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TITLE

Brief communication: Influence of snow cover on albedo reduction by snow algae

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ABSTRACT

Snow algae contribute to snowmelt by darkening the surface, reducing its albedo. However, the potential consequences of algae under the surface (such as after a fresh snowfall) on albedo reduction is not known. In this study, we examined the impact of sub-surface snow algae on surface energy absorption. The results indicate energy absorption across all analysed wavelength ranges when snow algae are snow-covered, an effect that was correlated with both cell densities and chlorophyll-a concentrations. These findings suggest that snow algae lower albedo and thus increase snow melt even when snow-covered.

INTRODUCTION

Snow is the most reflective of natural surfaces on Earth, reflecting >90 % of visible radiation when freshly fallen (Skiles et al., 2018). The primary determinant of snow's albedo is its physical composition, primarily due to scattering at the interface between ice and air (Cook et al., 2017). However, the introduction of impurities reduces snow reflectance and enhances its absorption of solar energy. These impurities or contaminants can be abiotic (e.g., dust) and biotic (e.g., algae). The effects of biological albedo reduction (BAR)—the collective influence of biological communities on albedo—are receiving increasing attention. Indeed, snow algae can reduce the albedo of the snow by around 20 % (Lutz et al., 2014; Ganey et al., 2017; Khan et al., 2021), likely making blooms of snow algae the largest global contributor to BAR (Hotaling et al., 2021).

Snow algae blooms are common during summer in alpine and polar ecosystems when there is sufficient interstitial water to provide necessary habitat. Algae involved in this phenomenon are represented by genera *Chlamydomonas*, *Chloromonas,* and *Sanguina* (Hotaling et al., 2021) and color the snow red due to production of the carotenoid astaxanthin (Remias et al., 2005). The production of this pigment protects

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the cell against high UV radiation and allows it to gain heat through the absorption of visible light, melting the surrounding ice crystals to access nutrients and grow (Dial et al., 2018). Consequently, snow algae increase rates of melting when they increase in abundance (Hoham and Remias, 2020).

Snow algae predominantly bloom on the surface of melting snow, although can manifest below the surface (Skiles et al., 2018). The vertical distribution of snow algae within snowpack likely is an important factor in determining their impact on albedo. However, research that links snow algae to changes in albedo typically focuses on visible surface blooms (e.g., Ganey et al., 2017; Healy and Khan, 2023). Thus, the effects on BAR when snow algae are found beneath the surface have not been quantified.

In this study, we investigated the effects of subsurface snow algae on albedo. We measured the spectral albedo at different cell densities present in the same snow patch. To examine the impact of a snow cover on snow algae, we applied successive layers of clean snow from a nearby area and measured spectral albedo for increasing depths of overlying clean snow. Following this, we collected the biomass for analysis, measuring cell densities and chlorophyll-a concentrations. With these data we seek to advance our understanding of the effects of snow algae in alpine environments, where glaciers and snowfields are critical components of the water supply and are particularly susceptible to climate change.

METHODS

Study Site

Glacier National Park (GNP), referred as *Ya·qawiswit̓xuki* ("the place where there is a lot of ice") by the Kootenai tribe, is located in northwest Montana, United States. The park preserves one of the most ecologically intact temperate regions of the world. During the Little Ice Age, an estimated 146 glaciers were within the current boundaries of GNP. By 2005, only 51 of these glaciers persisted (Martin-Mikle and Fagre, 2019).

The experiment was conducted on a seasonal snowfield located at the northeast base of Clements Mountain (48°41'33" N 113°44'10" W) at Logan Pass. The snowfield, approximately 0.6 km^2, had a slope of 20-22° and a snow depth ranging from 50-125 cm. Snow algae could be clearly seen in the distance (~100 m). To control for variation in the presence of snow algae and other factors, we replicated our experiment across six plots, spaced at least 2 m apart from one another.

