1   **DOM concentration, optical parameters and attenuation of solar radiation in high-**

2   **latitude lakes across three vegetation zones**

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18

19 **Abstract**

20   High-latitude lakes usually have a high penetration of light, due to their low productivity

21 and low concentration of dissolved organic matter (DOM), but large variations in lake optical

22 properties can be found within and between regions. We investigated the underwater light

23 regimes in relation to DOM in 18 oligotrophic, high-latitude lakes across mountain birch

24 woodland, shrub tundra and barren tundra in NW Finnish Lapland. DOM variability was

25 measured by quantification of organic carbon and analysis of UV-visible absorbance and

26 fluorescence spectra. In 12 out of 18 lakes > 1% of PAR reached the lake bottom while UV

27 radiation exposure was more variable with 1% UVB depth ranging from 0.1 to > 12 m. Lakes

28 located in barren tundra had highest transparency, lowest DOC concentration and lowest

29 chromophoric DOM (CDOM) absorption (mean values: K_d PAR 0.3 m^{-1}, DOC 2.1 mg l^{-1}, a_{440}

30 0.4 m^{-1}), while lakes in shrub tundra and mountain birch forest were in general less transparent

31 although still clear with a mean DOC concentration of 4.7 mg l^{-1} and CDOM absorption (a_{440})

32 of 1.4 m^{-1}. Solar attenuation and lake transparency were correlated with CDOM absorption

33 (a_{440}), but the relationship was affected by the quality of organic matter and the concentration

34 of DOC. Our survey emphasizes the importance of catchment type on DOM characteristics and

35 lake optics and suggest that changes in vegetation zones will alter the overall aquatic light

36 milieu in oligotrophic high-latitude lakes. We predict that even small changes in CDOM quality

37 may largely change the UV radiation exposure of the studied high latitude lakes with likely

38 consequences on biota while changes in PAR may have smaller biological effects in these

39 shallow lakes that are already illuminated to the bottom even in the darkest systems.

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2

43 **Introduction**

44 The concentration and optical qualities of dissolved organic carbon (DOC) and, in particular its

45 chromophoric component, chromophoric dissolved organic matter (CDOM), play a major role

46 in determining and understanding how lake ecosystems respond to disturbances such as global

47 warming (Williamson *et al.,* 1999). They regulate the transmission of both photosynthetically

48 active radiation (PAR; 400-700 nm) and ultraviolet radiation (UVR; 280-400 nm) (Scully &

49 Lean, 1994; Morris *et al.,* 1995; Laurion, Vincent & Lean, 1997; Huovinen, Penttilä &

50 Soimasuo, 2003; Bracchini *et al.,* 2006) and therefore contribute to defining the species

51 composition in lakes (Rautio & Korhola, 2002), the ratio between auto- and heterotrophic

52 producers (Jansson *et al.*, 2000, Forsström, Roiha & Rautio, 2013), and the overall benthic and

53 pelagic productivity (Karlsson *et al.*, 2009).

54

55 The vegetation in the catchment, catchment to lake ratio, and the productivity of the lake have

56 a prominent impact on the concentration and composition of DOM. In small oligotrophic lakes

57 with low chlorophyll- a concentration and large catchment areas a high proportion of carbon is

58 derived from terrestrial and wetland sources dominated by higher terrestrial plant productivity

59 (Bade *et al.*, 2007). The organic carbon leaching from forests and wetlands constitute mainly

60 of slow-degrading and nutrient poor material dominated with humic and fulvic constitutes

61 (McKnight & Aiken, 1998; McKnight, Aiken & Smith, 1991; McKnight *et al.,* 1994) that are

62 the most important components in absorbing solar radiation (Morris *et al.,* 1995; Ferrari &

63 Dowell, 1998). CDOM can also be generated within the water body by decomposition of

64 phytoplankton or higher aquatic plant tissues (autochthonous input) scarce in fulvic and humic

65 constituents (Benner, 2003) resulting in deep penetration of solar radiation (McKnight *et al.*,

66 1994). UV-visible absorbance and fluorescence spectroscopy provide information on the origin

67 and chemical structure of DOM: autochthonous molecules of CDOM have a smaller absorbance

68 for a given wavelength than allochthonous molecules and show strong fluorescence between

69 the wavelengths 293-308 nm (with a secondary peak around 360 nm), whereas allochthonous

70 humic and fulvic materials fluoresce at longer wavelengths (McKnight, Aiken & Smith, 1991;

71 McKnight *et al.,* 2001; Belzile *et al.,* 2001).

72

73 Due to climatic warming, higher precipitation and associated vegetation and soil property

74 changes in lake catchment areas, higher inputs of terrestrial DOMh to high-latitude lakes are

75 expected (Vincent, Laurion & Pienitz, 1998; Sommaruga *et al*., 1999; Pienitz & Vincent, 2000;

76 ACIA, 2005; Meehl *et al.,* 2007). For other northern lakes, this scenario of increasing DOM is

77 not applicable since some areas are showing opposing trends of drought and cooling (Pienitz *et*

78 *al.,* 2004; Fallu *et al.,* 2005; Rolland *et al.,* 2008). Whatever the direction of change, climatic

79 change will not only alter the amount of DOM transported to high-latitude lakes, but may also

80 change its chemical composition and absorption characteristics, mainly because of

81 modifications that occur in the catchment vegetation (Curtis, 1998). These lakes already have

82 low DOC concentrations and even small changes in CDOM concentration will alter the PAR

83 and UVR penetration depth drastically (Vincent, Laurion & Pienitz, 1998; Rautio & Korhola,

84 2002; Bracchini *et al.*, 2006). Despite the fundamental floristic differences between different

85 vegetation zones across and near the northern tree line, the influence of the catchment type on

86 DOM composition at high latitudes has rarely been addressed.

87

88 In this study, our objectives were 1) to evaluate how lakes in different vegetation zones differ

89 from each other in their catchment features, DOM parameters and algal biomass, and 2) how

90 these contribute to defining the attenuation of solar radiation in lakes. We measured the

91 variability in DOM concentration, optical parameters and in the attenuation of solar radiation

92 from 18 high-latitude lakes along a transect from the northern treeline to barren tundra in NW

93 Finnish Lapland, including three distinct vegetation zones. We hypothesized that lakes within

94 each vegetation zone are more close to each other in their DOM variables than lakes between

95 zones, which would allow estimating how the lake optics and carbon dynamics will change

96 with climate change and moving vegetation zones. Information on lake optics and DOM

97 characteristics has previously been reported from the region only for one lake and some small

98 ponds (Rautio, Mariash & Forsström 2011; Roiha et al., 2012). This study was further carried

99 out to enhance knowledge on the quantity and quality of DOM and to assess the applicability

100 of DOM indices in high-latitude lakes. Because high-latitude lakes are often driven by benthic

101 production that relies on high transparency (Rautio & Vincent, 2006; 2007; Hessen & Leu,

102 2006; Karlsson & Säwström, 2009), and the majority of unproductive lakes are thought to be

103 light rather than nutrient limited (Karlsson *et al.*, 2009), it is crucial to understand the coupling

104 between DOM, solar attenuation and phytoplankton, and how this might change with respect

105 to global change.

106

107 **Materials and methods**

108 *Study area and sampling*

109 A set of 18 small to medium size high-latitude headwater lakes were sampled between

110 August 16 – 26 in 2004, during the autumn overturn. The study lakes are located about 450 km

111 north of the Arctic Circle (Figure 1) in NW Finnish Lapland (68-69°N, 20-22°E) and over a

112 range of different bedrock types. Four lakes are situated below the tree line (approx. 600 m

113 a.s.l.) in the mountain birch woodland (MBW), ten lakes in catchment areas with mires and

114 shrubs (ST), and four lakes in catchment areas with barren, rocky ground (BT), following the

115 vegetation zones for this region (Virtanen & Eurola, 1997). The lakes were selected to cover

116 large gradients in altitude, catchment and bedrock type, and optical characteristics. The study

117 area lies in the transition zone between the North Atlantic oceanic climate and the Eurasian

118   continental climate. Above the treeline, the vegetation mainly consists of low dwarf shrubs,

119   mosses, grasses and sedges. The catchment areas of the lakes are not impacted by direct human

120   activities. Table I summarizes the main environmental information of the lakes.

