Global warming causes the replacement of lichens by shrubs in alpine and Arctic ecosystems. Since shrubs have lower albedo than lichens, this shrub encroachment can lead to a positive climatic feedback, resulting in higher temperatures in the surroundings. Therefore, gaining knowledge on the surface albedo of shrubs and lichens is important. Environmental factors also influence the surface albedo, but have often been neglected, potentially leading to biased results. In an experimental setup, we analyzed albedos of the lichen species Cladonia stellaris, Flavocetraria nivalis and Cetraria islandica, and how albedo changes with a stepwise replacement by the dwarf shrub Empetrum nigrum. Albedo was measured with radiometers in a paired set up. By setting certain environmental variables and species composition (monocultures) to be constant, we quantified the impact of environmental factors such as cloud cover, aspect and zenith angle on the surface albedo of two lichen species. Surface albedo (mean values ± SD) differed between C. islandica (0.155 ± 0.015), C. stellaris (0.364 ± 0.019), F. nivalis (0.350 ± 0.022) and E. nigrum (0.154 ± 0.016), and an increase in shrub cover at the expense of lichen cover led to a corresponding decrease in albedo. A 0.6 reduction in clearness index (more clouds) produced a 0.054 albedo decline. On the north-facing aspect, albedo was 0.023 lower than on the south-facing aspect. Albedo increased by 0.032 with an increase in zenith angle of 15°. Albedo variations caused by these studied environmental factors significantly affect the radiation budget of alpine and Arctic vegetation. We therefore stress the importance of considering environmental factors when surface albedos are estimated. Likewise, our species-specific measurements can be a basis for further studies of the impact of climate change on alpine and Arctic vegetation and species-related feedback mechanisms.

Keywords: alpine and Arctic ecosystems, climate change, radiation budget, radiometer, surface albedo, vegetation

Introduction

Global warming causes an expansion of shrubs in alpine and Arctic areas (Sturm et al. 2001, Myers-Smith et al. 2011). This shrub encroachment entails the decrease of...
other, less competitive species, with lichens being particularly vulnerable (Cornelissen et al. 2001, Elmendorf et al. 2012). However, lichens are not only impacted by a changing climate, they also potentially affect the climate themselves (Porada et al. 2016). One reason for this is the high albedo, the reflected solar energy, of many lichen species relative to other vegetation (Aartsma et al. 2020).

A reduction of lichen cover due to shrub expansion implies a lowering of the albedo, making more solar radiation available for absorption at the surface. This shift in vegetation may therefore produce a positive climatic feedback, leading to further warming (Chapin et al. 2005). Climatic feedbacks involved in shrub expansion in alpine and Arctic ecosystems are seen as research priority (Myers-Smith et al. 2011), and different attempts have been made to estimate surface albedo (Blok et al. 2011, Williamson et al. 2016).

Albedo is not only influenced by the vegetation composition, but also by environmental factors that affect the amount of incoming radiation received at the surface. For instance, both an enhanced cloud cover and a reduced zenith angle are expected to decrease the albedo (Goodin and Isard 1989, Lafleur et al. 1997, Juszak et al. 2016). In addition, variations in topography can affect albedo measurements (Hao et al. 2018, Aartsma et al. 2020). Hence, to assess the impact of lichen decline on the radiation budget, it is important to consider the effect of these environmental factors. However, previous studies of albedos of different vegetation types do compare the albedos while either neglecting the impact of environmental variables, or not considering those as strongly as they should be considered, potentially leading to biased results.

Research on the impact of these environmental factors on the surface albedo of lichens requires local measurements with radiometers. Such research complements recent surface albedo studies based on remote sensing methods (Stoy et al. 2012, Cohen et al. 2013) that do not allow for a detailed analysis of the different environmental factors. Another important advantage of local measurements is that they can be applied to specific species. Indeed, species-specific studies of surface albedo of shrubs and lichens are considered fundamental (Stoy et al. 2012, Williamson et al. 2016).

In this study, we aimed at answering the following questions through an experimental study set up: 1) what is the albedo of different lichen species, and of varying coverages of lichens and shrubs? 2) How do variations in environmental factors, such as cloud cover, aspect and zenith angle impact lichen albedo?

