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1 **Increasing temperature and productivity change biomass, trophic pyramids and community level**
2 **omega-3 fatty acid content in subarctic lake food webs**

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7 Running head: Climate & land-use effects on subarctic lakes

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22 Key words: food web structure, trophic pyramid, trophic level, nutrients, DOC, forestry, land-use, omega-3
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24 Abstract

25 Climate change in the Arctic is outpacing the global average while land-use is intensifying due to exploitation of
26 previously inaccessible or unprofitable natural resources. A comprehensive understanding of how the joint effects
27 of changing climate and productivity modify lake food web structure, biomass, trophic pyramid shape and
28 abundance of physiologically essential biomolecules (omega-3 fatty acids) in the biotic community is lacking.
29 We conducted a space-for-time study in 20 subarctic lakes spanning a climatic (+3.2°C and precipitation: +30%)
30 and chemical (dissolved organic carbon: +10mg L⁻¹, total phosphorus: +45µg L⁻¹ and total nitrogen: +1000µg
31 L⁻¹) gradient to test how temperature and productivity jointly affect the structure, biomass and community fatty
32 acid content (eicosapentaenoic acid [EPA] and docosahexaenoic acid [DHA]) of whole food webs. Increasing
33 temperature and productivity shifted lake communities towards dominance of warmer, murky-water adapted taxa,
34 with a general increase in the biomass of primary producers, and secondary and tertiary consumers, while primary
35 invertebrate consumers did not show equally clear trends. This process altered various trophic pyramid structures
36 toward an hour glass shape in the warmest and most productive lakes. Increasing temperature and productivity
37 had negative fatty acid content trends (mg EPA+DHA g⁻¹ dry weight) in primary producers and primary
38 consumers, but not in secondary and tertiary fish consumers. The massive biomass increment of fish led to
39 increasing areal fatty acid content (kg EPA+DHA ha⁻¹) towards increasingly warmer, more productive lakes, but
40 there were no significant trends in other trophic levels. Increasing temperature and productivity are shifting
41 subarctic lake communities towards systems characterised by increasing dominance of cyanobacteria and
42 cyprinid fish, although decreasing quality in terms of EPA+DHA content was observed only in phytoplankton,
43 zooplankton and profundal benthos.

44

45 1. Introduction

46 Temperature has increased much faster in Arctic regions than the global average, and rate of warming is expected
47 to further accelerate in the future (Cohen et al. 2014). In subarctic Fennoscandia, mean annual air temperature
48 has increased circa 2 °C since 1850 and temperature and precipitation are further predicted to change by +2–5 °C
49 and +10–30%, respectively, by the end of the 21st century (IPCC 2015: RCP2.6–RCP8.5). Furthermore,
50 precipitation in the region is more likely to fall as rain rather than snow (e.g. Dai and Song 2020). Such climatic
51 shifts will expand catchment vegetation towards higher altitudes and latitudes, promoting overall greening and

52 facilitating changing land-use practices. In particular, forestry and agriculture are likely to replace traditional
53 livelihoods such as reindeer herding, subsistence hunting and fishing (Schindler and Smol 2006; Huntington et
54 al. 2007). Expanding transport networks, settlements, oil drilling and mining activities are rapidly changing the
55 hydrology and productivity of freshwaters (Cott et al. 2015; Denisov et al. 2020; Zubova et al. 2020). Joint effects
56 of changes in climate and land-use in catchment area causes increased leaching of terrestrial dissolved organic
57 carbon, nitrogen and phosphorous, with serious impacts on freshwater species richness, community structure and
58 food web processes (Jeppesen et al. 2012, Nieminen et al. 2015, Hayden et al. 2019, Laske et al. 2019).

59 Globally, species richness tends to show a decreasing trend from the tropics towards the poles, with this linked
60 to a gradient of decreasing temperature and productivity (for overview see e.g. Gaston 2000, Hillebrand 2004).
61 The latitudinal gradient in species richness may be linked to multi-trophic level diversity and food chain length
62 due to common underlying drivers of ecosystem size and productivity (Gaston 2000, Takimoto and Post 2013,
63 Baiser et al. 2019). Productivity and ecosystem size are inherently linked, for example large lakes tend to be less
64 productive but provide broader feeding or breeding areas for diverse communities, with subsequent effects on
65 food chain length (Post et al. 2000; Takimoto et al. 2012, Ward and McCann 2017). Food chain length determines
66 the number of trophic levels and thus largely governs the strength of top-down and bottom-up processes. In
67 systems with three or more trophic levels, primary production is suggested to be resource limited (bottom-up
68 regulation), primary consumers top down regulated and secondary consumers resource limited (Hairston et al.
69 1960, Oksanen et al. 1981, Hansson et al. 2013). Together with bottom-up regulation, top-down predator
70 mediated community-level trophic cascades have been suggested as a factor shaping food web structure driving
71 opposing trends in the biomass of sequential trophic level (i.e. each second trophic level biomass is high; Paine
72 1980, Carpenter et al. 1985, 2001). These processes govern the shape of trophic (Eltonian) pyramids, which may
73 show different forms from a classic pyramidal shape where energetic loss in each trophic level leads to
74 accumulation of max. circa 10% of produced biomass to next trophic level, and in certain cases may even show
75 inverted pyramids (Elton 1927, Brown et al. 2004, McCauley et al. 2018). Simple food webs in low diversity and
76 productivity ecosystems may be prone to size-structured populations, trophic cascades and inverted trophic
77 pyramids, but generally there is very little clear evidence of how food web biomass and trophic pyramid shape
78 are influenced by temperature and productivity gradients.

79 Subarctic regions provide an excellent natural setting to study this phenomenon as they straddle boreal and Arctic
80 biomes, providing clear diversity, climatic and productivity gradients with relatively simple food webs (Hayden

81 et al., 2017). Furthermore, the subarctic landscape is scattered with lakes that provide abundant and well defined
82 ecosystems for food web diversity studies (Lau et al. 2020). Increasing temperature and productivity has been
83 shown to shift subarctic lake communities towards more numerous, diverse, smaller-bodied, warmer-water
84 adapted taxa which are more reliant on pelagic energy sources (Hayden et al. 2017, Hayden et al. 2019). However,
85 we do not know how increasing temperature and productivity affects energy transfer efficiency and thus biomass
86 distribution across different trophic levels. Aquatic food webs in many Arctic areas are based on production and
87 transfer of lipids from primary producers to top consumers, where seasonal storage of lipids is important for
88 survival and reproduction of long lived organisms at higher trophic levels (e.g. Jørgensen et al. 1997, Armstrong
89 and Bond 2013). An important subgroup of lipids are polyunsaturated fatty acids (PUFAs), providing essential
90 components for cell development and functioning, however the distribution of lipids and fatty acids varies
91 greatly among taxa and trophic levels. While there are several PUFAs, eicosapentaenoic acid (20:5n-3, EPA)
92 and docosahexaenoic acid (22:6n-3, DHA) are considered the most important since they are essential for growth,
93 neural development and reproduction of consumers (Arts et al, 2001, Bou et al. 2017, Yeşilayer and Kaymak
94 2020). Only certain algae groups, such as dinoflagellates, diatoms and cryptophytes, are able to produce EPA
95 and DHA efficiently and are abundant in cold and nutrient poor lakes (Taipale et al. 2013, 2016). However, warm
96 and eutrophic lake primary producer communities, often dominated with cyanobacteria, are inefficient in EPA
97 and DHA production (Müller-Navarra et al. 2000, 2004, Taipale et al. 2013, 2016). Some species can convert
98 shorter chain fatty acids to EPA and DHA (Geya et al. 2016, Ishikawa et al. 2019), but in many vertebrates this
99 process is considered energetically expensive and thus direct sources from high quality prey are often selected
100 (Twining et al. 2016, Keva et al. 2019). This suggest that at a food web level, differences in primary producer
101 communities induced by temperature and productivity may govern the quality of higher trophic levels (Hixson
102 and Arts 2016, Colombo et al. 2020).