121   For this study, all the lakes were visited once, and water samples were taken from a depth

122   of 1m with ajj water sampler (Limnos Ltd, Turku, Finland). In addition, three of the deepest

123   lakes were sampled from deeper water layers (Table I). Water temperature, pH and conductivity

124   were all measured *in situ* using a YSI 63 pH and conductivity instrument (YSI Incorporated,

125   Yellow Springs, USA). Alkalinity, ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_{3+2}-N),

126   orthophosphate phosphorus (PO_4-P), total phosphorus (TP), total nitrogen (TN), silica (SiO_2-

127   S), and turbidity were analyzed in the Lapland Regional Environmental Centre using the

128   standard methods of the National Board of Waters in Finland. DOC concentration was analyzed

129   as non-purgeable organic carbon with Shimadzu TOC 5000A and chlorophyll *a* according to

130   Jefferey and Humphrey (1975) at the Lammi Biological Station. Phytoplankton samples, also

131   taken at 1 m depth, were preserved with acid Lugol's solution and analyzed with an inverted

132   microscope according to Utermöhl (1958). Phytoplankton biovolumes were calculated from

133   cell densities based on measurements of the size of the species and the approximation of the

134   shapes to geometrical figures. Biomass was calculated from measured algal volumes assuming

135   a density of 1.

136

137   *DOM analyses and light measures*

138   DOM absorbance spectra were measured from filtered lake water as in Forsström, Roiha

139   & Rautio, 2013. The spectral slopes of various range (275 to 295, 350 to 400 and 300 to 650

140   nm), as well as the slope ratio S_R ($S_{275-295}$ to $S_{350-400}$) were used to describe DOM quality

141   (Stedmon, Markager & Kaas, 2000; Helms *et al.*, 2008). In addition, we used the approach

142   introduced by Loiselle *et al.* (2009), and calculated the spectral slope for each 20 nm interval

143 between 200 and 500 nm and plotted the resulting slopes by the center wavelength of each

144 range to create spectral slope curves as function of wavelength, $(S(\lambda), nm^{-1})$. The regression

145 coefficients (r^2) were, in general, greater than 0.99, and the addition of a constant to the

146 regression model, as suggested by Stedmon, Markager and Kaas (2000) did not result in a better

147 fit. We used $S280$ and $S390$ as indicators of algal or humic substances (Loiselle et al. 2009).

148 Additionally, absorption at 320 and 440 nm is used as a measure of CDOM concentration and

149 color and DOC specific a_{320} as a proxy of the degree of DOM color. Specific UV absorbance

150 (SUVA) at 254 nm was calculated as the absorbance at 254 nm divided by the DOC

151 concentration to estimate variation in landscape features and, hence, in the source of carbon

152 (Weishaar *et al.,* 2003). For comparison, CDOM absorbance was measured from one

153 allochthonous (water taken from a nearby bog) as well as one autochthonous (a *Scenedesmus*

154 sp. culture) source.

155 From each sample, a synchronous fluorescence spectrum (SFS) was measured with a

156 Cary Eclipse fluorescence spectrophotometer (Varian Inc., USA) as employed by Belzile,

157 Gibson and Vincent (2002). The wavelength difference between excitation and emission beams

158 was 14 nm. Fluorescence scans were standardized to quinine sulphate units (QSU) using a

159 standard of quinine sulfate dehydrate (Sigma-Aldrich no. 22640) dissolved in 0.02 N sulfuric

160 acid and corrected for the absorption within the sample (inner filter effect) according to

161 McKnight *et al.* (2001). To characterize DOM composition, we calculated integrated areas of

162 different wavebands (Retamal *et al.,* 2007): low molecular weight compounds (LMW, emission

163 range 280-323 nm), medium molecular weight compounds (MMW, emission range 324-432

164 nm) and high molecular weight compounds (HMW, emission range 433-595 nm) and used their

165 relative proportion (Lλ/Hλ and Mλ/Hλ) to describe CDOM composition. In addition,

166 humification index (HI), a measure of the degree of polycondensation and humification of

167 DOM, was calculated according to Kalbitz, Geyer and Geyer (1999) from synchronous

168 fluorescence scans as a quotient of fluorescence intensity at 470 and 360 nm.

169   Transmission of downwelling UV irradiance (at 320, 340 and 380 nm) and PAR was

170 measured with a PUV500 radiometer (Biospherical, San Diego, USA) *in situ* at each site.

171 Diffuse attenuation coefficients (K_d) of UVR and PAR in the water column were obtained from

172 the slope of the linear regression of the natural logarithm of down-welling irradiance (E_d) versus

173 depth (Z), $\ln(E_{d(Z)}) = -K_d Z + c$, where the constant $c = \ln(E_{d(0-)})$, with $E_{d(0-)})$ being the irradiance

174 just below the water surface.

175

176 *Statistical analyses*

177 Differences in catchment features, DOM parameters and algal biomass among vegetation zones

178 were tested using ANOSIM followed by pairwise t-tests to identify differences. Data were

179 normalised and Euclidian distances were used to generate resemblance matrix. A similarity

180 percentage analysis (SIMPER routine) was used to assess the percentage contribution of each

181 variable to the observed dissimilarities among vegetation zones. Principal component analyses

182 (PCA, normalized values, Euclidean distances) with segmented bubble plots were used to

183 visualize vegetation zones and associated statistically most important environmental variables

184 that likely regulate light attenuation. Lake Kilpisjärvi was omitted from these analyses due to

185 its large size that was two magnitudes of orders larger in catchment area, lake area and depth

186 than the other lakes making it an outlier for most variables.

187   BIOENV analyses routine were used to identify which environmental variables or

188 combination of variables (altitude, catchment to lake ratio, catchment slope, turbidity, chl-a,

189 phytoplankton biomass, DOC, SUVA, HI, a_{440}, $S_{300-650}$, Lλ/Hλ, Mλ/Hλ, S280, %LMW,

190 %MMW, %HMW) best explained the changes in light attenuation (K_d *PAR, K_d 320* nm) and

191 transparency (transparency ratio) when lake data from different vegetation zones were pooled.

192   Other environmental variables were omitted from the analyses due to their high Pearson

193   correlation (r > 0.90) with some included variables or because of missing values. The lakes

194   Korsajärvi and Koddojavri were excluded as some of their DOM variables were outliers. The

195   statistical analyses were carried out in Primer (version 7) and JMP (version 11). A significant

196   level α = 0.05 was used for all statistical tests.

197

198   **Results**

199   *Catchment and morphological parameters*

200   With the exception of Lake Kilpisjärvi (lake area 3710 ha, max depth 57 m), the MBW

201   lakes were small (lake area 5-20 ha) and shallow (max depth 2 m). ST lakes had a relatively

202   high range of size and depth (lake area 1-100 ha, max depth 4-24 m), whereas BT lakes were

203   amongst the smallest (lake area 1-10 ha), but two of them were relatively deep (max depth 9

204   and 12 m. Ratio of catchment to lake area ranged from 3 to 11 in MBW, from 7 to 42 in ST and

205   from 4 to 32 in BT. Mean slope of the catchment was generally highest in ST (Table I).

206   According to ANOSIM, there was a difference in catchment and morphological

207   parameters according to vegetation zones (R = 0.412; p = 0.004) with all pairwise comparisons

208   (p < 0.05 for all). Catchment slope contributed to explaining the variability between all zone

209   comparisons (27-48%) while other important variables were altitude (39-62%) and catchment

210   to lake ratio (26-29%). Figure 2a shows the PCA ordination of the lakes with the variability in

211   catchment slope and catchment to lake ratio in different lakes.

212

213   *Temperature, water chemistry and algal biomass*

214   Due to their shallowness, the majority of lakes (11) were isothermal during the sampling.

215   Lake water temperature varied between 5.9 and 11.9 ºC being highest at lowest altitudes.

216   Conductivity had highest range in ST, between 0.7 and 4.3 mS m^{-1}. The pH of three lakes, two

217   from MBW and one from BT, was < 6 (Ristijärvi, Koddojärvi, 1009) and the rest between 6.7

218   and 7.8. Alkalinity averaged 0.125 mmol l^{-1}. All lakes had low nutrient concentrations

219   (inorganic nutrients mainly below the detection limit, total P 3-13 µg l^{-1} and total N 71-410 µg

220   l^{-1}) and low turbidity (< 1.0 FNU), with highest values generally measured from MBW.