Measurements of spectral reflectance

On 1 August 2023, spectral reflectance of the six study plots was measured using an ASD FieldSpec 4 spectroradiometer (Malvern Panalytical, UK) and a pistol grip device that allows a directional measurement with a field of vision of α = 25° (**Figure 1A**). Since snow and ice albedo is sensitive to the direction of incoming solar irradiance, all measurements were taken consecutively on the same day (between 1:00 PM and 3:00 PM) under the same conditions: clear-sky, facing the sun, and with a constant measurement angle of 60° and a distance between the optical fiber and a target of 5 cm.

To assess the influence of snow cover on the albedo impacts of snow algae, a PVC cylinder (7.6-cm radius) was placed on the surface of the algae bloom and an initial measurement of surface reflectance (i.e., albedo of the snow algae) was made. Next, subsurface snow free of apparent abiotic or biotic contaminants affecting albedo was collected near each plot using a plastic scoop. This snow was then sequentially arranged in layers of 0.5 cm each, eventually reaching a total depth of 2.0 cm (**Figure 1B**). This depth was used as it has been identified as the point below which the physical characteristics of the snowpack pose challenges for the snow algae to grow (Cook et al., 2017).

Reflectance measurements were repeated in triplicate after adding each successive 0.5-cm layer. The average of the reflectance of uncovered snow algae was used as a reference in each plot to assess the increase in albedo resulting from the addition of snow layers. We also measured the spectral reflectance of snow in an area devoid of evident biotic or abiotic impurities after removing the top centimeter of snow to obtain a reference for the maximum attainable sunlight reflection within the surveyed snow field at that time. We assumed that the physical characteristics of the snow were consistent across the sampled plots during the sampling period. Because carotenoids (absorbing in the 400-580 nm range) and chlorophylls (absorbing in the 600-700 nm range) distinctly influence the spectral reflectance of algae-containing snow (Painter et al., 2001), these specific wavelength ranges were chosen as optimal for investigating how algae affect albedo reduction across varying snow depths.

Sample collection, pigment analysis, and cell counts

Following spectral reflectance measurements for each plot, the snow within the PVC cylinder (**Figure 1B**) and a 2 cm deep core corresponding to the same surface where albedo measurements were conducted (**Figure 1C**) were both collected. The snow was placed in a sterile plastic bag and immediately transferred to the laboratory for further analysis.

Of the total volume of the sample (~70 mL), a 100-µL aliquot was used to count cells, and the rest of the volume was filtered onto ashed 0.7-µm pore size Whatman^{TM} GF/C filters. Filters for chlorophyll analysis were extracted overnight in 90 % acetone for fluorometric analysis using the acid-correction method (EPA Method 445.0) on a Turner 10-AU Fluorometer (with Optical Kit #10-037R). Cell counts were conducted using a counting chamber (Hausser Scientific) and a light microscope (Leitz LaborLux S, with 10x objective).

The final concentrations of chlorophyll-a and cell density for each plot were calculated considering the final sample volumes and a constant volume of snow added on top of each plot (assuming snow density 0.2 g cm^{-3}).

Statistical analysis

We used Pearson correlations to assess relationships between biological and physical parameters of the snow. Statistically significant effects of increasing snow layer depth were determined with an ANOVA test. To better understand the relationships between algae biomass and albedo increase, linear regression analysis was performed.