103 Our main aim in this study was to test how increasing temperature and productivity change structure, biomass
104 and nutritional quality of food web components from primary producers to top consumers using a gradient of
105 Fennoscandian subarctic lakes (n=20) spanning a climate and land-use gradient. Omega-3 fatty acids, EPA and
106 DHA, were selected as proxies for quality of food web components, since they are physiologically important
107 biomolecules for consumers. First, we hypothesized (H1) that communities shift towards warmer and more
108 murky-water adapted species, with a concurrent increase in food web biomass, and expected that increases in
109 algae and fish biomass along the gradient would have effects on trophic pyramid shape (Jeppesen et al. 2010,

110 Hayden et al. 2017, McCauley et al. 2018). Secondly, we hypothesised (H2) that cyanobacteria form an increasing
111 proportion of the phytoplankton communities in warmer and more productive lakes (Przytulska et al. 2017), thus
112 lowering nutritional quality of primary producers. As such, we expected that this difference would be passed
113 through all higher trophic levels (Müller-Navarra et al. 2000, Taipale et al. 2016). Finally, we hypothesized (H3)
114 that increasing temperature and productivity would increase total community biomass including an increase in
115 physiologically important EPA and DHA of the total lake community (Jeppesen et al. 2000, Hayden et al. 2019).

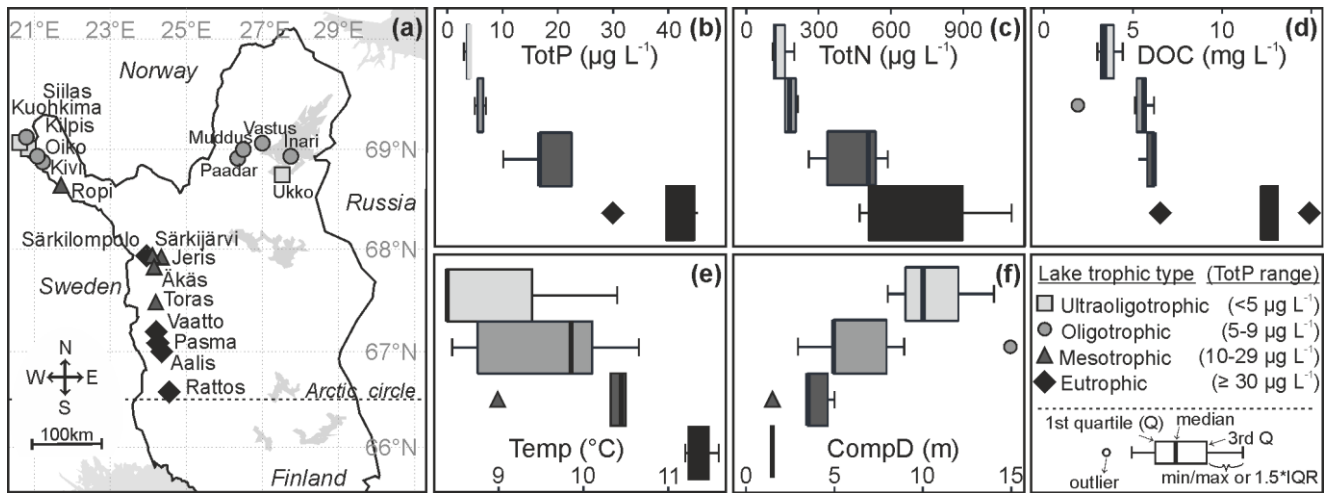
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117 2. Materials and Methods

118 2.1 Environmental variables

119 We sampled 20 lakes, located in Finnish Lapland across the Tornio-Muoniojoki and Paatsjoki watercourses,
120 spanning northern European climatic (average air temperature in June–September from 1980–2010: 8.4–11.6°C
121 and precipitation 197–257 mm a⁻¹) and water chemistry (dissolved organic carbon; DOC: 1.9–14.9 mg L⁻¹, total
122 phosphorus; TotP: 3–48 µg L⁻¹ and total nitrogen; TotN: 110–1100 µg L⁻¹) gradients (Table S1, Fig. 1). Here,
123 all lakes are considered subarctic and located north of Arctic Circle (AMAP 1998). Climatic differences originate
124 from latitudinal and altitudinal gradients, with temperature and precipitation lowest in northernmost lakes and
125 progressively increasing towards the south. Climatic data were derived from nine Finnish Meteorological
126 Institute weather stations situated within the study region and refer to long-term (1981–2010) average open-water
127 season June–September air temperature and annual precipitation as rain (Hayden et al. 2019). Differences in lake
128 productivity originate predominantly from variation in vegetation and land-use practices within the catchment
129 (Jussila et al. 2014). The northernmost lakes are situated near pristine areas with anthropogenic impacts limited
130 to nature tourism and reindeer herding, and from the timberline southwards industrial forestry activities including
131 large-scale clear-cut areas, site preparation and intensive ditching (Jussila et al. 2014; Hayden et al. 2017; Ahonen
132 et al., 2018, Table S1). Catchment area characteristics and land-use variables were derived with the Finnish
133 Environment Institute VALUE-tool combining catchment and CORINE-database and open map data (Hayden et
134 al. 2017; Ahonen et al. 2018). Lake location (coordinates, altitude), morphometrical data (area, depth, mean
135 depth, volume) and water physical-chemistry (nutrients, light) were derived from the Finnish Environment
136 Institute (HERTTA-database) and National Survey of Finland, or from our own sampling (Table S1). We
137 measured visible light in the water column (LI-COR, A-250, visible light 400–700 nm) at deepest point of lake

138 or sampling area (largest lakes) to define 1% surface light level i.e. compensation depth needed to define
 139 proportions of the three major lake habitats littoral, profundal and pelagic (Table S1). Lake trophic states were
 140 categorized with TotP concentrations to ultraoligotrophic ($< 5 \mu\text{g L}^{-1}$, $n=3$), oligotrophic ($5\text{--}9 \mu\text{g L}^{-1}$, $n=7$),
 141 mesotrophic ($10\text{--}29 \mu\text{g L}^{-1}$, $n=5$) and eutrophic ($\geq 30 \mu\text{g L}^{-1}$, $n=5$) (Fig. 1; Nürnberg 1996). Phytoplankton,
 142 pelagic zooplankton, littoral and profundal benthic macroinvertebrates (here after benthos) and fish were sampled
 143 in the years 2009-2017. The sampling period was always in late summer (August–September).



144
 145 Fig. 1. Map of the study region (a) in northern Fennoscandia and boxplot figures of the basic lake chemistry (b–d) and
 146 physics (e–f) of the sampled lakes. The study lakes are marked with grey shade shapes (a) or boxes (b–f) indicating different
 147 lake types (light grey = ultraoligotrophic, grey = oligotrophic, dark grey = mesotrophic, black = eutrophic). Abbreviations
 148 in x-axes labels are named as following: TotP=total phosphorous (B), TotN = total nitrogen (c), DOC = dissolved organic
 149 carbon (d), Temp = average air temperature in June–September 1981–2010 (e), CompD = compensation depth i.e. water
 150 depth where 1% surface light is left (f).