221   Chlorophyll *a* concentration varied between 0.2 µg l^{-1} and 2.4 µg l^{-1} and phytoplankton biomass

222   was low (less than 0.5 mg l^{-1}) in all the study lakes. Only in the deepest lake (Kilpisjärvi) of the

223   three that were sampled from two different water layers, was chlorophyll *a* markedly lower in

224   the deeper water layer compared to the 1m depth (Table I). Most lakes were dominated by

225   chrysophytes (Chrysophyceae), but in a few lakes the dominating algal group was green algae

226   (Chlorophyceae), cryptophytes (Cryptophyceae) or dinoflagellates (Dinophyceae).

227   Dinoflagellates were most common in MBW lakes with high DOC and color (Korsajärvi,

228   Koddojärvi and Ristijärvi) (L. Forsström, unpublished data).

229   ANOSIM identified two groups separating the lakes above (combined zones ST and BT) and

230   below the tree line (MBW) in water chemistry (R = 0.317; p = 0.003) and algal biomass (chl-a

231   and biomass) (R = 0.343; p = 0.003). Figure 2b shows the distribution of Chl-a and

232   phytoplankton biomass in lakes from different catchment areas.

233

234   *DOC concentration and DOM characteristics*

235   DOC concentration varied from 1.5 to 16.2 mg l^{-1} (Table II). Average DOC concentration

236   was 9.7 mg l^{-1} in MBW, 3.0 mg l^{-1} in ST and 2.1 mg l^{-1} in BT. CDOM absorption coefficient at

237   320 nm ranged from 1.0 to 61.0 m^{-1} (mean values: MBW 26.3 m^{-1}, ST 4.0 m^{-1}, BT 3.3 m^{-1}).

238   CDOM absorption coefficient at 440 nm, an indication of color, varied from 0.1 to 9.4 m^{-1}, with

239   only two MBW lakes having values > 1.1 m^{-1}. DOC specific absorptivity varied from 0.4 to 3.8

240   mg $^{-1}$ m^{-1}. SUVA$_{254}$, a parameter indicating DOM quality, varied from 0.3 l mg^{-1} m^{-1} in barren

241   tundra to 6.2 l mg^{-1} m^{-1} in mountain birch forest. Average SUVA$_{254}$ was 2.9 l mg^{-1} m^{-1} in MBW,

242     $1.4 \, \mathrm{l \, mg^{-1} \, m^{-1}}$ in ST and $1.0 \, \mathrm{l \, mg^{-1} \, m^{-1}}$ in BT. The spectral slope coefficient, S, had the smallest

243   variation (0.014-$0.02 \, \mathrm{nm^{-1}}$) when calculated for the shortest wavelengths; 275-295 nm. Slopes

244   for 300-650 nm and 350-400 nm had relatively similar ranges of variation (0.006-0.017 and

245   0.005-$0.017 \, \mathrm{nm^{-1}}$, respectively), but it is noteworthy that S for these wavelength bands could

246   not be calculated for all the study lakes: the BT lakes 1009 and Kuorroladdu had very low

247   absorption, causing excessive interference around 350 nm, the area where the light source

248   switches from UV to visible light. As the interference absorption at 320 nm could not be reliably

249   measured, the spectral slope for these two lakes was calculated between 385-650 nm. In

250   addition, sample from Lake Koddojavri (MBW) should have been diluted for reliable

251   measurements for the shortest wavelengths (< 300 nm).

252   In addition to traditional absorption slopes, spectral slope curves, $S(\lambda)$, were used to

253   describe differences in CDOM (Table II). Spectral slope values showed a large variation over

254   the considered wavelengths (0.004-$0.100 \, \mathrm{nm^{-1}}$). S_{280}, an indication of algal-derived DOM

255   (Loiselle *et al.* 2009) was lowest in MBW lakes (mean $0.017 \, \mathrm{nm^{-1}}$, min $0.014 \, \mathrm{nm^{-1}}$, max 0.018

256     $\mathrm{nm^{-1}}$) and highest in BT lakes (mean $0.019 \, \mathrm{nm^{-1}}$, min $0.016 \, \mathrm{nm^{-1}}$, max $0.025 \, \mathrm{nm^{-1}}$). S_{390},

257   associated with fulvic acids (Loiselle *et al.,* 2009), was lowest in BT lakes (mean $0.013 \, \mathrm{nm^{-1}}$,

258   min $0.009 \, \mathrm{nm^{-1}}$, max $0.017 \, \mathrm{nm^{-1}}$) and highest in MBW lakes (mean $0.017 \, \mathrm{nm^{-1}}$, min 0.017 nm$^-$

259   ^{1}, max $0.017 \, \mathrm{nm^{-1}}$). Shape of the spectral slope curve varied considerably between lakes from

260   different vegetation zones (Figure 3a). Curves from the two highly-colored MBW lakes,

261   Korsajärvi and Koddojavri, had high resemblance to bog-water taken from Markkinasuo

262   (68°29'N, 22°16'E), a bog located close to the study region. These lakes show highest values

263   in spectral slopes at around 350-390 and only a small peak at S_{280} with a maximum at around

264   S_{390}. In contrast, ST and BT lakes show similarities to a curve measured from a *Scenedesmus*

265   phytoplankton culture, with a high peak at S_{280}. However, at S_{390} they were closer to the DOM

266   from bog than from phytoplankton with a relatively high peak at S_{390}.

267

268   Synchronous fluorescence scans enabled further characterization of CDOM quality and

269   identification of the CDOM sources, and showed differences between the study lakes (Figure

270   3b). All lakes showed a fluorescence peak around 280-300 nm, indicating autochthonous

271   CDOM, only the intensity varied reflecting concentration of CDOM in lakes from different

272   vegetation zones. In all but two barren tundra lakes (1009 and Stuorralampi) the highest relative

273   contribution of fluorescence was observed in the area of medium molecular weight, indicative

274   of components originating from allochthonous processes. The highest share of LMW

275   fluorescence, around 25% of total fluorescence, was found in lakes Kuorroladdu (MBW) and

276   Somaslompolo (ST), two lakes with very high transparency. The highest MMW fluorescence,

277   close to 50% of total fluorescence, was found in Kuorroladdu (BT), Peeralampi (ST) and

278   Kilpisjärvi (MBW), whereas the highest HMW fluorescence was measured from 1009 (BT)

279   and Stuorralampi (BT). Lλ/Hλ varied between 0.3 and 1.0, whereas Mλ/Hλ varied between 0.9

280   and 2.1. Both ratios had a highest range in the barren tundra. The humification index (HI)

281   ranged from 0.5 to 0.9 (Table II). Lake Koddojavri (MBW) showed such a high inner-filter

282   effect (Lakowicz, 2006), that it was omitted from the SFS results.

283   In lakes where sampling was done from two different depths, DOC concentration and

284   a_{CDOM} were lower or similar and DOC-specific a_{CDOM}, a^*_{320}, was higher in deeper samples

285   compared to samples taken from the 1m depth (Table II). In Kilpisjärvi (MBW) and Saanajärvi

286   (ST), $SUVA_{254}$ was higher in the hypolimnion than in the epilimnion, but in Mallajärvi (ST) it

287   was the opposite. The relative amount of LMW fluorescence and Lλ/Hλ was always lower and

288   HI higher in samples taken from the hypolimnion than in the epilimnion, but other indicators

289   of DOM quality did not have an even trendS(λ) curves showed only minor differences when

290   calculated from different depths (data not shown).

291   Several variables in the DOM dataset were highly correlated with each other, with highest

292   correlations observed between a_{320} and a_{440} (Pearson's correlation r = 0.988), $S_{275-295}$ and S_{290}

293   (r = 0.983), $S_{300-650}$ and S_{390} (r = 0.960), $S_{350-400}$ and S_{390} (r = 0.934) and a^{*}_{320} and SUVA (r =

294   0.910). The DOM variables DOC, SUVA, SR, HI, a_{440}, S_{280}, $S_{300-650}$, Lλ/Hλ, Mλ/Hλ %LMW,

295   %MMW and %HMW were selected for ANOSIM which identified statistical differences in

296   them according to vegetation zones (R = 0.496; p = 0.008) As for catchment parameters, all

297   vegetation zones were different from each other (pairwise comparisons; p < 0.05 for all). a_{440}

298   (24-34%), DOC (25-32%) and SUVA (22-27%) explained the variability between lakes below

299   and above the tree line while S_{280} (45%) separated the ST and BT lakes from each other. The

300   distribution of a_{440} and S_{280} is shown in Fig. 2c.

