1   TITLE

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

3   algae

4   AUTHORS

5   Pablo Almela[1], James J. Elser[2], J. Joseph Giersch[2], Scott Hotaling[3] and Trinity L.

6   Hamilton[1*]

7   (1) Department of Plant and Microbial Biology, University of Minnesota, St. Paul, MN

8   55108, USA

9   (2) Flathead Lake Biological Station, University of Montana, Polson, MT 59860, USA

10   (3) Department of Watershed Sciences, Utah State University, Logan, UT 84322, USA

11   Correspondence to: Trinity L. Hamilton (trinityh@umn.edu)

12

13   ABSTRACT

14   Snow algae contribute to snowmelt by darkening the surface, reducing its albedo.

15   However, the potential consequences of algae under the surface (such as after a fresh

16   snowfall) on albedo reduction is not known. In this study, we examined the impact of

17   sub-surface snow algae on surface energy absorption. The results indicate energy

18   absorption across all analysed wavelength ranges when snow algae are snow-covered,

19   an effect that was correlated with both cell densities and chlorophyll-a concentrations.

20   These findings suggest that snow algae lower albedo and thus increase snow melt

21   even when snow-covered.

22

23   INTRODUCTION

24   Snow is the most reflective of natural surfaces on Earth, reflecting >90 % of visible

25   radiation when freshly fallen (Skiles et al., 2018). The primary determinant of snow's

26   albedo is its physical composition, primarily due to scattering at the interface between

27   ice and air (Cook et al., 2017). However, the introduction of impurities reduces snow

28   reflectance and enhances its absorption of solar energy. These impurities or

29   contaminants can be abiotic (e.g., dust) and biotic (e.g., algae). The effects of

30   biological albedo reduction (BAR)—the collective influence of biological communities

31   on albedo—are receiving increasing attention. Indeed, snow algae can   reduce the

32   albedo of the snow by around 20 % (Lutz et al., 2014; Ganey et al., 2017; Khan et al.,

33   2021), likely making blooms of snow algae the largest global contributor to BAR

34   (Hotaling et al., 2021).

35   Snow algae blooms are common during summer in alpine and polar ecosystems when

36   there is sufficient interstitial water to provide necessary habitat. Algae involved in this

37   phenomenon are represented by genera *Chlamydomonas*, *Chloromonas,* and

38   *Sanguina* (Hotaling et al., 2021) and color the snow red due to production of the

39   carotenoid astaxanthin (Remias et al., 2005). The production of this pigment protects

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

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

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

60

61 METHODS

62 *Study Site*

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

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

74

75 *Measurements of spectral reflectance*

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

84   To assess the influence of snow cover on the albedo impacts of snow algae, a PVC
85   cylinder (7.6-cm radius) was placed on the surface of the algae bloom and an initial
86   measurement of surface reflectance (i.e., albedo of the snow algae) was made. Next,
87   subsurface snow free of apparent abiotic or biotic contaminants affecting albedo was
88   collected near each plot using a plastic scoop. This snow was then sequentially
89   arranged in layers of 0.5 cm each, eventually reaching a total depth of 2.0 cm (**Figure
90   1B**). This depth was used as it has been identified as the point below which the
91   physical characteristics of the snowpack pose challenges for the snow algae to grow
92   (Cook et al., 2017).

93   Reflectance measurements were repeated in triplicate after adding each successive
94   0.5-cm layer. The average of the reflectance of uncovered snow algae was used as a
95   reference in each plot to assess the increase in albedo resulting from the addition of
96   snow layers. We also measured the spectral reflectance of snow in an area devoid of
97   evident biotic or abiotic impurities after removing the top centimeter of snow to obtain a
98   reference for the maximum attainable sunlight reflection within the surveyed snow field
99   at that time. We assumed that the physical characteristics of the snow were consistent
100 across the sampled plots during the sampling period. Because carotenoids (absorbing
101 in the 400-580 nm range) and chlorophylls (absorbing in the 600-700 nm range)
102 distinctly influence the spectral reflectance of algae-containing snow (Painter et al.,
103 2001), these specific wavelength ranges were chosen as optimal for investigating how
104 algae affect albedo reduction across varying snow depths.