151 2.2 Community composition and biomass

152 Quantitative phytoplankton taxa samples for eight of the study lakes were extracted from the HERTTA database
 153 (Finnish Environment Institute) and from a previous study for an additional six lakes (Taipale et al. 2016).
 154 Samples were collected from the epilimnion (0–2 m) with a Limnos or corresponding water sampler in late
 155 summer (August–September) and stored in Lugol solution with added formaldehyde. Phytoplankton cell counts
 156 were calculated under a microscope using the Utermöhl technique (Utermöhl 1958). Biomass estimations were
 157 done using taxa morphology specific geometric formulas (Hillebrand et al. 1999) and adjusted with
 158 experimentally derived carbon-mass ratios (Menden-Deuer and Lessard 2000). Phytoplankton community

159 composition was calculated as class specific percentage from carbon biovolume (g C L^{-1}), and dry mass [dw] per
160 unit area was calculated as well (kg dw ha^{-1} , hereinafter biomass) using lake specific euphotic zone.

161 Quantitative pelagic zooplankton samples were collected with a net (diameter 25 cm, mesh size 50 μm) using
162 three replicate vertical hauls from the deepest point of each lake (or, in very large lakes, the deepest point of the
163 sampling area) and immediately stored in a 5% formaldehyde solution (Hayden et al. 2017). We collected pelagic
164 zooplankton for fatty acid analyses from the same point using repeated vertical hauls and these samples were
165 condensed, frozen and freeze-dried in the laboratory. In quantitative samples, all crustaceans were identified to
166 class level, and the body size of 30 first encountered individuals of each class were measured for density and
167 biomass calculations. Biomass was calculated from identified individuals and length measured taxa using size-
168 biomass (length to dry weight) conversion factors from McCauley (1984). The overall zooplankton community
169 composition was calculated as taxon specific percentage from dry mass biovolume (mg dw L^{-1}) and biomass was
170 calculated (kg dw ha^{-1}) using lake specific average depth.

171 Benthic macroinvertebrates were collected only from soft bottom with an Ekman grab (area 272 cm^2) from a
172 transect (depths 1, 2, 3, 5, 10, 15, 20, 30, 40 m) spanning from the littoral zone to the deepest point of lake or
173 sampling area. Three separate replicates were taken from each depth and animals were stored in plastic buckets
174 with lake water followed by sorting in laboratory. Animals were identified to lowest feasible level, sorted,
175 counted and total wet biomass of each taxa were weighed (accuracy 0.1 mg) and areal biomass (g ww m^{-2}) was
176 calculated for each sample using Ekman area to m^2 conversion factor 36.8. For the lake specific biomass
177 calculations, we transformed wet weights to dry weights by using a conversion factor of 0.2 for all taxa (Smit et
178 al. 1993). For each lake, we used water column light level to define compensation depth to define which sampling
179 depths belong to littoral ($\geq 1\%$ light) or profundal ($< 1\%$ light). Then whole lake bathymetry was used to calculate
180 mean benthic macroinvertebrate biomass (kg dw ha^{-1}) in soft sediments in littoral and profundal regions.

181 Fish were sampled from three major lake habitats (littoral, profundal and pelagic) using a gill net series
182 composing of eight 30 m long and 1.8 m high nets (mesh sizes 12–60 mm knot to knot) and one Nordic net with
183 dimensions of 30 \times 1.5 m (12 mesh sizes 5–55 mm). A minimum of three gill netting nights per major habitat was
184 conducted and sampling amount was increased proportional to lake area (Malinen et al. 2014; Hayden et al.
185 2017). Fishing depth of gill nets were verified with echosounder and each fishing period length was recorded
186 with accuracy of a minute. In most cases, gill nets were set overnight in the evening and collected during

187 following morning (6–10 hours soaking time), but in the most eutrophic lakes we had to use shorter sampling
188 time (<2 hours) to avoid oversaturation due to a massive increase in fish density in these lakes (Hayden et al.
189 2017). Fish were immediately killed during net lifting by cerebral concussion and chilled in ice. In the field
190 laboratory, each fish was identified to species level, but whitefish (*Coregonus lavaretus*) were assigned to the
191 morph (subspecies) level and whitefish × vendace (*Coregonus albula*) hybrids were separated based on
192 morphology and colour, as well as head shape and gill raker count (Kahilainen et al. 2011, Kahilainen et al.
193 2017). This subspecies level delineation was considered essential as many of the northern lakes in the study area
194 are dominated by variable proportions of ecologically contrasting whitefish morphs (2–4 morphs in a lake) that
195 play differential roles in food web structure, energy flows and fatty acid dynamics (Thomas et al. 2017, Thomas
196 et al. 2019).

197 Total length (accuracy 1 mm) and wet mass (0.1 g) were measured and the relative abundance of each species
198 was calculated as catch per unit effort (CPUE) i.e. number of individual per species gill net⁻¹ hour⁻¹. In addition
199 to gill net data, we have previously collected both relative abundance (CPUE) and quantitative estimates of
200 whitefish and vendace density in pelagic habitat (individuals ha⁻¹) by using vertical echosounding and gill netting
201 from subset of the lakes analysed in the current study (Malinen et al. 2014). We calculated a linear regression
202 equation between CPUE and echosounding derived quantitative density in order to transform relative densities
203 of whitefish and vendace to absolute densities. As one or both of these species are present in all sampled lakes,
204 we used their calculated absolute density and their proportion of total catches to get fish density values for
205 different species in each lake. These density values for each species and their mean individual mass in gill net
206 catch were multiplied to get biomass (kg ha⁻¹). For consistency with other trophic levels, we transformed fish
207 wet weight to dry weight with conversion factor of 0.2 (e.g. Ahlgren et al. 1996). In trophic level analyses, fish
208 were classified as secondary consumers i.e. invertivorous (most species and morphs) and tertiary consumers i.e.
209 piscivorous species (only pike, *Esox lucius*; burbot, *Lota lota*, Arctic charr, *Salvelinus alpinus*; brown trout, *Salmo*
210 *trutta*; and >20 cm perch *Perca fluviatilis*) based on previous dietary and stable isotope studies of a subset of the
211 studied lakes (Kahilainen and Lehtonen 2003, Thomas et al. 2017, Hayden et al. 2019).