301

302   *PAR and UV attenuation*

303   The transparency over the PAR waveband (400–800 nm) was generally high, with K_d

304   values < 0.8 m^{-1} for all but two MBW lakes (Korsajärvi 2.6 m^{-1} and Koddojavri 2.4 m^{-1}) (Table

305   III). In 12 out of 18 lakes, > 1% of PAR reached the lake bottom. K_d at 320 nm, representing

306   attenuation of UV-B radiation, varied between 3.1 and 70.4 m^{-1}for the MBW lakes, between

307   1.2 and 7.7 m^{-1} for ST lakes, and between 0.3 and 5.9 m^{-1} for BT lakes. In two BT lakes (1009

308   and Stuorralampi) more than 1% of UV-B radiation reached the lake bottom and the average

309   depth of 1% at 320 nm was 2.4 m. The inferred attenuation depth of UV ($Z_{UV1\%}$/Z_{max}) expressed

310   as a proportion of lake maximum depth varied from 3% to 100%, and was more than 10% in

311   10 lakes. The transparency ratio (1% depth of 320 nm UV relative to the 1% depth of PAR)

312   varied between 3.5% and 50.9%, the average being 12.8%. Because K_d320 and 1% UV-B depth

313   as well as K_dPAR and 1% PAR depth were highly correlated (r > 0.9), the 1% depth values

314   were excluded from the ANOSIM. The vegetation zones separated from each other (R= 0.384,

315   p = 0.001) but according to SIMPER only the shrub tundra (ST) zone was different from the

316 two other while lakes below tree line (MBW) and on barren tundra (BT) were similar. The high

317 variability within MBW and ST lakes (Fig. 2d) and the low number of lakes in these zones

318 prevented SIMPER to separate them from each other. K_{d320} explained most of the variability

319 between MBW and ST lakes (48%) while transparency ratio explained the difference between

320 ST and BT lakes (96%).

321 The BIOENV analyses identified a440 as the most important environmental variable

322 explaining light attenuation (K_d320 and K_dPAR) and transparency of the lakes studied (Table

323 IV, Fig. 4). Alone it explained 77% of the data variability but when considered with different

324 combinations with S_{380}, S_{280}, DOC, SUVA and HI these parameters explained more of the

325 variability than a440 alone. However, these supplementary variables alone explained clearly less

326 of the light parameters than a440 (Table IV).

327

328 **Discussion**

329 Our data for high-latitude lakes from northern Finland show that DOM has a major

330 influence on underwater UV-B and PAR attenuation and transparency ratio. Absorbance at 440

331 nm (a440) with spectral slope at 390 nm (S_{390}) explain nearly 90% of the optical variability

332 between lakes while S_{280}, DOC, SUVA and HI also importantly contributed to defining the light

333 milieu in the lakes. The dominant importance of a440 is consistent with observations from other

334 high latitude or mountain regions (Laurion, Vincent & Lean, 1997; Laurion *et al.,* 2000; Belzile,

335 Gibson & Vincent, 2002) while S_{390} is an indicator of fulvic acids of DOM (Loiselle *et al*.,

336 2009) that contribute to increasing DOM color and therefore influence PAR and UV

337 attenuation.

338

339 *Landscape control of lake optics*

340   Although our study lakes were located in a relatively small region of NW Finland, the

341   results demonstrate that high-latitude lakes are not a cohesive group of lakes. Despite their

342   globally low levels of some common features, such as low nutrient levels, low phytoplankton

343   biomass and high transparency, they display high variability in catchment properties, lake

344   morphology and DOM characterization depending on the lake's location in the landscape. Such

345   variability in especially morphological features is typical for postglacial lakes (Pienitz, Doran

346   & Lamoureux 2008). Our analyses indicated that the lakes from below the tree line, from shrub

347   tundra and from barren tundra separate from each other according to their catchment variables

348   and DOM composition. Similar landscape control on lake physical and chemical parameters

349   have been earlier documented for the same geographical area but using a different set of abiotic

350   and biotic variables (Rautio 2001; Mariash *et al*., 2011; Roiha *et al*., 2012). The most unified

351   group of lakes based on several variables was shrub tundra, despite the fact that it contained the

352   highest number of lakes. The observed deviation from the other zones was mainly explained by

353   catchment slope, catchment to lake ratio, a_{440}, K_d and transparency ratio. Other important

354   factors were the ratio of catchment slope, DOC, SUVA, S_{280} and $S_{300-650}$. Taken together these

355   factors indicate that DOM optics were different in different vegetation zones and imply that

356   changes in zone locations will likely cause shifts in the light milieu of the lakes and

357   subsequently in their productivity (Pienitz & Vincent, 2000; Karlsson *et al*., 2009).

358   The variation in DOC has commonly been shown to be closely linked with UV and PAR

359   attenuation (Schindler *et al*., 1996) and to be controlled by catchment area properties, lake

360   morphometry and the relationship between catchment area to lake surface area (Williamson *et*

361   *al.*, 1996; McKnight *et al.*, 1997; Sommaruga *et al.,* 1999; Bukaveckas & Robbins-Forbes,

362   2000; Xenopoulos *et al.,* 2003; Winn *et al.,* 2009). DOC concentration of our study lakes was

363   low (median 2.7 mg l^{-1}) and the range was comparable to results reported from the Adirondack

364   Mountain Regions (Bukaveckas & Robbins-Forbes, 2000) and from Alaska and the NE USA

365   region (Morris *et al.,* 1995). In our study, DOC contributed to light attenuation as a

366   supplementary variable (with SUVA and HI) but no significant correlation was found between

367   lake morphometric properties, size or topography of the catchment area and DOC. The

368   concentration of DOC neither varied significantly among vegetation zones but here it is

369   important to keep in mind the relative small number of lakes per zone that most likely restricted

370   identifying some associations. However, DOC was negatively correlated with altitude ($r = -$

371   0.54), which can be related to altitudinal changes in catchment properties (e.g. less organic soils

372   at higher elevations and variation in vegetation along an elevation gradient). A similar

373   relationship between DOC and altitude has been reported in other comparable studies (e.g.,

374   Sommaruga *et al.,* 1999).

375

376   *The relative importance between DOC and DOM parameters*

377   The present study supports the conclusion that DOM is better than DOC in explaining

378   differences in light attenuation in low DOC lakes of high-latitude and high-altitude areas

379   (Morris *et al.,* 1995; Laurion *et al.,* 2000; Sommaruga, 2001). The spectral irradiance across

380   the PAR and UV ranges was tightly controlled by a_{440} that is often used as an indicator of

381   CDOM color. Because a_{440} and a_{320} were highly correlated ($r = 0.988$) we used only a_{440} as an

382   explanatory variable in our analyses but it is good to keep in mind that absorption in general

383   provides an excellent indicator of spectral attenuation and can be used as an index of K_d when

384   direct spectral measures are not possible. Absorbance measures are also faster, easier and

385   cheaper to make than any of the other DOM measures, including analyses of DOC

386   concentration and calculations of most spectrophotometric and spectrofluorometric data

387   variables.

388   Spectral attenuation correlated also with DOC but the relationship was not always

389   predictable. In general, there was a positive correlation between DOC and K_dPAR ($r = 0.707$),

390 and DOC and K_d320 (r = 0.692), but the relationship was not always linear. Lake

391 Vuobmegasvarri (BT) and Lake Somaslompolo (ST) had the same DOC concentration (2.5 mg

392 l^{-1}), but the measured K_d320 differed considerably, the former lake having a relatively high

393 K_d320 (5.9 m^{-1}) leading to a 1% UV penetration depth of only 0.8 m, whereas the latter lake

394 had a relatively low K_d320 (1.2 m^{-1}), with a 1% UV penetrating to 3.8 m. These differences in

395 the solar attenuation were likely due to differences in CDOM composition. SUVA and a^*_{320}

396 indicated that DOC of Lake Vuobmegasvarri is more terrestrial compared to Lake

397 Somaslompolo (SUVA: 2.2 and 0.6 mg^{-1} m^{-1}, a^*_{320} 2.1 and 0.5 m^{-1}, respectively). Same

398 difference is seen in the ratio between S_{280} to S_{390}. HI was slightly lower and the relative

399 proportion of LMW fluorescence higher in Somaslompolo, reflecting a higher contribution of

400 autochthonous carbon. Both lakes are closed-basin lakes, but while the catchment area of

401 Vuobmegasvarri is mostly covered by various dwarf shrubs, grasses and sedges, the catchment

402 of Somaslompolo consists mostly of esker and rock. Somaslompolo is also much larger and

403 deeper, which means that all material entering the lake from the catchment is mixed into a larger

404 volume of water.