105

106 *Sample collection, pigment analysis, and cell counts*

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

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

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

122

123 *Statistical analysis*

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

128

RESULTS AND DISCUSSION

Snow algae biomass: cell densities and chlorophyll concentrations

131 The amount of snow algae present is a crucial determinant of their contribution to BAR
132 (Hotaling et al., 2021). Plots with different color intensities were sampled and two
133 approaches were used to estimate its biomass to account for the variability of algal
134 abundance present within the studied snow patch (Cook et al. 2017). Cell densities
135 ranged from 35,000 to 210,500 cells mL^{-1} (**Table S1**). These biomass levels are
136 comparable to the findings reported in the North Cascades by Healy and Khan (2023),
137 but higher than the reported by Lutz et al., (2016) in the Arctic, suggesting large
138 variability in cell densities in snow algae blooms. When we analysed the concentrations
139 of chlorophyll-a, plot 6 had the highest levels (24.3 x 10^{-6} mg mL^{-1}), nearly an order of
140 magnitude greater than those found in plot 4 (2.7 x 10^{-6} mg mL^{-1}). The rest of the
141 samples ranged in between 3.2 and 10.4 x 10^{-6} mg mL^{-1} (**Table S1**). Cell density and
142 chlorophyll-a concentration were strongly correlated (R=0.93; p=0.01). This finding is
143 relevant as chlorophyll quantity within an individual cell varies between species and
144 can change over time as a photoacclimation mechanism (e.g., Felip and Catalan,
145 2000). Hence, the association between pigmentation and cell abundance indicates the
146 suitability of both methods in assessing biomass concentration within this snow algae
147 bloom.

148

Albedo reduction of snow algae on and beneath the surface

150 Snow algae blooms dominate primary production on snow and ice fields (e.g., Lutz et
151 al., 2014; Hamilton and Havig, 2017; Ganey et al., 2017; Havig and Hamilton, 2019;
152 Khan et al., 2021). As photosynthetic organisms, snow algae require light to grow and
153 their blooms support other microorganisms in the ecosystem (Lutz et al., 2016). Snow
154 algae absorb light energy primarily in the ranges where their specific pigments absorb
155 light most effectively. Across the full spectrum that we measured (350-1150 nm), we
156 observed a significant negative correlation between algal biomass and surface albedo
157 (-0.96; p<0.001), demonstrating a sizable BAR effect. Our albedo measurements of the
158 snow algae also showed strong light absorption within the 400–580 nm range
159 (carotenoids) and 600–700 nm range (chlorophylls) compared to clean snow (**Figure
160 2**). For these absorption spectra, we observed an expected significant negative
161 correlation between cell density and light reflectance for carotenoids (-0.91; p<0.05)
162 and chlorophylls (-0.93; p<0.05). Similar findings were noted in relation to Chl-a
163 concentrations (-0.86; p<0.05 and -0.90; p<0.05, respectively). These results align with
164 prior research (e.g., Painter et al., 2001) and indicate substantial light absorption by
165 algal cells. Collectively, these results show that the radiative influence of snow algae is
166 greatest in the visible region, where pigments efficiently absorb light, but also occurs in
167 the near-infrared region of the solar spectrum.

168 When we assessed how the spectral albedo of snow algae between 350-1150 nm
169 (**Figure 2**) related to the depth of the snow added, we observed an increase in
170 reflectance with depth of overlying snow for all plots (p<0.00). The same results were
171 obtained for the absorption ranges of carotenoids (p<0.00) and chlorophylls (p<0.00).
172 These findings show that the presence of a snow cover significantly influences the
173 overall energy balance and radiative properties of snow algae blooms. However, the

174 increase in albedo for snow algae upon adding snow layers showed significant
175 variation among plots (**Figure 3A**). On average, the overall spectral albedo (350-1150
176 nm) increased by 59 % and 81 % with the addition of 0.5 cm and 2.0 cm of snow,
177 respectively. Albedo for wavelengths influenced by chlorophylls showed similar values,
178 while for carotenoid-specific wavelengths the increases in albedo were 100 % for 0.5
179 cm and 141 % for 2.0 cm of snow. Linear regression analysis indicated a robust
180 positive correlation between albedo increases and snow algal biomass (**Figure 3B**).
181 This finding clarifies the relatively weak correlation between albedo and snow layers
182 when considering all samples, implying, not unexpectedly, that the influence of snow
183 cover on a snow algae bloom is contingent upon the algal biomass present.
184 The albedo for the 2.0 cm experimental snow layer on the snow algae was not as high
185 as that seen in clean snow (**Figure 3A**), showing significant differences in the studied
186 spectral ranges (p<0.00). These findings indicate that the reference of clean snow
187 exhibits greater reflectivity, revealing that energy absorption increases across all
188 analysed wavelengths even when snow algae are covered by snow up to 2.0 cm. The
189 efficiency of snow algae in absorbing sunlight may be crucial for sustained energy
190 capture, enabling snow algae to thrive under low-light conditions but also to accelerate
191 melting rates that sustain liquid water for nutrient uptake and growth. Our data indicate
192 that this melting occurs even when snow algae occur under the snow surface and are
193 undetectable to the naked eye.

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

207

208 CONCLUSIONS

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

219

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.