RESULTS AND DISCUSSION

Snow algae biomass: cell densities and chlorophyll concentrations

The amount of snow algae present is a crucial determinant of their contribution to BAR (Hotaling et al., 2021). Plots with different color intensities were sampled and two approaches were used to estimate its biomass to account for the variability of algal abundance present within the studied snow patch (Cook et al. 2017). Cell densities ranged from 35,000 to 210,500 cells mL^{-1} (**Table S1**). These biomass levels are comparable to the findings reported in the North Cascades by Healy and Khan (2023), but higher than the reported by Lutz et al., (2016) in the Arctic, suggesting large variability in cell densities in snow algae blooms. When we analysed the concentrations of chlorophyll-a, plot 6 had the highest levels (24.3×10^{-6} mg mL^{-1}), nearly an order of magnitude greater than those found in plot 4 (2.7×10^{-6} mg mL^{-1}). The rest of the samples ranged in between 3.2 and 10.4×10^{-6} mg mL^{-1} (**Table S1**). Cell density and chlorophyll-a concentration were strongly correlated (R=0.93; p=0.01). This finding is relevant as chlorophyll quantity within an individual cell varies between species and can change over time as a photoacclimation mechanism (e.g., Felip and Catalan, 2000). Hence, the association between pigmentation and cell abundance indicates the suitability of both methods in assessing biomass concentration within this snow algae bloom.

Albedo reduction of snow algae on and beneath the surface

Snow algae blooms dominate primary production on snow and ice fields (e.g., Lutz et al., 2014; Hamilton and Havig, 2017; Ganey et al., 2017; Havig and Hamilton, 2019; Khan et al., 2021). As photosynthetic organisms, snow algae require light to grow and their blooms support other microorganisms in the ecosystem (Lutz et al., 2016). Snow algae absorb light energy primarily in the ranges where their specific pigments absorb light most effectively. Across the full spectrum that we measured (350-1150 nm), we observed a significant negative correlation between algal biomass and surface albedo (-0.96; p<0.001), demonstrating a sizable BAR effect. Our albedo measurements of the snow algae also showed strong light absorption within the 400–580 nm range (carotenoids) and 600–700 nm range (chlorophylls) compared to clean snow (**Figure 2**). For these absorption spectra, we observed an expected significant negative correlation between cell density and light reflectance for carotenoids (-0.91; p<0.05) and chlorophylls (-0.93; p<0.05). Similar findings were noted in relation to Chl-a concentrations (-0.86; p<0.05 and -0.90; p<0.05, respectively). These results align with prior research (e.g., Painter et al., 2001) and indicate substantial light absorption by algal cells. Collectively, these results show that the radiative influence of snow algae is greatest in the visible region, where pigments efficiently absorb light, but also occurs in the near-infrared region of the solar spectrum.

When we assessed how the spectral albedo of snow algae between 350-1150 nm (**Figure 2**) related to the depth of the snow added, we observed an increase in reflectance with depth of overlying snow for all plots (p<0.00).The same results were obtained for the absorption ranges of carotenoids (p<0.00) and chlorophylls (p<0.00). These findings show that the presence of a snow cover significantly influences the overall energy balance and radiative properties of snow algae blooms. However, the increase in albedo for snow algae upon adding snow layers showed significant variation among plots (**Figure 3A**). On average, the overall spectral albedo (350-1150 nm) increased by 59 % and 81 % with the addition of 0.5 cm and 2.0 cm of snow, respectively. Albedo for wavelengths influenced by chlorophylls showed similar values, while for carotenoid-specific wavelengths the increases in albedo were 100 % for 0.5 cm and 141 % for 2.0 cm of snow. Linear regression analysis indicated a robust positive correlation between albedo increases and snow algal biomass (**Figure 3B**). This finding clarifies the relatively weak correlation between albedo and snow layers when considering all samples, implying, not unexpectedly, that the influence of snow cover on a snow algae bloom is contingent upon the algal biomass present. The albedo for the 2.0 cm experimental snow layer on the snow algae was not as high as that seen in clean snow (**Figure 3A**), showing significant differences in the studied spectral ranges ($p<0.00$). These findings indicate that the reference of clean snow exhibits greater reflectivity, revealing that energy absorption increases across all analysed wavelengths even when snow algae are covered by snow up to 2.0 cm. The efficiency of snow algae in absorbing sunlight may be crucial for sustained energy capture, enabling snow algae to thrive under low-light conditions but also to accelerate melting rates that sustain liquid water for nutrient uptake and growth. Our data indicate that this melting occurs even when snow algae occur under the snow surface and are undetectable to the naked eye.

