for estimating ground lichen cover and biomass. Our approach introduces a new way to use drones for lichen assessment by integrating drone-derived NDVI and tree height data into the sampling design.

Our study highlights that different lichen cover assessment methods can produce highly divergent results. We recommend the point-intercept method for assessing lichen cover and height due to its objectivity and consistency across observers, despite that it requires more time to finalize and a tendency to yield higher cover values compared to visual estimates. At the same time, we encourage the development and accessibility of alternative approaches. Image segmentation shows promise for delivering accurate and consistent cover estimates efficiently, making it an attractive alternative for collecting lichen cover data necessary in our method, as well as for providing training data for lichen mapping models that incorporate remote sensing images, and for future volume-to-biomass relationships.

The slope of 0.0148, we derived from data in the reviewed literature and used to relate lichen volume to biomass, is applicable beyond the scope of our study. However, further research is needed to clarify the observed differences between studies. Additionally, research is needed to develop objective, accurate, and efficient methods for measuring lichen height, as our findings reinforce previous research demonstrating the importance of considering both lichen cover and height in biomass estimation.

CRediT authorship contribution statement

Erik Cronvall: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sven Adler:** Writing – review & editing, Methodology, Conceptualization. **Per Sandström:** Writing – review & editing, Funding acquisition, Conceptualization. **Anna Skarin:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data and R scripts are available at https://doi.org/10.5281/zenodo.11440778.

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