405 Similarly, Lake Vuobmegasvarri (BT) and Lake 613 (MBW) with relatively comparative

406 UV attenuation behavior (K_d320 5.9 and 6.3 m^{-1}, respectively), had very different DOC

407 concentrations (2.6 and 6.9 mg l^{-1}, respectively). Located in the barren tundra Lake

408 Vuobmegasvarri does not have a high DOC concentration per se but this carbon seems to be

409 dominated by terrestrial compounds as suggested by the relative high values of a440, a^*_{320}, and

410 SUVA. Lake Vuobmegasvarri is small and shallow and has the highest catchment to lake area

411 of the whole data set likely explaining the DOM composition efficient in solar absorbance.

412 The lack of correlation between DOC, DOM and light parameters is consistent with

413 earlier observations. When comparing different biomes, Jaffé *et al.* (2008) did not find a

414 correlation between DOC and any of their DOM quality parameters, and concluded that

415   variations in DOM quality were not necessarily associated with DOC concentration. The lack

416   of correlation is in some lakes also related to iron (Fe). Fe concentrations > 2mg l^{-1} are known

417   to have an effect on the UV absorbance of DOC (Weishaar *et al.,* 2003). Fe was not analysed

418   during this study, but previous work from the same area indicate low Fe concentrations (mean

419   0.14 mg l^{-1} for mountain birch woodland (n = 25) and 0.04 mg l^{-1} for barren tundra (n = 8))

420   (Korhola, Weckström & Blom, 2002) that should not influence UV absorbance.

421

422   *Phytoplankton as light attenuator*

423   Concentration of Chl-*a* was lower in our study lakes compared to other studies dealing

424   with water column optics of high-altitude or high-latitude lakes (Morris *et al.,* 1995;

425   Bukaveckas & Robbins-Forbes, 2000; Laurion *et al.*, 2000). Even with somewhat higher

426   chlorophyll concentrations, the role of Chl-*a* in light attenuation has proved to be low in some

427   comparable studies (Morris *et al.,* 1995; Bukaveckas & Robbins-Forbes, 2000), and no

428   correlation between K_dPAR and Chl-*a* was found in our study either. Chl-*a* explained only 39%

429   of light variability. Laurion *et al.* (2000) found a weak but significant correlation between

430   K_dPAR and Chl-*a* (but not between K_d320 and Chl-*a*) in lakes from the Alps and Pyrenees, but

431   those lakes had, in general, higher Chl-*a* concentrations than in our data (mean Chl-*a* 1.6 µg l^{-1}

432   vs. 0.7 µg l^{-1}, respectively). Our Chl-*a* samples were only taken from one depth (1 m), but

433   since most lakes were isothermal during the sampling, we consider this one sample to be

434   representative of the whole water column.

435   The weak but significant positive correlation between Chl-*a* and DOC (r = 0.16) and

436   phytoplankton biomass and DOC (r = 0.29) found in this study, likewise in lakes situated in the

437   Adirondack area, USA (Bukaveckas & Robbins-Forbes, 2000) may result from a reduction of

438   photoinhibition and an increase of nutrients associated with higher levels of DOC. The finding

439   is interesting in respect to current climate change scenarios. Taken in conjunction with some

440   whole-lake experiments (e.g., Carpenter *et al.,* 1998) these studies suggest that increasing DOC

441   concentrations expected at high-latitudes due to global warming and associated vegetation

442   shifts can lead to higher accumulation of algal biomass. However, other studies have not found

443   a similar relationship (Sommaruga *et al.,* 1999), and a simple measure of Chl-*a* does not give

444   any information on changes in species composition or productivity. Our study lakes had very

445   diverse and differing phytoplankton communities (L. Forsström, unpublished data), and it is

446   likely that they will react differently to possible changes. A mesocosm study conducted in the

447   same area showed a decrease of primary production, but an increase of the proportion of

448   mixotrophic algae when DOC was added (Forsström, Roiha & Rautio, 2013). Bukaveckas and

449   Robbins-Forbes (2000) concluded that DOC might be the major factor explaining the variation

450   of primary productivity in lakes that are remotely situated from human induced eutrophication,

451   but more studies are needed to assess the role of DOC for primary production in these areas.

452

453   *Current light climate and prospections for future*

454   Light penetrated deeply in the studied lakes. Attenuation of visible light varied in our data

455   set from the values previously reported for the clearest inland waters at high latitudes or high

456   altitudes ($K_d < 0.2$ m^{-1}) (Kirk, 1994; Morris *et al.,* 1995; Bukaveckas & Robbins-Forbes, 2000;

457   Laurion *et al.*, 2000) and for values reported for highly colored lakes located in boreal and

458   alpine regions ($K_d > 2.0$ m^{-1}) (Lindell, Gráneli & Tranvik, 1996; Ask *et al.*, 2009). The average

459   depth of 1% at 320 nm (2.4 m) is higher than the average calculated for sub-alpine lakes (1.9

460   m), but lower than the average for alpine lakes (8.1 m) (Rose *et al.,* 2009). The average

461   transparency ratio (12.8%) was close to the average calculated for sub-alpine lakes (12.6%),

462   but the ratio in Lake 1009 (50.9%) was close to the highest values reported in alpine lakes (Rose

463   *et al.*, 2009). In contrast to alpine lakes, our lakes are very shallow, and in several study lakes

464   the UV exposure compared to lake depth ($Z_{320\ nm\ 1\%}/Z_{max}$) was high enough (between 10-100%)

465   so that harmful effects to organisms are likely. A similar observation has also been reported for

466   some lakes in our study region in the studies by Rautio & Korhola (2002 a; b). In 12 of 18 lakes

467   > 1% of PAR reached the bottom having an important consequence for the total primary

468   productivity of these systems; in many transparent, oligotrophic northern lakes >50% of the

469   total system (pelagic plus benthic) primary production is confined to the bottom (Björk-

470   Ramberg & Ånell 1985, Rautio *et al.*, 2011).

471   Thawing permafrost and transformations of mires and wetlands that are consequences of

472   warming temperatures (IPCC 2013) have an important influence for the solar attenuation. Also

473   the more subtle changes in catchment characteristics related to changes in vegetation cover will

474   modify DOM in the receiving water bodies. Our data show a strong K_d UVB response to small

475   changes in CDOM and suggest that even minor shifts in CDOM quality may largely change the

476   UV radiation exposure of transparent high latitude lakes with likely consequences on biota.

477   Similar responses will occur for K_d PAR, however, the changes may not be large enough to

478   cause major shifts in the relative importance of pelagic and benthic primary production in the

479   studied lakes that are currently illuminated to the bottom due to the combination of shallow

480   lake depth and low CDOM concentration and color.

481

489

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676   of CDOM fluorescence to differentiate the sources and fate of DOM in Lake Taihu and its
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678

679

680 Table I. Catchment and morphological parameters, temperature, water chemistry and algal parameters of the study lakes. Altitude above sea level (Alt a.s.l.; m),

681 maximum lake depth (Max depth; m), lake area (ha), catchment area (Catch area; ha), catchment to lake area (C to L area), catchment slope (C slope; mean %),

682 temperature (T; °C), pH, alkalinity (Alk; mmol l^{-1}), conductivity (Cond; mS m^{-1}), ammonium (NH$_4$; µg l^{-1}), nitrate and nitrite (NO$_{3+2}$; µg l^{-1}), phosphate (PO$_4$;

683 µg l^{-1}), total nitrogen (TN, µg l^{-1}), total phosphorus (TP; µg l^{-1}), silica (SiO$_2$; µg l^{-1}), turbidity (Turb; FNU), chlorophyll-a (Chl; µg l^{-1}) and phytoplankton biomass

684 (Phyto biom; mg l^{-1}).