Material and methods

Experimentally, we measured the surface albedo of three lichen species: Cladonia stellaris, Flavocetraria nivalis (both light lichens) and Cetraria islandica (a dark lichen), and of the evergreen shrub Empetrum nigrum. All species are common in alpine and Arctic ecosystems (Ahti and Oksanen 1990, Tybirk et al. 2000). We collected the specimens in mountain areas in southern Norway prior to the experimental measurements, which were conducted in the nearby lowlands (59°24′47″N, 9°04′10″E), from April to June 2019. We arranged the specimens of each species on a flat, circular, wooden board with an area of 2.4 m², creating a species cover of 100% (Fig. 1). This lichen set up did not change for the different measurements, i.e. the measurements were always conducted on the same specimens. We placed a radiometer 20 cm above the surface, with the sensor over the center of the board, leading to a measurement area of 1.8 m², with a buffer area around. The CNR4 net radiometers measured the incoming and reflected shortwave radiation (between 300 and 2800 nm) in W m⁻². Two radiometers were available for the study. Therefore, we conducted measurements pairwise; our control, a 100% cover of F. nivalis was paired with one of the other species or species combinations (Table 1). The different percentages of C. stellaris and E. nigrum were set to mimic the impact of shrub encroachment on the surface albedo.

We placed the paired surfaces side by side with 5 m distance between them, at the same location every day. Measurements were done every five seconds, and logged as average per minute. We set one measurement interval in the experiment to 30 min, and divided each measurement day into three parts (morning, solar noon and afternoon) with one measurement interval each. We only conducted measurements at zenith angles < 60°, since the accuracy of the radiometers decreases with larger solar zenith angles (Kipp and Zonen 2014). Measurements on horizontal surfaces were conducted for all species.

To study how each of the three environmental factors (cloud cover, aspect and zenith angle) influences the albedo, we kept all but the factor of interest constant (Table 1). We only studied those factors for the species F. nivalis and C. stellaris. To study the effect of aspect on albedo, we tilted the boards consecutively towards the north and the south with a slope angle of 8°. Measurements at solar noon were conducted to study the impact of the zenith angle on the albedo, leading to a decreasing zenith angle over the time of the field season, since the course of the sun changes from day to day. The starting points of the morning and afternoon measurements on the other hand were moved to assure fixed zenith angles, to quantify the impact of aspect and cloud cover. The start of the measurements was estimated based on data from Sunearthtools (2019) to match the respective zenith angles. As a proxy for cloud cover, we calculated the clearness index for each of the measurement intervals (Liu and Jordan 1960, Duffie and Beckman 2013). The clearness index is a value between 0 and 1 with low values indicating cloudy conditions and high values indicating clear sky. See the Supporting information for calculations. When studying the impact of clouds on albedo, only measurements of flat surfaces during morning and afternoon were included.

Measured albedo of the different study species, and for the stepwise replacement of C. stellaris by E. nigrum (increase of E. nigrum cover and decrease of C. stellaris cover at 25% step levels) was visualized in box plots. To test for the effect of environmental factors on the albedo measurements, generalized mixed-effects models were used, applying beta distribution with a logit function, and measuring date as random.
factor on the intercept to account for several measurements per day. We set up separate models for each environmental factor of interest (Table 2). To validate the models, we plotted the model residuals against fitted values and each explanatory variable (Zuur et al. 2009). All analyses were conducted in R ver. 4.0.2 (<www.r-project.org>), with the package glmmTMB (Brooks et al. 2017).

**Results**

The surface albedo differed between species, and each of the environmental factors significantly impacted the albedo. The mean (± SD) albedo was highest for *C. stellaris* (0.364 ± 0.019) and *F. nivalis* (0.350 ± 0.022), and lowest for *C. islandica* (0.155 ± 0.015) and *E. nigrum* (0.154 ± 0.016).

Table 1. Experimental albedo measurement combinations of all species with corresponding abbreviations and coverage. The number of measurement intervals per combination is presented per aspect and daytime setup with zenith angles shown in brackets (HM = horizontal surface, measured in the morning (zenith angle: 58°); NM = north-facing surface, measured in the morning (zenith angle: 55°); SM = south-facing surface, measured in the morning (zenith angle: 53°); HN = horizontal surface, measured at noon (variable zenith angle); HA = horizontal surface, measured in the afternoon (zenith angle: 58°); NA = north-facing surface, measured in the afternoon (zenith angle: 53°); SA = south-facing surface measured in the afternoon (zenith angle: 55°)). The superscript letters correspond to the descriptive and statistical analyses the measurements were applied to (*a* species differences, *b* cloud cover, *c* aspect, *d* zenith angle).