212 2.3 Lipid extraction and fatty acid analysis

213 Homogenized freeze-dried (–50 °C for 48 h) invertebrate and fish dorsal muscle samples were weighed ca. 0.5–
214 1 mg and 3–4 mg respectively to kimax glass test tubes. If material was not limited, duplicate samples were

215 analysed. Fatty acids were analysed as methyl esters (e.g. Taipale et al. 2016), identified and quantified using a
216 gas chromatograph attached to mass spectrometer. Samples were spiked with nonadecylic acid (PLFA c19:0).
217 Lipids were extracted with 3 ml of chloroform-methanol solution (2:1 vol) and with sonicator (15 min). Ultra-
218 pure water (0.75ml of MilliQ) was add to kimax tubes to separate water soluble compounds from lipids. Lipid
219 extract was evaporated and 3 ml of 1% H₂SO₄ add to kimax tube which was incubated in +50 °C for 20 h to
220 produce fatty acid methyl esters (FAMEs). The produced FAMEs were diluted with hexane and analysed using
221 a gas chromatograph attached to a mass spectrometer (GC-2010 Plus and QP-2010 Ultra, Shimadzu, Japan) with
222 Zebron ZB-FAME column (30 m + 5m guardian × 0.25 mm × 0.2 μm). At the begin of the each GCMS run, the
223 column temperature was held in 50°C for 1 min, followed by raising with 10 °C min⁻¹ to 130 °C, 7 °C min⁻¹ to
224 180 °C, 2 °C min⁻¹ to 200 °C and was held there for 3 min which after the colon temperature was raised with 10
225 °C min⁻¹ to 260 °C. The injection temperature was 270 °C and the interface temperature 250 °C, total column
226 flow being 27.5 mL min⁻¹ and linear velocity 36.3 cm s⁻¹.

227 Fatty acids were identified based on ion spectrums and quantified based on four-point standard mixture
228 calibration curves (15 ng μL⁻¹, 50 ng μL⁻¹, 100 ng μL⁻¹, 250 ng μL⁻¹; GLC 566c, Nu-Chek Prep, USA) with
229 GCMS solution software version 4.42 (Shimadzu, Japan). The calibration curves were ran before each run. The
230 coefficient of determination between peak area and standard FA concentrations were always higher than 0.999.
231 To validate the calibration curves, we run at least one external EPA and DHA standard (Sigma Aldrich
232 CRM47571 & CRM47570) per batch, average recovery % ± RSD of the analysed external standards were 119.2
233 ± 21.4 % (n=11) and 104.9 ± 20.5 % (n=11) for EPA and DHA. The average sum of percent error between sample
234 duplicate (n=47) FA profiles and EPA+DHA contribution were 2.0 ± 1.3 % and 0.6 ± 0.7 %, respectively. The
235 mean ± SD recovery of our internal standard nonadecylic acid in our samples was 90.7 ± 24.2% (n=503) and the
236 individual recovery % was used to adjust the sample FA concentrations. EPA and DHA were the only fatty acids
237 used in the subsequent data analysis.

238 We combined a small subset of fatty acid data from previous studies having a different focus (Taipale et al. 2016,
239 Vesterinen et al. 2020). Total dataset consisted of 868 samples (Table S2: phytoplankton=32, zooplankton=26,
240 littoral benthos=209, profundal benthos=34, invertivorous fish=377, piscivorous fish=190). Community specific
241 lake average FA sample coverage of taxa specific biomass contributions stands as following: phytoplankton 93.2
242 ± 5.4 %, littoral benthos 59.6 ± 24.3 %, profundal benthos 71.9 ± 19.9 %, invertivorous fish 92.9 ± 9.0 %,

243 piscivorous fish 89.7 ± 23.0 % Table S3. For zooplankton only bulk samples were used in community quality
244 calculations, thus assuming coverage being 100% (Table S3).

245 2.4. Lake specific community EPA + DHA content and areal content calculations

246 Computational phytoplankton EPA + DHA content ($\text{mg g}^{-1} \text{C}$) was calculated for study lakes using the class
247 specific carbon mass and their corresponding FA production estimates from laboratory experiments (Taipale et
248 al. 2016). The laboratory-culture experiment derived FA production of phytoplankton taxa might be different
249 from those found in nature, due to varying environmental conditions in natural environments. However, we think
250 this estimation is relevant as microscopy data of phytoplankton community composition and biomass data was
251 available for the study systems. For the consumer communities, EPA + DHA content ($\text{mg g}^{-1} \text{dw}$) was weighed
252 with taxa specific biomass contribution (%) determined for each lake and taxa, except for zooplankton which was
253 sampled as a whole community. Lake, habitat and taxa specific mean FA content values was used in the
254 community EPA + DHA calculations where possible. If taxa specific fatty acid content was unavailable from a
255 lake, we used measured taxa average FA content from different habitat (for benthos) or same type of lakes (e.g.
256 oligotrophic), with this we supplemented our FA sample coverage near to 100% for each community (Table S3).

257 Biomass calculations (in section 2.2.) facilitated the calculation of trophic pyramids, where total food web
258 biomass was divided among trophic levels. Here, we followed above classifications where the first trophic level
259 are primary producers (i.e. phytoplankton), the second is primary consumers (zooplankton and benthic
260 macroinvertebrates), the third is secondary consumers (invertivorous fish), whilst the fourth is tertiary consumers
261 (piscivorous fish). To calculate community EPA + DHA mass per unit area ($\text{kg EPA + DHA ha}^{-1}$, herein after:
262 areal content) for primary producers and different consumers, we multiplied community biomass (kg dw ha^{-1})
263 and EPA + DHA content. For fish community areal EPA+DHA content we used only muscle tissue of fish instead
264 of whole fish. Furthermore, we used community EPA + DHA areal content (kg FA ha^{-1}) to calculate trophic
265 pyramids for these assimilated biomolecules through food webs. Our biomass calculations should be considered
266 as minimum estimates, since we did not have any quantitative biomass and FA data from littoral primary
267 producers (periphyton, macrophytes) nor small organisms such as bacteria, rotifers and microbenthos.

268 2.5 Statistical methods

269 We calculated a climate-productivity index (CPI) that equals the principal component analysis (PCA) axis one
270 based on lake chemistry (TotP, TotN, DOC), and catchment properties (air temperature, precipitation) to reduce

271 the number of environmental variables when testing H1 and H2 (Table S1, Hayden et al. 2019). Here, the PC1
272 axis (i.e. CPi) explained 81% of the variation in lake environmental data, and was the only PC used in subsequent
273 analyses (Fig. S1) due to inherent collinearity with land-use practices (Hayden et al. 2019). Within the final
274 derived index, lakes with higher temperature and productivity receive higher CPi values. We built general linear
275 models with forward and backward selection predicting each community biomass with CPi, prey item quality
276 (EPA+DHA content) and predator biomass, where Akaike information criterion (AIC) was used for selection of
277 the best models. To summarize general linear model results, CPi was the main factor affecting community
278 biomass (Table S4-5). Therefore, we used a simple linear regression model to examine the relation between CPi
279 (PC1 scores) and community total biomass (H1) and EPA + DHA areal content (H2). We also used linear
280 regression analysis to test the dependence of community EPA + DHA areal content on lake total biomass (H3).
281 An alpha level of 0.05 was used in each statistical analysis and tests were conducted using R through RStudio
282 version 3.4.1 with the default base package (R Core Team 2017). Figures were drawn using base graphics and
283 ggplot2 package (Wickham 2016).