685

Lake (code)	Alt a.s.l.	Max depth	Lake area	Catch area	C to L area	C slope	T	pH	Alk	Cond	NH$_4$	NO$_{3+2}$	PO$_4$	TN	TP	SiO$_2$	Turb	Chl	Phyto biom
Mountain birch woodland (MBW)																			
Kilpisjärvi (NF000K)	473	57	3710	27100	7	8	11.9	7.2	0.172	2.6	6.0	14.0	<2	100	6	1.2	0.2	0.61	0.11
Kilpisjärvi 30 m							8.7	7.7	0.165	2.6	12.0	26.0	<2	140	5	1.3	0.2	0.13	0.04
Korsajärvi (NF0356)	528	2	20	212	11	2.9	7.1	6.9	0.102	1.3	7.0	<2	<2	320	13	3.0	0.9	2.38	0.42
Ristijärvi (NF0354)	571	2	11	32	3	2.2	7.2	5.6	0.017	0.4	<5	<2	<2	220	7	0.4	0.5	0.67	0.41
Koddojavri (NF0344)	571	2	5	56	11	2.7	7.3	5.3	0.021	0.9	7.0	4.0	<2	410	11	2.7	0.7	1.08	0.17
Shrub tundra (ST)																			
Mallalampi (NF000M)	602	4	1	42	42	6.7	9.7	7.4	0.186	2.5	<5	3.0	<2	96	4	4.4	0.2	0.34	0.08
Lake 613 (NF0026)	613	5	15	396	26	7.5	10.2	7.2	0.107	1.6	<5	<2	2.0	120	11	3.2	0.3	0.57	0.06
Saanajärvi (NF0009)	679	24	70	525	8	13.1	11.7	6.8	0.181	3.2	<5	<2	<2	110	5	1.1	0.2	0.75	0.07
Saanajärvi 16 m							7.1	7.0	0.181	3.4	8.0	17.0	<2	120	5	1.2	0.2	0.71	0.07
Masehjavri (NF0016)	680	11	17	158	10	4.4	8.8	7.3	0.132	1.6	<5	<2	<2	140	6	2.4	0.3	0.45	0.11
Peeralampi (NF0076)	696	7	25	414	17	6.5	10.3	7.2	0.128	2.0	<5	<2	<2	130	7	3.5	0.4	0.96	0.17
Toskaljärvi (NF0202)	704	22	100	1338	13	9.1	8.5	7.8	0.392	4.3	<5	4.0	<2	74	7	1.5	0.3	0.36	0.14
Somaslompolo	760	10	16	163	10	7.2	7.7	7.4	0.172	3.1	5.0	4.0	<2	85	8	2.2	0.4	0.87	0.18

(NF0223)

Kohpejavri (NF0108)	774	4	21	220	11	7.0	6.5	7.3	0.099	1.5	<5	<2	<2	120	5	2.8	0.3	0.28	0.16
Mallajärvi (NF0002)	776	13	17	118	7	10.3	10.6	6.7	0.050	0.7	<5	3.0	<2	81	6	1.5	0.3	0.71	0.06
Mallajärvi 8 m							10.2	6.8	0.047	3.5	<5	4.0	<2	79	5	1.5	0.3	0.69	0.14
Porevarri (NF0261)	794	6	11	166	15	4.4	7.2	7.4	0.213	3.6	<5	<2	<2	110	9	2.9	0.5	0.86	0.31
Barren tundra (BT)																			
Kuorroladdu (NF0221)	900	9	6	45	10	5	5.9	7.3	0.106	2.6	<5	2.0	<2	71	7	0.9	0.3	0.44	0.09
Vuobmegasvarri (NF0099)	900	4	1	39	32	10.6	7.5	6.9	0.108	1.5	6.0	<2	<2	120	6	2.5	0.5	0.44	0.11
Lake 1009 (NF0033)	1009	12	10	98	10	6.5	8.8	5.8	0.011	0.4	<5	4.5	<2	72	4	2.5	0.1	0.16	0.03
Stuorralampi (NF000S)	1024	2	1	4	4	2	6.7	6.8	0.057	1.9	<5	4.0	<2	85	3	1.0	0.3	0.21	0.04

686

687 Table II. DOC and DOM characteristics of the study lakes. Dissolved organic carbon (DOC; mg l^{-1}), absorption coefficient of dissolved organic matter at 440
688 nm (a_{440}; m^{-1}), absorption coefficient at 320 nm (a_{320}; m^{-1}), a_{320} divided by the DOC concentration (a^*_{320}; mg^{-1} m^{-1}), UV absorbance at 254 nm measured in
689 inverse meters divided by the DOC concentration (SUVA, mg^{-1} m^{-1}), spectral slope for light absorption by DOM calculated on wavebands 300-650 nm, 275-
690 295 nm and 350-400 nm (S; nm^{-1}), ratio of $S_{275-295}$ to $S_{350-400}$ (S_R), spectral slope at 280 and 390 nm (S280, S390), percentage of the integrated area of low
691 (%LMW), medium (%MMW) and high (%HMW) molecular weight compounds from total integrated area under the synchronous fluorescence spectrum, ratio
692 of fluorescence integrated over the waveband 280-323 nm (Lλ/Hλ) and 433-595 nm (Mλ/Hλ) to that over the waveband 433-595 nm and humification index
693 (HI). Nd = no data.

Lake (code)	DOC	a_{440}	a_{320}	a^*_{320}	SUVA	$S_{300-650}$	$S_{275-295}$	$S_{350-400}$	S_R	S280	S390	%LMW	%MMW	%HMW	Lλ/Hλ	Mλ/Hλ
Mountain birch woodland (MBW)																
Kilpisjärvi (NF000K)	2.7	0.5	3.3	1.2	1.55	0.0166	0.0186	0.0127	1.5	0.0175	0.0169	24.0	48.5	27.5	0.9	1.8
Kilpisjärvi 30 m	2.2	0.5	3.1	1.4	1.82	0.0165	0.0187	0.0125	1.5	0.0186	0.0169	14.9	45.4	39.7	0.4	1.1
Korsajärvi (NF0356)	13.8	4.8	34.3	2.5	2.46	0.0156	0.0142	0.0167	0.9	0.0140	0.0172	18.7	43.0	38.3	0.5	1.1
Ristijärvi (NF0354)	6.1	0.9	6.6	1.1	1.25	0.0163	0.0173	0.0155	1.1	0.0169	0.0169	23.6	39.1	37.3	0.6	1.0
Koddojavri (NF0344)	16.2	9.4	61.0	3.8	6.16	0.0150	nd	0.0164	2.2	0.0180	0.0167	nd	nd	nd	nd	nd
Shrub tundra (ST)																
Mallalampi (NF000M)	2.8	0.6	4.1	1.5	0.94	0.0159	0.0173	0.0133	1.3	0.0166	0.0168	18.6	42.3	39.2	0.5	1.1
Lake 613 (NF0026)	6.9	0.8	5.7	0.8	0.98	0.0160	0.0174	0.0150	1.2	0.0166	0.0176	16.5	44.8	38.7	0.4	1.2
Saanajärvi (NF0009)	3.3	0.6	3.6	1.1	1.42	0.0164	0.0186	0.0140	1.3	0.0176	0.0166	19.9	44.7	35.4	0.6	1.3
Saanajärvi 16 m	3.0	0.5	3.6	1.2	1.49	0.0161	0.0179	0.0128	1.4	0.0173	0.0168	15.3	52.3	32.4	0.5	1.6
Masehjavri (NF0016)	4.0	1.1	7.7	1.9	2.18	0.0159	0.0167	0.0152	1.1	0.0162	0.0171	15.5	45.6	38.9	0.4	1.2
Peeralampi (NF0076)	3.6	1.0	6.6	1.9	2.08	0.0156	0.0161	0.0145	1.1	0.0155	0.0166	14.4	48.8	36.8	0.4	1.3
Toskaljärvi	1.5	0.3	1.8	1.2	1.47	0.0152	0.0176	0.0085	2.1	0.0168	0.0155	23.0	39.2	37.8	0.6	1.0