| Measurement combinations | Number of measurements/aspect and daytime (and zenith angle in °) |
|--------------------------|---------------------------------------------------------------|
| Abbreviation             | Species            | Cover (%) | HM (58) | NM (55) | SM (53) | HN (var) | NA (53) | SA (55) | HA (58) | Σ         |
| CS/FN                    | *C. stellaris*    | 100       | 14<sup>a</sup> | 15<sup>c</sup> | 15<sup>c</sup> | 15<sup>d</sup> | 15<sup>c</sup> | 14<sup>c</sup> | 14<sup>a</sup> | 102 |
|                          | *F. nivalis*      | 100       | 16<sup>a</sup> | 16<sup>c</sup> | 16<sup>c</sup> | 16<sup>d</sup> | 16<sup>c</sup> | 15<sup>c</sup> | 15<sup>a</sup> | 110 |
| CI/FN                    | *C. islandica*    | 100       | 4<sup>a</sup>  | –        | –        | –        | –        | –        | 4<sup>a</sup>  | 8  |
|                          | *F. nivalis*      | 100       | 4<sup>a</sup>  | –        | –        | 4<sup>d</sup> | –        | –        | 4<sup>a</sup>  | 12 |
| EN25&CS75/FN             | *E. nigrum*       | 25        | 3<sup>a</sup>  | –        | –        | –        | –        | –        | 3<sup>a</sup>  | 6  |
|                          | *C. stellaris*    | 75        |            |        |        |          |          |          |            |     |
|                          | *F. nivalis*      | 100       | 3<sup>a</sup>  | –        | –        | 3<sup>d</sup> | –        | –        | 3<sup>a</sup>  | 9  |
| EN50&CS50/FN             | *E. nigrum*       | 50        | 3<sup>a</sup>  | –        | –        | –        | –        | –        | 2<sup>a</sup>  | 5  |
|                          | *C. stellaris*    | 50        |            |        |        |          |          |          |            |     |
|                          | *F. nivalis*      | 100       | 3<sup>a</sup>  | –        | –        | 3<sup>d</sup> | –        | –        | 2<sup>a</sup>  | 8  |
| EN75&CS25/FN             | *E. nigrum*       | 75        | 3<sup>a</sup>  | –        | –        | –        | –        | –        | 3<sup>a</sup>  | 6  |
|                          | *C. stellaris*    | 25        |            |        |        |          |          |          |            |     |
|                          | *F. nivalis*      | 100       | 3<sup>a</sup>  | –        | –        | 3<sup>d</sup> | –        | –        | 3<sup>a</sup>  | 9  |
| EN/FN                    | *E. nigrum*       | 100       | 2<sup>a</sup>  | –        | –        | –        | –        | –        | 2<sup>a</sup>  | 4  |
|                          | *F. nivalis*      | 100       | 2<sup>a</sup>  | –        | –        | 2<sup>d</sup> | –        | –        | 2<sup>a</sup>  | 6  |
| **Σ**                    |                  |           | 60        | 31       | 31       | 46       | 31       | 29       | 57       | 285 |
Discussion

With the experimental albedo measurements of lichen species compared to the shrub species *E. nigrum*, we provide species-specific albedo measurements that give important insights into the impact of shrub encroachment on albedo in alpine and Arctic areas. In these areas, lichen heaths are important vegetation types, and at the same time these vegetation types are considered to be one of the most vulnerable (Bjerke 2011). Experimental warming studies indicate that the decrease of lichen heaths will continue with an ongoing increase of temperature (Walker et al. 2006, Elmendorf et al. 2012). According to our study, a potential shift from lichen-dominated to shrub-dominated vegetation can lead to a clear decrease in albedo. This decrease is considerably more than the change in albedo induced by a shift in generalized landscape units (e.g. tundra to forest) often used to project future climate warming scenarios (Chapin et al. 2005). However, in most cases this alteration in vegetation may not be happening abruptly, but rather gradually, as a stepwise replacement of lichens by shrubs. Our measurements were set up to simulate this stepwise replacement, showing that the decrease in albedo is strongly related to the increase of shrubs. These results can provide clues for more detailed radiation budget analyses of shifting vegetation types. For example, considering an average incoming shortwave radiation of 188 W m\(^{-2}\) during July in Norway (Hagos et al. 2014), our albedo measurements suggest that the net shortwave radiation can increase locally with a maximum of 39.4 W m\(^{-2}\) (33%) when a hypothetical lichen heath with 100% *C. stellaris* will turn into shrub vegetation of 100% *E. nigrum*. A more moderate change, a conversion from a lichen-dominated heath (e.g. 75% lichen with 25% shrubs) to a shrub-dominated vegetation (e.g. 75% shrubs with 25% lichen) will lead to an increase in net shortwave radiation of 21.2 W m\(^{-2}\) (16%) during days in July (for calculation see Supporting information). In land surface models, lichens are often aggregated together with other cryptogams such as bryophytes, despite their distinct physical differences (Beringer et al. 2001, Stoy et al. 2012, Wullschleger et al. 2014, Porada et al. 2016, Drue1 et al. 2017). In an earlier field study (Aartsma et al. 2020), we found a difference in albedo between lichen heaths dominated by *Cladonia* spp. versus lichen heaths dominated by *Favocetaria nivalis* and *Alectoria ochroleuca*, showing the importance and necessity of considering individual lichen species when measuring the albedo of lichen heaths in the field. Our experimental measurements, revealing large difference in albedo between dark- and light-coloured lichen species reinforces those earlier findings.