Our results have implications for remote sensing of snow algae and its impacts on albedo. Efforts to use remote sensing for the identification and quantification of snow algae have increased in recent years, making it an effective tool for analysing the temporal evolution of snow algae blooms at a regional scale (e.g., Khan et al., 2021; Engstrom et al., 2022). However, sub-surface snow algae may elude detection in visible range scans and might also be undetected by direct measurements and ground-based methods typically required for precise, detailed analysis, and data validation (Gray et al., 2020). Therefore, explicit efforts to sample and quantify subsurface snow algae in these assessments should be considered. In addition, the near-infrared region seems particularly suitable as a target for its detection. In cases where remote sensing proves insufficient for detection, studying snow algae impact on BAR by ground-based methods will be crucial for understanding their impact and integrating those effects into watershed melt models.

CONCLUSIONS

Current research on the remote detection of snow algae has largely been focused on using satellite images that depend on the presence of surficial blooms. Our findings indicate energy absorption across all analysed wavelengths ranges even when snow algae were covered by snow and are not visible. These findings also suggest potential metabolic activity and increased melt rates when snow algae occur under the snow surface and are undetectable to the naked eye and to remote sensing. The extent to which subsurface snow algae contribute to overall albedo reduction and snow melt has implications for alpine ecosystems, glacier health, hydrology, and water resources. Therefore, more detailed investigations are needed of the presence and abundance of sub-surface snow algae as well as their impact on BAR.

FIGURE CAPTIONS

Figure 1. (A) Spectral albedo assessment of a snow algae bloom using a spectroradiometer and a pistol grip optical fiber device. (B) A controlled environment for each assessment was established using a PVC cylinder, incorporating layers of snow ranging from 0.5 to 2.0 cm above the snow algae. (C) The plot defined by the PVC cylinder represents the sample surface for measuring spectral albedo. Snow collected from this area was later analysed for snow algae biomass. (D) Microscopic view of snow algae (Chlamydomonadaceae).

Figure 2. Variations in spectral albedo (350-1150 nm) observed between snow algae blooms and the various layers of added snow. Lines represent the mean of 3 replicates. The spectral albedo of clean snow was measured once and serves as a reference applied to all measurements.

Figure 3. (A) Percentage increase in reflectance compared to the snow algae bloom for the various snow layers added within the specified spectral albedo ranges (350-1150 nm, 600-700, and 400-580 nm). (B) Results of linear regression analysis correlating the increase in albedo with snow layer depth and cell density.

AUTHOR CONTRIBUTIONS

PA and TH designed the study. PA conducted the field experiments and the laboratory analysis. PA wrote the initial manuscript. All authors contributed to interpreting the data and writing the final manuscript.

COMPETING INTERESTS

The authors declare that they have no conflict of interest.

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Figure 1.

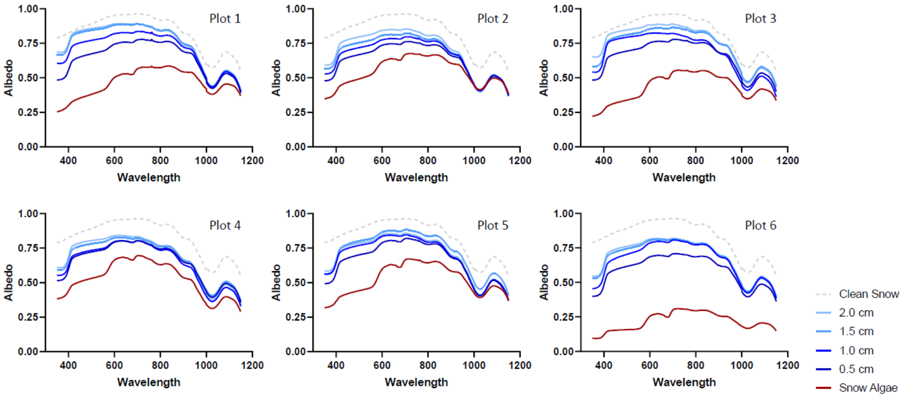
Plot 1
Plot 2
Plot 3
Plot 4
Plot 5
Plot 6
Albedo
1.00
0.75
0.50
0.25
0.00
400
600
800
1000
1200
Wavelength
Clean Snow
2.0 cm
1.5 cm
1.0 cm
0.5 cm
Snow Algae