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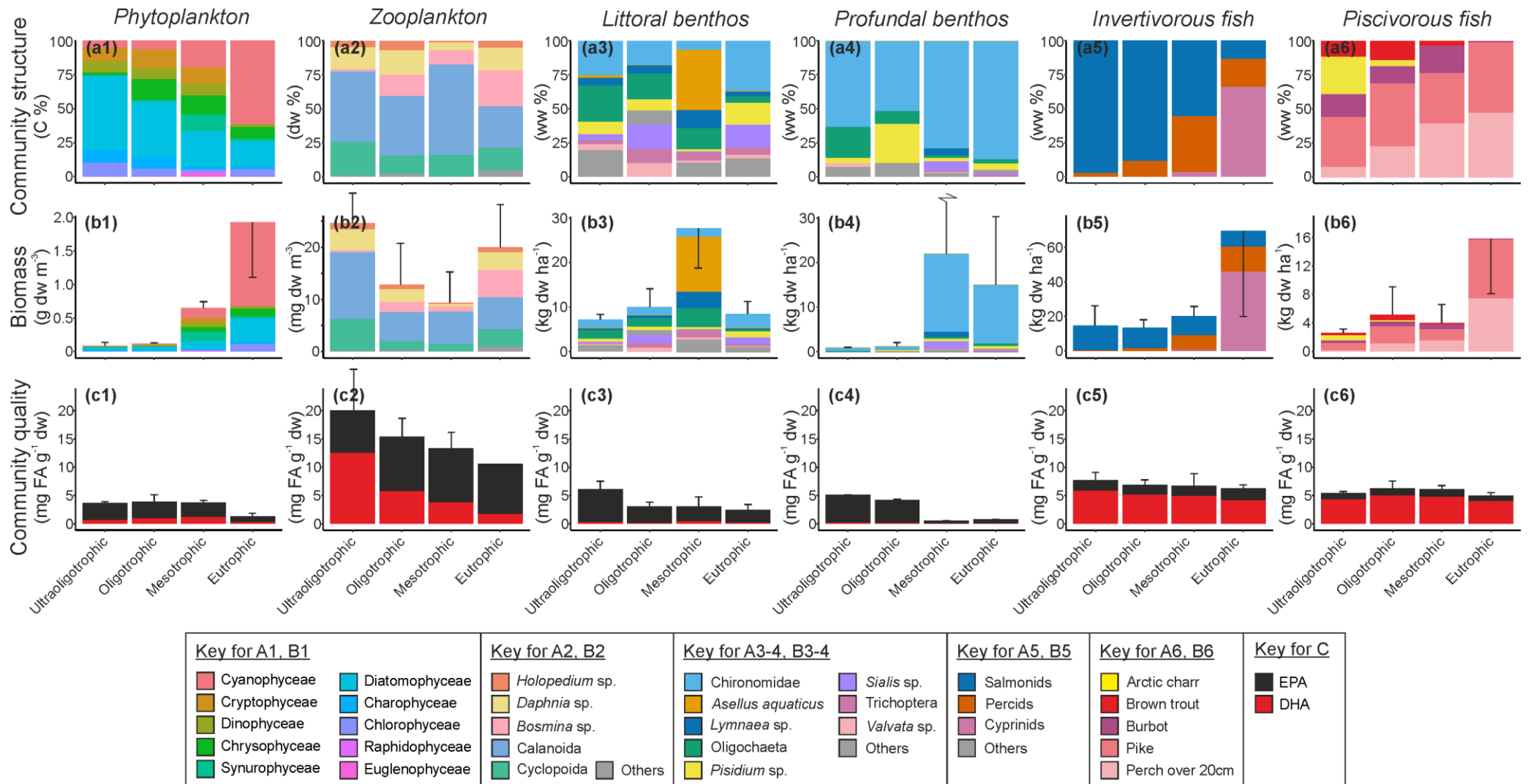
285 3. Results

286 3.1 Changes in community structure, food web biomass and trophic pyramid shape (H1)

287 Lake communities showed shifts from cold to warmer adapted taxa with increasing temperature and productivity
288 (Fig. 2). Phytoplankton changed from diatom dominated communities in ultraoligotrophic lakes towards
289 cyanobacteria dominance in eutrophic lakes (Fig. 2 a1). Copepods contributed 50–80% of the total zooplankton
290 community biomass along this gradient and calanoids had the highest biomass percentage in every lake type.
291 However, copepod contribution was lowest in eutrophic lakes where cladocerans, especially *Bosmina* had a high
292 biomass percentage (Fig. 2 a2). Littoral benthos communities were diverse throughout the lake gradient (Fig. 2
293 a3): *Asellus* sp. and *Lymnaea* sp. reached the highest proportional contribution in mesotrophic lakes, whereas
294 oligochaetes had the highest biomass contribution in ultraoligotrophic lakes and lowest in eutrophic lakes.
295 Profundal benthos was mainly dominated by chironomids and their biomass contribution increased from
296 ultraoligotrophic lakes (ca. 50%) towards eutrophic lakes (ca. 90%) (Fig. 2 a4). Invertivorous fish communities
297 were dominated by salmonids (whitefish, vendace) in ultraoligotrophic lakes; by percids (perch and ruffe,
298 *Gymnocephalus cernuus*) and salmonids in oligotrophic-mesotrophic lakes; and by cyprinids (roach *Rutilus*

299 *rutilus*, bleak *Alburnus alburnus*) in eutrophic lakes (Fig. 2 a5). Piscivorous pike and perch increased their
300 biomass contribution progressively from ultraoligotrophic lakes (ca. 35% and 5%) towards eutrophic lakes (ca.
301 50% for both species), whilst piscivorous Arctic charr and brown trout disappeared completely along the same
302 gradient (Fig. 2 a6).

303 Phytoplankton mean mass increased more than twenty-fold between ultraoligotrophic (0.08 ± 0.05 ; mean \pm SD g
304 dw m^{-3}) and eutrophic lakes 1.9 ± 0.8 g dw m^{-3} (Fig. 2 b1), which was also evident for biomass along our lake
305 gradient CPi (PC1) from north to south based on linear regression analysis (Fig. 3 a1). The lowest zooplankton
306 biomass was observed in mesotrophic lakes (9.27 ± 5.96 mg dw m^{-3}) (Fig. 2 b2), however no clear trend in
307 biomass was observed along the lake gradient (CPi) based on linear regression (Fig. 3 a2). The overall highest
308 littoral benthos biomass was observed in mesotrophic lakes (Fig. 2 b3), but no clear trend in biomass along the
309 continuous CPi axis (Fig. 3 a3). The profundal benthos biomass was low in ultraoligotrophic lakes (0.4 ± 0.3 kg
310 dw ha^{-1}) and increased towards eutrophic lakes (8.2 ± 11.3 kg dw ha^{-1}). This trend was mainly caused by
311 increasing chironomid biomass (Fig. 2 b4) and driven mainly by extremely high profundal benthos densities in
312 two lakes with low oxygen (Fig. 3 a4). Generally invertivorous fish biomass was circa five times higher in
313 eutrophic lakes (69.7 ± 49.0 kg dw ha^{-1}) compared to other lake types (pooled average: 15.8 ± 12.9 kg dw ha^{-1})
314 (Fig. 2 b5; Fig. 3 a5). The biomass of piscivorous fish was around four times higher in eutrophic lakes ($15.9 \pm$
315 7.8 kg dw ha^{-1}) than other lake types (pooled average: 4.2 ± 3.2 kg dw ha^{-1}). (Fig. 2 b6), and a clear linear trend
316 along the CPi axis was observed (Fig. 3 a6). These massive increases in primary producer and secondary
317 consumer biomass compared primary and tertiary consumers were evident in changes to the trophic pyramid
318 shape (Fig. 4, Fig. S2). Ultraoligotrophic and oligotrophic lakes showed variable shapes from typical pyramids
319 to inverted pyramids to across different lakes, whilst most mesotrophic lakes were generally typical pyramids
320 and eutrophic lakes had hour glass shaped biomass distributions (Fig. 4, Fig. S2).