ACKNOWLEDGEMENTS

We thank N. Boyer, C. Hansen, H. Klip, and K. Coates for technical assistance in the field and lab.

FINANCIAL SUPPORT

This work was supported by grants #2113783 (to JJE) and #2113784 (to TLH) from the National Science Foundation. SH was supported by Agriculture and Food Research Initiative Competitive Grant #2021-69012-35916 from the USDA National Institute of Food and Agriculture.

REFERENCES

Cook, J. M., Hodson, A. J., Gardner, A. S., Flanner, M., Tedstone, A. J., Williamson, C., Irvine-Fynn, T. D. L., Nilsson, J., Bryant, R. and Tranter, M. Quantifying bioalbedo: a new physically based model and discussion of empirical methods for characterising biological influence on ice and snow albedo. Cryosphere, 11, 2611–2632, https://doi.org/10.5194/tc-11-2611-2017, 2017.

Dial, R. J., Ganey, G. Q. and Skiles, S. M. What color should glacier algae be? An ecological role for red carbon in the cryosphere. FEMS Microbiol. Ecol., 94, fiy007, https://doi.org/10.1093/femsec/fiy007, 2018.

260

261 Engstrom, C. B., Williamson, S. N., Gamon, J. A., and Quarmby, L. M. Seasonal
262 development and radiative forcing of red snow algal blooms on two glaciers in British
263 Columbia, Canada, summer 2020. Remote Sens. Environ., 280, 113164,
264 https://doi.org/10.1016/j.rse.2022.113164, 2022.

265 Felip, M., and Catalan, J. The relationship between phytoplankton biovolume and
266 chlorophyll in a deep oligotrophic lake: decoupling in their spatial and temporal
267 maxima. J. Plankton Res., 22, 91-106, https://doi.org/10.1093/plankt/22.1.91, 2000.

268 Ganey, G. Q., Loso, M. G., Burgess, A. B., and Dial, R. J. The role of microbes in
269 snowmelt and radiative forcing on an Alaskan icefield. Nat. Geosci., 10, 754–759,
270 https://doi.org/10.1038/ngeo3027, 2017.

271 Gray, A., Krolikowski, M., Fretwell, P., Convey, P., Peck, L. S., Mendelova, M., Smith,
272 A. G., and Davey, M. P. Remote sensing reveals Antarctic green snow algae as
273 important terrestrial carbon sink. Nat. Commun., 11, 2527,
274 https://doi.org/10.1038/s41467-020-16018-w, 2020.

275 Hamilton, T. L., and Havig, J. Primary productivity of snow algae communities on
276 stratovolcanoes of the Pacific Northwest. Geobiology, 15, 280-295,
277 https://doi.org/10.1111/gbi.12219, 2017.

278 Havig, J. R., and Hamilton, T. L. Snow algae drive productivity and weathering at
279 volcanic rock-hosted glaciers. Geochim. Cosmochim. Acta., 247, 220-242.
280 https://doi.org/10.1016/j.gca.2018.12.024. 2019.

281 Healy, S. M., and Khan, A. L. Albedo change from snow algae blooms can contribute
282 substantially to snow melt in the North Cascades, USA. Commun. Earth Environ., 4,
283 142, https://doi.org/10.1038/s43247-023-00768-8, 2023.

284 Hoham, R. W., and Remias, D. Snow and glacial algae: a review1. J. Phycol., 56, 264-
285 282, https://doi.org/10.1111/jpy.12952, 2020.

286 Hotaling, S., Lutz, S., Dial, R. J., Anesio, A. M., Benning, L. G., Fountain, A. G., Kelley,
287 J. L., McCutcheon, J., Skiles, S. M., Takeuchi, N., and Hamilton, T. L. Biological albedo
288 reduction on ice sheets, glaciers, and snowfields. Earth. Sci. Rev., 220, 103728,
289 https://doi.org/10.1016/j.earscirev.2021.103728, 2021.

290 Khan, A. L., Dierssen, H. M., Scambos, T. A., Höfer, J. and Cordero, R. R. Spectral
291 characterization, radiative forcing and pigment content of coastal Antarctic snow algae:
292 approaches to spectrally discriminate red and green communities and their impact on
293 snowmelt. Cryosphere, 15, 133–148, https://doi.org/10.5194/tc-15-133-2021, 2021.

294 Lutz, S., Anesio, A. M., Jorge Villar, S. E., and Benning, L. G. Variations of algal
295 communities cause darkening of a Greenland glacier. FEMS Microbiol. Ecol., 89, 402–
296 414, https://doi.org/10.1111/1574-6941.123512014, 2014.