Figure 2.

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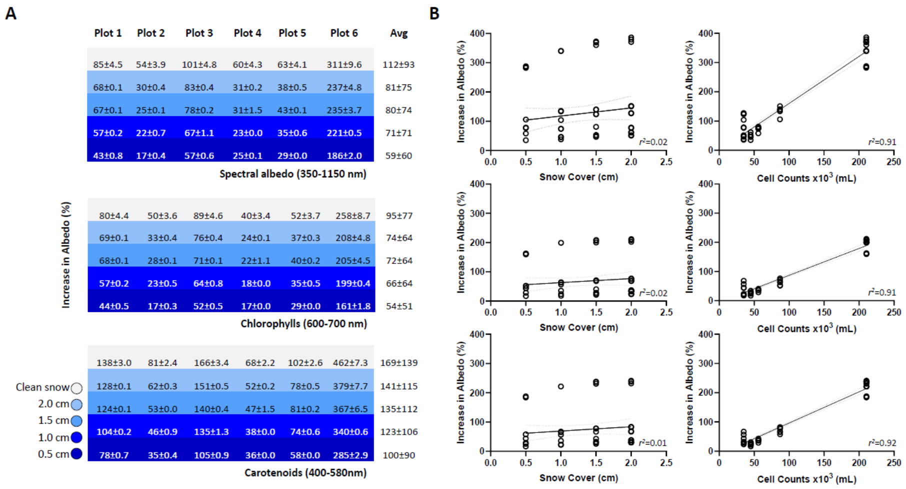

Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Avg
85±4.5	54±3.9	101±4.8	60±4.3	63±4.1	311±9.6	112±93
68±0.1	30±0.4	83±0.4	31±0.2	38±0.5	237±4.8	81±75
67±0.1	25±0.1	78±0.2	31±1.5	43±0.1	235±3.7	80±74
57±0.2	22±0.7	67±1.1	23±0.0	35±0.6	221±0.5	71±71
43±0.8	17±0.4	57±0.6	25±0.1	29±0.0	186±2.0	59±60

Spectral albedo (350-1150 nm)

Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Avg
80±4.4	50±3.6	89±4.6	40±3.4	52±3.7	258±8.7	95±77
69±0.1	33±0.4	76±0.4	24±0.1	37±0.3	208±4.8	74±64
68±0.1	28±0.1	71±0.1	22±1.1	40±0.2	205±4.5	72±64
57±0.2	23±0.5	64±0.8	18±0.0	35±0.5	199±0.4	66±64
44±0.5	17±0.3	52±0.5	17±0.0	29±0.0	161±1.8	54±51

Chlorophylls (600-700 nm)

	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Avg
	138±3.0	81±2.4	166±3.4	68±2.2	102±2.6	462±7.3	169±139
Clean snow ○	128±0.1	62±0.3	151±0.5	52±0.2	78±0.5	379±7.7	141±115
2.0 cm ●	124±0.1	53±0.0	140±0.4	47±1.5	81±0.2	367±6.5	135±112
1.5 cm ●	104±0.2	46±0.9	135±1.3	38±0.0	74±0.6	340±0.6	123±106
1.0 cm ●	78±0.7	35±0.4	105±0.9	36±0.0	58±0.0	285±2.9	100±90
0.5 cm ●							

Carotenoids (400-580nm)

Figure 3.