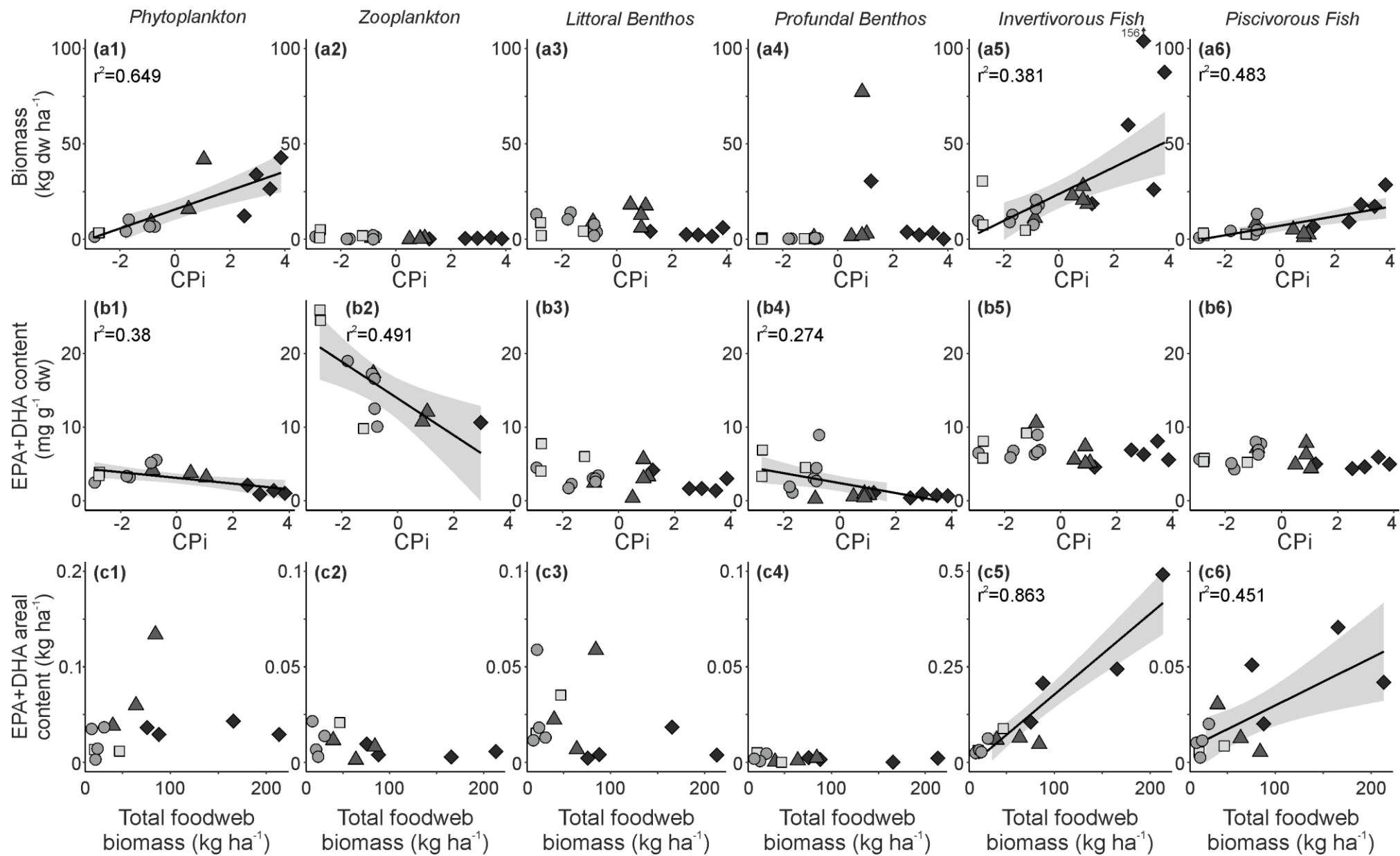
321
 322 Fig. 2. Community structure (a), biomass (b) and computed community quality (FA content, c) across different lake types (x-axis). Food web community compartments: phytoplankton (1),
 323 zooplankton (2), littoral benthos (3), profundal benthos (4), invertivorous fish (5) and piscivorous fish (6) are presented in different columns. The coloured bars indicate average taxa values of
 324 different lake types as following: normalized relative community composition (a: biomass %), lake type average biomass (b1: g dw m^{-3} , b2: mg dw m^{-3} , b3–b6: kg dw ha^{-1}) and lake type average
 325 community EPA and DHA content (c: $\text{mg FA g}^{-1} \text{dw}$). Lake specific community bulk FA content is derived from the FA analysed bulk sample (c2: zooplankton) and calculated for other food
 326 web community compartments (c1, c3–c6) from taxa specific biomass contribution and fatty acid content. Whiskers on top of the lake type average (b and c rows) represents + SD.

327 3.2 Changes in fatty acid content of food web components (H2)

328 Phytoplankton quality (EPA + DHA) was highest in oligotrophic and mesotrophic lakes, and clearly the lowest
329 in eutrophic lakes (Table S6, Fig. 2 c1). Zooplankton quality was the highest in ultraoligotrophic lakes ($20.1 \pm$
330 $8.9 \text{ mg g}^{-1} \text{ dw}$; mean \pm SD) and progressively decreased towards eutrophic lakes ($10.6 \text{ mg g}^{-1} \text{ dw}$) (Fig. 2 c2),
331 but due to high variance and low sample size the EPA + DHA distributions did not differ statistically among the
332 lake types (Table S6). Benthos quality was limited to the presence of EPA. Littoral and profundal benthos quality
333 were the highest in ultraoligotrophic lakes and the lowest in eutrophic lakes (Table S6, Fig. 2 c3–4). There was
334 no statistically significant differences in quality of invertivorous and piscivorous communities between lake types
335 as EPA+DHA content remained stable (Table S6, Fig. 2 c5–6). EPA and DHA content of primary producers and
336 consumers decreased along the CPi axis, but there was no statistically significant trend in secondary or tertiary
337 consumers (Fig. 3 b1–6, Fig. S3).

338 3.3 Changes in community EPA + DHA areal content (H3)

339 The highest values of community EPA + DHA areal content came from invertivorous fish (pooled average \pm SD:
340 $0.188 \pm 0.214 \text{ kg ha}^{-1}$), followed by piscivorous fish ($0.050 \pm 0.054 \text{ kg ha}^{-1}$), phytoplankton ($0.036 \pm 0.030 \text{ kg}$
341 ha^{-1}), littoral benthos ($0.023 \pm 0.019 \text{ kg ha}^{-1}$), pelagic zooplankton ($0.015 \pm 0.026 \text{ kg ha}^{-1}$) and profundal benthos
342 ($0.007 \pm 0.017 \text{ kg ha}^{-1}$), respectively. Trends in EPA + DHA areal content of phytoplankton, zooplankton, and
343 benthos communities with total food web biomass were not significant (Fig. 3 c1-4), though showing generally
344 opposing patterns between trophic levels: EPA + DHA areal content of phytoplankton community was smallest
345 in oligotrophic lakes but remained relatively stable in meso- and eutrophic lakes, whilst invertebrate taxa showed
346 the opposite pattern. The areal contents of EPA + DHA of invertivorous (adj. $r^2=0.86$) and piscivorous
347 (adj. $r^2=0.45$) fish communities were positively related to total biomass of food web (Fig. 3 c5–6, Table S7).
348 Community EPA + DHA areal content showed a similar pattern as total biomass along the studied lake gradient,
349 emphasizing the fundamental link between total community biomass and EPA + DHA areal content (Fig. 3a, c,
350 Table S7).