(NF0202)																
Somaslompolo (NF0223)	2.5	0.3	1.0	0.4	0.56	0.0087	0.0190	0.0047	4.0	0.0179	0.0100	24.2	39.4	36.4	0.7	1.1
Kohpejavri (NF0108)	3.3	0.7	4.3	1.3	1.54	0.0156	0.0175	0.0142	1.2	0.0168	0.0163	18.5	45.1	36.4	0.5	1.2
Mallajärvi (NF0002)	2.4	0.3	1.9	0.8	0.94	0.0150	0.0170	0.0107	1.6	0.0167	0.0149	18.3	41.5	40.2	0.5	1.0
Mallajärvi 8 m	2.4	0.3	1.8	0.8	0.89	0.0154	0.0171	0.0107	1.6	0.0170	0.0155	13.2	41.4	45.5	0.3	0.9
Porevarri (NF0261)	2.7	0.6	3.4	1.3	1.51	0.0156	0.0167	0.0135	1.2	0.1063	0.0161	22.4	41.1	36.6	0.6	1.1
Barren tundra (BT)																
Kuorroladdu (NF0221)	1.9	0.2	nd	nd	0.43	nd	nd	nd	nd	0.0141	0.0155	25.0	51.0	23.9	1.0	2.1
Vuobmegasvarri (NF0099)	2.6	0.8	5.1	2.0	2.24	0.0155	0.0159	0.0148	1.1	0.0156	0.0166	20.5	41.8	37.7	0.5	1.1
Lake 1009 (NF0033)	1.6	0.1	nd	nd	0.26	nd	nd	nd	nd	0.0255	nd	13.6	36.6	49.8	0.3	0.7
Stuorralampi (NF000S)	2.2	0.3	1.6	0.7	0.86	0.0140	0.0173	0.0087	2.0	0.0168	0.0137	22.0	37.1	40.9	0.5	0.9

694

695 Table III. PAR and UV characteristics in the lakes. K_d vertical attenuation coefficient for downward photosynthetically active radiation (K_d PAR; m^{-1}) and at

696 320 nm (K_d 320; m^{-1}), attenuation depth of UV expressed as a proportion of lake maximum depth ($Z_{320\ 1\%}/Z_{max}$, %), 1% PAR depth, 1% UVB depth and 1%

697 depth of 320 nm UV relative to the 1% depth of PAR (Transparency ratio)

Lake (code)	K_d PAR	K_d 320	$Z_{320\ 1\%}/Z$ max	1% PAR depth	1% UVB depth	Transparency ratio
Mountain birch woodland (MBW)						
Kilpisjärvi (NF000K)	0.2	3.1	3	19.1	1.5	7.7
Korsajärvi (NF0356)	2.6	41.0	5	1.8	0.1	6.2
Ristijärvi (NF0354)	0.7	7.3	25	Bottom	0.6	10.0
Koddojavri (NF0344)	2.4	70.4	5	1.9	0.1	3.5
Shrub tundra (ST)						
Mallalampi (NF000M)	0.5	3.7	20	Bottom	1.2	12.6
Lake 613 (NF0026)	0.6	6.3	10	Bottom	0.7	9.6
Saanajärvi (NF0009)	0.3	4.1	4	16.4	1.1	6.9
Masehjavri (NF0016)	0.5	7.1	4	10.2	0.6	6.3
Peeralampi (NF0076)	0.5	7.7	7	Bottom	0.6	6.5
Toskaljärvi (NF0202)	0.3	2.2	8	16.4	2.1	12.8
Somaslompolo (NF0223)	0.2	1.2	30	Bottom	3.8	17.2
Kohpejavri (NF0108)	0.6	5.1	20	Bottom	0.9	10.7
Mallajärvi (NF0002)	0.3	1.8	13	Bottom	2.6	13.9
Mallajärvi 8 m						

Porevarri (NF0261)	0.4	3.6	17	Bottom	1.3	9.9
Barren tundra (BT)						
Kuorroladdu (NF0221)	0.1	0.6	56	Bottom	7.8	15.2
Vuobmegasvarri (NF0099)	0.6	5.9	15	Bottom	0.8	9.3
Lake 1009 (NF0033)	0.2	0.3	100	Bottom	Bottom	50.9
Stuorralampi (NF000S)	0.4	2.1	100	Bottom	Bottom	20.7

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700

701 Table IV. Combination of environmental variables, taken *k* at the time, giving the largest rank correlation p_s,

702 between environmental and light parameter similarity matrices. Bold indicates best combination overall.

703 a440: absorbance at 440 nm, S280: spectral slope at 280 nm, DOC: dissolved organic carbon, SUVA: UV

704 absorbance at 254 nm measured in inverse meters divided by the DOC concentration, S390: spectral slope at

705 390 nm HI: humification index, and chl: chlorophyll-a.

706

k	Best variable combinations (p_s)						
1	a440	S280	DOC	SUVA	S390	HI	Chl
	(0.73)	(0.54)	(0.49)	(0.49)	(0.46)	(0.39)	(0.39)
2	**a440, S390**						
	(0.87)						
3	a440, S390, S280						
	(0.81)						
4	DOC, a440, S390, S280						
	(0.79)						
5	DOC, SUVA, HI, a440, S390						
	(0.80)						

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709 **Figure captions**

710 Figure 1. Map of the area showing the study sites and vegetational zones. Lakes located in the barren

711 tundra are marked with black dots, lakes in shrub tundra with white dots and lakes in mountain birch

712 woodland with grey dots.

713

714 Fig. 2. Segmented bubble plot PCA ordinations for a) catchment and morphological parameters, b)

715 phytoplankton, c) CDOM characteristics and d) UV and PAR attenuation. Segment sizes are

716 proportional to the values of catchment slope (C slope), catchment to lake ratio (C to L), chl-a

717 concentration (chl-a), phytoplankton biomass (Biomass), absorption coefficient at 440 nm (a440),

718 spectral slope at 280 nm (S280), diffuse attenuation coefficient for UV-B (Kd$_{320}$) and transparency

719 ratio (T ratio) in different lakes. The numbers indicate vegetation zones. 1: mountain birch

720 woodland (MBW), 2: shrub tundra (ST) and 3: barren tundra (BT).

721

722 Figure 3. a) Spectral slope curves for absorption measurements and b) synchronous fluorescence

723 spectroscopy scans of CDOM of lakes from barren tundra (Mallajärvi), shrub tundra (Lake 613) and

724 mountain birch woodland (Korsajärvi). Spectral slopes are also shown for DOM from a bog and a

725 *Scenedesmus* sp. phytoplankton culture to indicate differences between allochthonous and

726 autochthonous carbon sources. Breaks in lines are for values that did not meet the regression

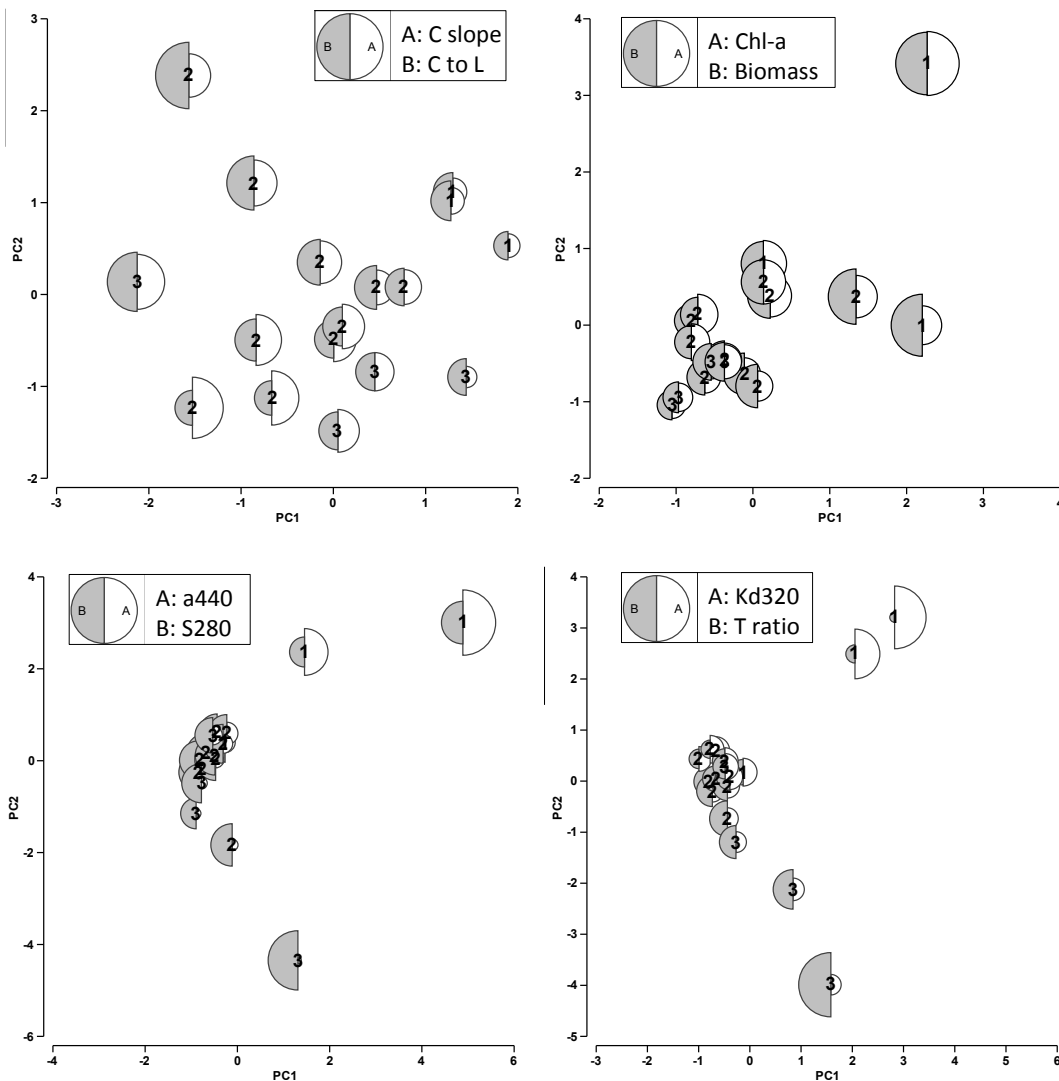727 coefficient requirement r2 > 0.95 (see methods for explanation).