In our study we show that there is a difference in albedo even between different lichen species. We measured considerably lower albedos for *C. islandica* than for *C. stellaris* and *F. nivalis*, indicating the importance of considering particular species for albedo estimations. However, species specific albedo measurements are rare. One example is Petzold and Rencz (1975), who measured a lower albedo for *C. stellaris* (0.22) than we did (0.37). An explanation for the differences could be that Petzold and Rencz (1975) measured under natural conditions while we measured with strictly controlled environmental factors.

Our study strongly highlights the importance of environmental factors, such as cloud cover, surface aspect and zenith angle for the albedo measurements of lichen surfaces. Previous studies indicate the importance of environmental conditions for the albedo of alpine and Arctic vegetation surfaces (Goodin and Isard 1989, Lafleur et al. 1997, Yang et al. 2008, Juszak et al. 2016), but none has quantified their impact by keeping other factors and species composition constant, as we did with our measurements in lichen monocultures. Environmental factors can influence the albedo in different ways. For instance, we show that enhanced cloud cover decreases the albedo. This is caused by a larger fraction of diffuse radiation during cloudy conditions, which penetrates deeper into the vegetation compared to direct radiation (Lafleur et al. 1997, Juszak et al. 2016). Likewise, our measurements demonstrate that the

| Factor of interest | n     | Fixed factors          | Estimate (SE) | z-value | p-value |
|-------------------|-------|------------------------|---------------|---------|---------|
| Clearness index   | 88    | Clearness index        | 0.400 (0.040) | 9.97    | < 0.001 |
|                   |       | Species                | 0.065 (0.014) | 4.54    | < 0.001 |
| Aspect            | 122   | Clearness index        | 0.272 (0.023) | 11.66   | < 0.001 |
|                   |       | Species                | 0.038 (0.008) | 4.78    | < 0.001 |
|                   |       | Aspect (South)         | 0.110 (0.008) | 13.70   | < 0.001 |
| Zenith angle      | 46    | Zenith angle           | 0.010 (0.001) | 8.85    | < 0.001 |
|                   |       | Clearness index        | 0.121 (0.030) | 4.02    | < 0.001 |
|                   |       | Species                | 0.039 (0.010) | 3.76    | < 0.001 |
albedo is lower when zenith angles are relatively small, since the radiation can penetrate more easily into the canopy when the solar radiation comes from more straight above (Goodin and Isard 1989, Juszak et al. 2016). Our results also reveal that variations in topography affect albedo measurements. A reason can be the strong difference in received solar radiation between south- and north-facing slopes (Hao et al. 2018, Aartsma et al. 2020).

Although our study shows that there are clear species specific differences in albedo, differences in albedo between vegetation types in alpine and Arctic areas can be small, often less than 0.02 (Beringer et al. 2005, Juszak et al. 2016, Williamson et al. 2016). However, these small differences can contribute to a relevant change in the large-scale climate (Chapin et al. 2005). According to our study, variations in albedo resulting from differences in environmental factors can be of similar magnitude as variations between vegetation types. Therefore, we stress the importance of including environmental conditions in in-situ albedo measurements for future climate change predictions in alpine and Arctic areas.

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Author contributions

Stefanie Reinhardt and Peter Aartsma share first authorship. Stefanie Reinhardt: Conceptualization (equal); Formal analysis (supporting); Funding acquisition (supporting); Methodology (equal); Project administration (supporting); Supervision (supporting); Validation (equal); Visualization (supporting); Writing – original draft (lead); Writing – review and editing (supporting). Peter Aartsma: Conceptualization (equal); Data curation (supporting); Formal analysis (lead);
Funding acquisition (supporting); Investigation (lead); Methodology (equal); Project administration (supporting); Supervision (supporting); Validation (equal); Visualization (lead); Writing – original draft (supporting); Writing – review and editing (supporting). Konstanse Skøyen: Data curation (lead); Investigation (equal); Writing – review and editing (supporting). Hans Renssen: Conceptualization (equal); Funding acquisition (lead); Methodology (equal); Project administration (lead); Supervision (lead); Validation (equal); Writing – review and editing (lead).

Data availability statement

Data are available from the Figshare Digital Repository: <https://doi.org/10.23642/usn.16960852.v1> (Aartsma et al. 2021).

Supporting information

The supporting information associated with this article is available from the online version.

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