352 Fig. 3. Linear regression models showing (a–b): Community biomass (kg dw ha^{-1}) and quality ($\text{mg EPA+DHA g}^{-1} \text{ dw}$)
353 against climate-productivity index (CPI) and (c): EPA + DHA areal content ($\text{kg EPA+DHA ha}^{-1}$) against total food web
354 biomass (kg dw ha^{-1}). Food web community compartments: phytoplankton (1), zooplankton (2), littoral benthos (3),
355 profundal benthos (4), invertivorous fish (5) and piscivorous fish (6) are presented in different columns. The grey shaded
356 shapes indicate different lake trophy corresponding to Fig. 1: light grey square = ultraoligotrophic, grey dot = oligotrophic,
357 dark grey triangle = mesotrophic, black diamond = eutrophic. Linear regressions fits (bolded line), 95% confidence limit
358 (grey shaded areas) and adjusted coefficient of determination (r^2) are presented in the figures if the model was statistically
359 significant ($p < 0.05$). Linear regression equations, F statistics, adjusted r^2 and p values are presented for each model in Table
360 S6.

361 4. Discussion

362 4.1 Major trends

363 Based on our findings, we suggest that increasing temperature and productivity fundamentally alter the structure
364 and function of subarctic lake communities. Here, warmer, more nutrient rich waters promote communities with
365 an increasing share of blue-green algae, smaller-bodied zooplankton, smaller benthic macroinvertebrate taxa and
366 warmer water adapted cyprinid fishes. Moreover, we observed clear positive trends in biomass in each second
367 trophic level (i.e. phytoplankton and invertivorous fish), which increased along the lake gradient. Deviating trends
368 in contrasting trophic levels had subsequent effects on shaping trophic pyramids, where only eutrophic lakes
369 seems to settle into a common hour glass shape. The omega-3 content ($\text{mg EPA + DHA g}^{-1} \text{ dw}$) of primary
370 producers and consumers decreased along the climate-productivity gradient, but these trends were not observed
371 in longer living secondary and tertiary consumers (i.e. fishes). Increasing total biomass of food webs along the
372 climate-productivity gradient increased community EPA + DHA areal content, with this especially visible in
373 invertivorous and piscivorous fish communities.

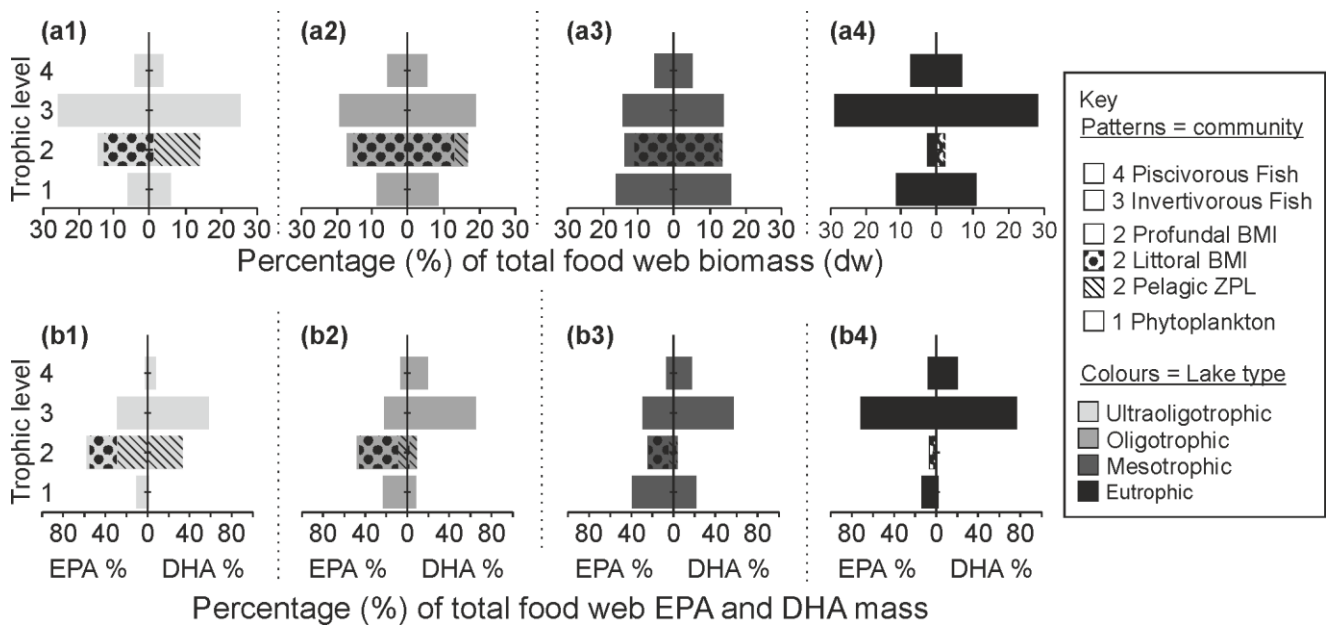
374 4.1 Changes in community structure, biomass and trophic pyramids (H1)

375 Across our study lake gradient — from northern ultraoligotrophic lakes to eutrophic lakes — food webs shifted
376 towards dominance of warmer and murky water adapted species. These changes were the clearest in primary
377 producers, where communities moved from diatom dominance to cyanobacteria, and secondary consumers,
378 where salmonids were replaced by cyprinids. While many of our biomass calculations follow the relative density
379 results, obtained in a previous study conducted along a partially overlapping gradient (Hayden et al. 2017), there
380 were clear differences in biomass trends among trophic levels. Here, primary producers and secondary consumer

381 biomass increased most dramatically from cold ultraoligotrophic lakes towards warm eutrophic systems, but there
382 were no clear trends in primary consumers and biomass increment of tertiary consumers was shallower. Past food
383 web level studies have found similar patterns, whereby phytoplankton and invertivorous fish biomass tend to
384 respond most strongly to increasing nutrient concentrations (Hanson and Leggett 1982, Jeppesen et al. 2000,
385 Carpenter et al. 2001). Moreover, joint effects of increasing temperature and productivity boost food web level
386 change where oligotrophic subarctic lakes are mainly fuelled by benthic algae, but gradually shift towards
387 phytoplankton derived energy sources towards warmer and more productive lakes (Vadeboncoeur et al. 2003,
388 Hayden et al. 2019). As key drivers of the biomass increment in our data set for primary producers are
389 cyanobacteria and for secondary consumers cyprinid fish those are both adapted to warm waters (Kosten et al.
390 2012, Rolls et al. 2017). Both are competitively superior in warmer and productive environment as many
391 cyanobacterial taxa can fix nitrogen directly from air and form dense colonies to avoid predation, whilst cyprinids
392 across the region have omnivorous diets and very high fecundity (Kosten et al. 2012; Winfield and Nelson 1991,
393 Lappalainen et al. 2008). Such uneven changes in community structure and biomass in different trophic levels
394 were critical in shaping food webs and trophic pyramids.