728

729 Figure 4. Relationship between absorption coefficient at 440 nm (a440) and different light

730 parameters: diffuse attenuation coefficient for UV-B (Kd$_{320}$) and PAR (Kd$_{PAR}$), and for the

731 transparency ratio

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Fig. 2. Segmented bubble plot PCA ordinations for a) catchment and morphological parameters, b) phytoplankton, c) CDOM characteristics and d) UV and PAR attenuation. Segment sizes are proportional to the values of catchment slope (C slope), catchment to lake ratio (C to L), chl-a concentration (chl-a), phytoplankton biomass (Biomass), absorption coefficient at 440 nm (a440), spectral slope at 280 nm (S280), diffuse attenuation coefficient for UV-B (Kd_{320}) and transparency ratio (T ratio) in different lakes. The numbers indicate vegetation zones. 1: mountain birch woodland (MBW), 2: shrub tundra (ST) and 3: barren tundra (BT).

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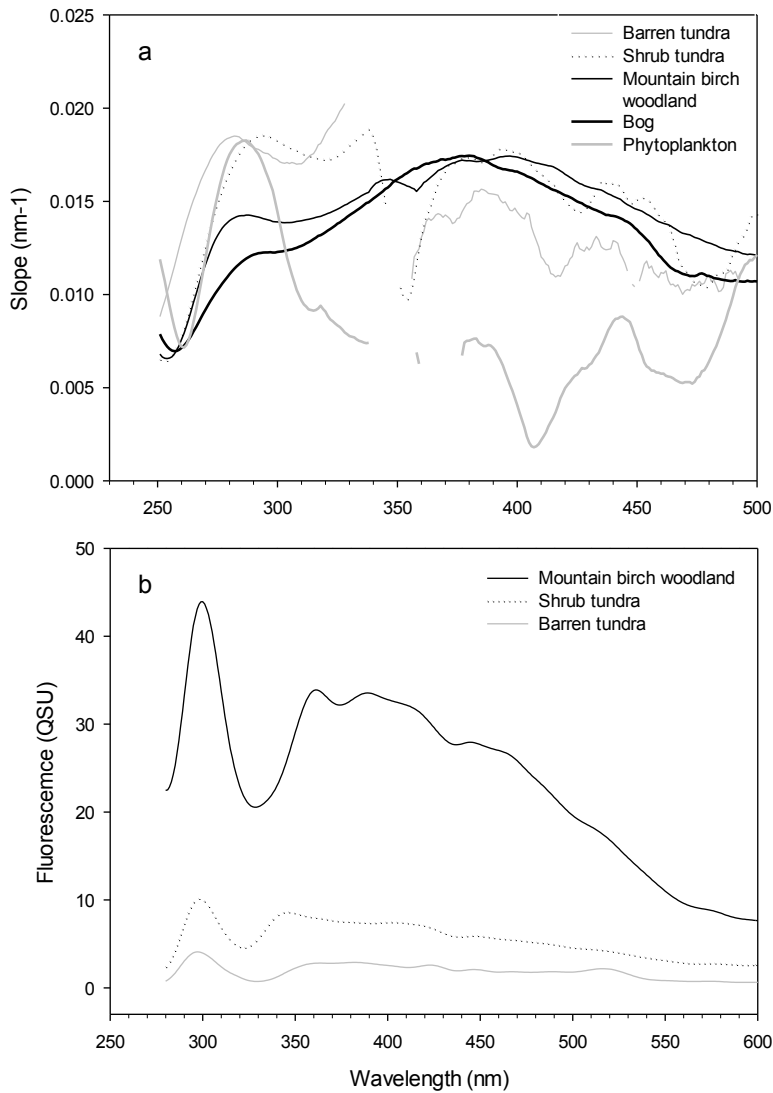
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Fig. 3. a) Spectral slope curves for absorption measurements and b) synchronous fluorescence
spectroscopy scans of CDOM of lakes from barren tundra (Mallajärvi), shrub tundra (Lake 613)
and mountain birch woodland (Korsajärvi). Spectral slopes are also shown for DOM from a bog
and a *Scenedesmus* sp. phytoplankton culture to indicate differences between allochthonous and
autochthonous carbon sources. Breaks in lines are for values that did not meet the regression
coefficient requirement r2 > 0.95 (see methods for explanation).

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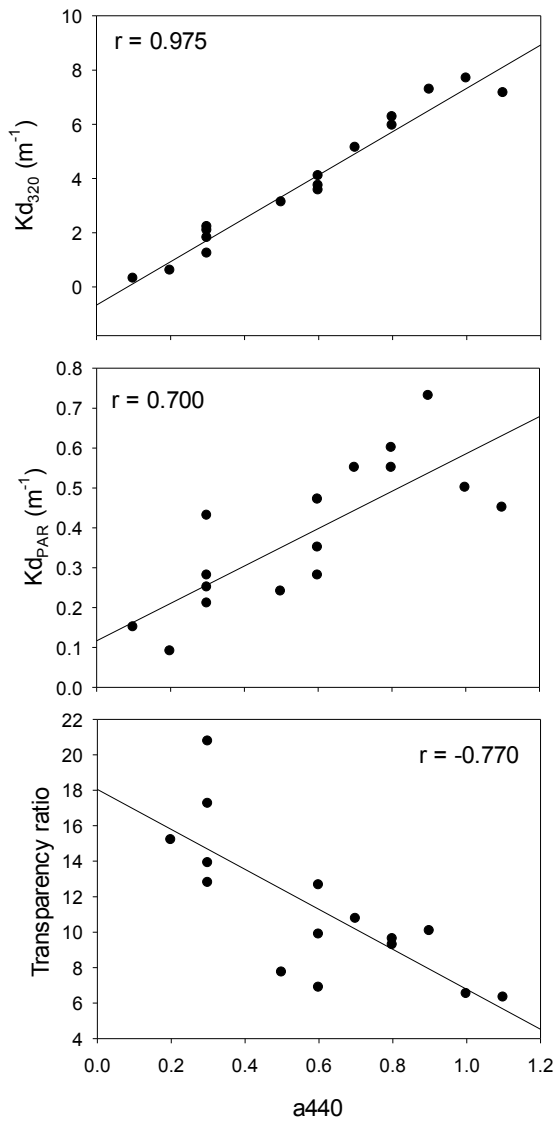
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764   Fig. 4. Relationship between absorption coefficient at 440 nm (a440) and different light parameters:

765   diffuse attenuation coefficient for UV-B (Kd_{320}) and PAR (Kd_{PAR}), and the transparency ratio

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