297 Lutz, S., Anesio, A. M., Raiswell, R., Edwards, A., Newton, R. J., Gill, F., and Benning,
298 L. G. The biogeography of red snow microbiomes and their role in melting arctic
299 glaciers. Nat. Commun., 7, 11968, https://doi.org/10.1038/ncomms11968, 2016.

300 Martin-Mikle, C. J., and Fagre, D. B. Glacier recession since the Little ice Age:
301 Implications for water storage in a Rocky Mountain landscape. Arct. Antarct. Alp. Res.,
302 51, 280-289, https://doi.org/10.1080/15230430.2019.1634443, 2019.

303   Onuma, Y., Takeuchi, N., Tanaka, S., Nagatsuka, N., Niwano, M., and Aoki, T.:
304   Physically based model of the contribution of red snow algal cells to temporal changes
305   in albedo in northwest Greenland, Cryosphere, 14, 2087–2101,
306   https://doi.org/10.5194/tc-14-2087-2020, 2020.

307   Painter, T. H., Duval, B., Thomas, W. H., Mendez, M., Heintzelman, S., and Dozier, J.
308   Detection and quantification of snow algae with an airborne imaging spectrometer.
309   Appl. Environ. Microbiol., 67, 5267–5272, https://doi.org/10.1128/AEM.67.11.5267-
310   5272.2001, 2001.

311   Skiles, S. M., Flanner, M., Cook, J. M., Dumont, M., and Painter, T. H. Radiative forcing
312   by light-absorbing particles in snow. Nat. Clim. Change., 8, 964-971,
313   https://doi.org/10.1038/s41558-018-0296-5, 2018.

314

315

316

317

318

319

320

321

322

323

324

325

326

327

328

329

330

331

332

333

334

335

336

337

338

339   Figure 1.

340

341

342

343

344

345

346

347

348

349

350

351

352

353

354

355

356

357
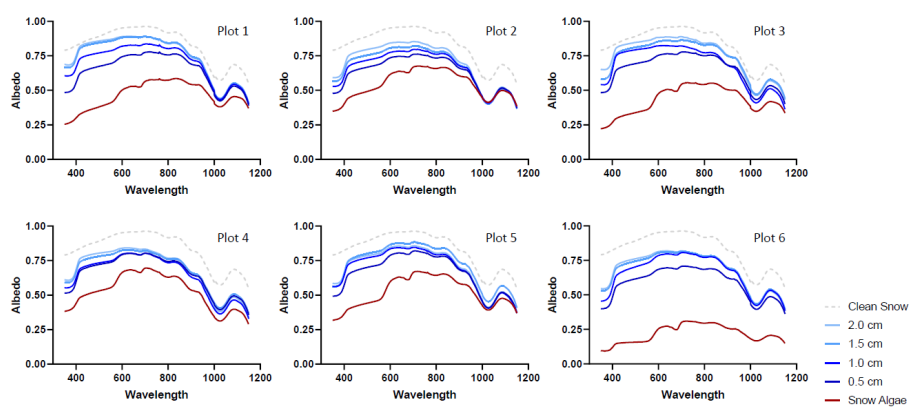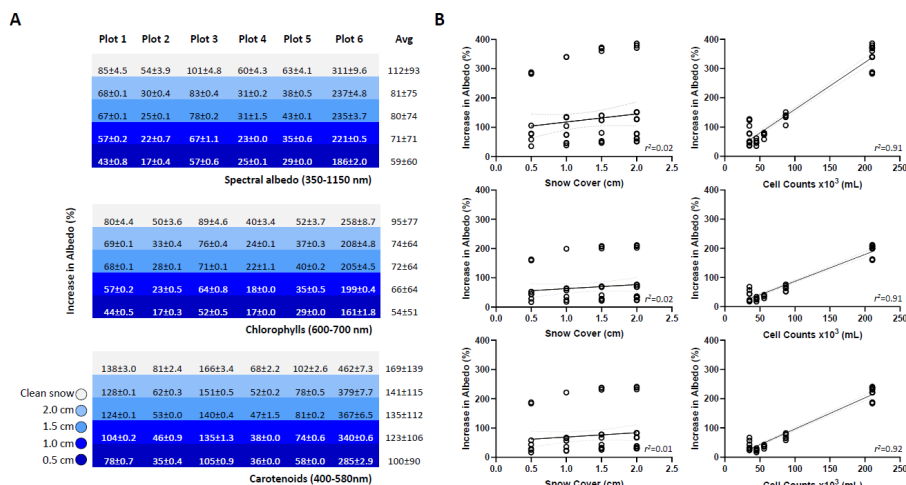
Figure 2.

380

381   Figure 3.

382

383

384

385

386

387

388

389

390

391

392

393

394

395

396

397

398

399

400

401