395 Biomass patterns across trophic levels showed contrasting trends in response to increasing temperature and
396 productivity. This corroborates the “Green World Hypothesis”, where primary producers (phytoplankton) are
397 bottom-up controlled by nutrients, and primary consumers (zooplankton and benthos) are top-down controlled
398 by invertivorous fish (Hairston et al. 1960). However, this model is a simplification of complex aquatic food
399 webs such as the study lakes, as all additionally contain tertiary consumers (e.g. Arctic charr, pike; although their
400 relative biomass and proportional contribution to trophic pyramids was variable). Whilst top consumers biomass
401 increment was shallower compared to invertivorous fish biomass with increasing temperature and productivity,
402 the most diverse piscivore communities colonizing all lake habitats inhabited coldest and most nutrient poor lakes
403 only. Previous work from these cold and clear lakes suggest a strong top-down role of piscivorous fish on
404 invertivorous fish density and biomass (Jensen et al. 2015, Thomas et al. 2017, Kahilainen et al. 2019). These
405 cold and nutrient poor lakes have generally low biodiversity that promotes both highly size structured fish
406 populations, i.e. strong year class dominance for 10–15 years, and potential for strong trophic cascades (Byström
407 2006, Hayden et al. 2014a, Kahilainen et al. 2019). This likely explains the diverse shape of trophic pyramids we
408 observed, especially in ultra-oligotrophic and oligotrophic lakes. Increasing temperature and nutrients are
409 fundamental controls that decrease piscivore top-down control and boost bottom-up processes, whereas trophic

410 pyramids seem to stabilize into an hourglass shape in eutrophic lakes. Such trophic pyramid shape is obviously
 411 very persistent as common biomanipulation efforts of mass removal of invertivorous consumers (e.g. roach) tend
 412 to quickly return to original state (Carpenter et al. 1985, Hansson et al. 1998). Therefore, it is likely that especially
 413 in eutrophic lakes the piscivore predation on invertivorous fish is not limiting their population size, as observed
 414 elsewhere (e.g. Bartrons et al. 2020). Nutrient concentration is well-known driver of alternative stable states of
 415 lakes (Scheffer and Carpenter 2003) and underlying mechanisms maintaining resilience of eutrophic state may
 416 include an hourglass shape of trophic pyramid driven by proportionally high biomass of primary producers and
 417 secondary consumers (Jeppesen et al. 2010). Yet, the nutrient level and reason for the possible tipping point of
 418 the lake food web communities should be further evaluated in future.



419
 420 Fig. 4. Relative biomass (a) and FA stock (b) pyramids by food web compartments for the lake types. The pyramid steps
 421 represent lake type averages of relative biomass or EPA+DHA areal content and are ordered with trophic level from bottom-
 422 up order: 1) phytoplankton, 2) invertebrates, 3) invertivorous fish and 4) piscivorous fish. The second trophic level
 423 (invertebrates) are divided among profundal benthos, littoral benthos and zooplankton with patterns: transparent, spots,
 424 stripes respectively. Different lake types, ultraoligotrophic, oligotrophic, mesotrophic and eutrophic respectively, are
 425 separated into different columns delineated with dashed lines and additionally with light grey, grey, dark grey, black
 426 respectively. The lake specific data is presented at Fig. S2. Abbreviations in legend are BMI = benthic macroinvertebrates
 427 and ZPL = zooplankton.

428 4.2 Changes in EPA+DHA content of food web components (H2)

429 The nutritional quality ($\mu\text{g EPA} + \text{DHA mg}^{-1} \text{ dw}$) of primary producers and consumers with short lifecycles (i.e.
430 invertebrates) showed a decreasing trend towards warmer and more productive lakes, while in secondary and
431 tertiary vertebrate consumers (i.e. fishes) such trends in nutritional quality were not apparent. Along the
432 environmental gradient, the phytoplankton community shifted towards more cyanobacteria-dominated
433 communities, which are non-EPA and non-DHA synthesizing phytoplankton (e.g. Taipale et al. 2016). The
434 decrease in zooplankton EPA + DHA content varied with an increasing abundance of small cladoceran and
435 cyclopoid copepods. There are many differences in life history strategies between different zooplankton taxa,
436 where the calanoid *Eudiaptomus graciloides*, the dominant copepod in cold oligotrophic lakes, tends to
437 accumulate lipids (including FAs) to survive winter, whereas short-lived cladocerans form resting stages and do
438 not need high body fat reserves (Hiltunen et al. 2016, Grosbois et al. 2017). In a recent study, Senar et al. (2019)
439 investigated a similar nutrient (total phosphorus 6–48 $\mu\text{g L}^{-1}$) and colour (dissolved organic carbon 2–10 mg L^{-1})
440 gradient in Canadian lakes, but did not record clear decrease in zooplankton taxa FA content. However, their
441 study region was warmer and did not contain strong temperature gradients, which have clear influence on lipid
442 rich copepod abundance in zooplankton communities and thus PUFA content (Gladyshev et al. 2011, Hiltunen
443 et al. 2016, Senar et al. 2019).

444 Decreasing nutritional quality ($\mu\text{g EPA} + \text{DHA mg}^{-1} \text{ dw}$) in primary producers was predicted to result in similar
445 trends in secondary and tertiary consumers (Ahlgren et al. 1996, Taipale et al. 2016). However, we did not find
446 this to be the case and instead the EPA + DHA content of fish population was generally stable, in contrast to our
447 second hypothesis. This could be related to diversity in lipid metabolism of different fish species during different
448 development stages, since our study included many fish species at different developmental stages. A range of
449 aquaculture and experimental studies indicate that EPA and DHA supplement increase fish individual growth
450 and to some extent the muscle FA content of adult fish (Bou et al. 2017, Yeşilayer and Kaymak 2020). However,
451 similar evidence from the wild is very difficult to obtain due to limited food resources, slow growth rate of fish,
452 long turnover time of muscle tissue, reproduction cycle, and species-specific differences in lipid storages
453 (Jørgensen et al. 1997, Thomas and Crowther 2015, Keva et al. 2019). One alternative for stable fish EPA + DHA
454 content could be that the ability for conversion of DHA from ALA varies greatly among fish species and
455 development stage (Geay et al. 2016, Kabeya et al. 2018, Ishikawa et al. 2019). Since, benthic macroinvertebrates
456 included only a minor amount of DHA as reported also previously, zooplankton is clearly the most likely dietary

457 source of DHA for fish (e.g. Makhutova et al. 2016; Vesterinen et al. 2020). The EPA + DHA content of fish
458 muscle did not differ among feeding habitats (zooplanktivore, benthivore, piscivore), possibly providing evidence
459 for selective transfer or utilization of FAs in fish (Strandberg et al. 2015). Previous results from subarctic lakes
460 indicated that the turnover rate of whitefish (*Coregonus lavaretus*) muscle is slow, and thus stable isotope ratios
461 and fatty acid content responded very slowly to any diet change (Thomas and Crowther 2015, Hayden et al.
462 2014a, Keva et al. 2019, Thomas et al. 2019). Our results did not support the idea that prey quality is essential to
463 supporting fish consumer biomass or quality. Together, these results suggest that lipid metabolism is variable and
464 complex among different fish species and their life stages, where generalization of temperature and productivity
465 induced responses to fatty acid content and even further to consumer biomass require more laboratory and field
466 work with wild fish populations.

467 4.3 Changes in community EPA + DHA areal content (H3)

468 The climate-productivity gradient of subarctic study lakes included both eutrophication and browning processes
469 from cold and clear water lakes toward warm and murky waters (Hayden et al. 2019). While the EPA + DHA
470 content of primary producers and consumers did show a clear decrease as suggested by earlier studies (Taipale
471 et al. 2016, Creed et al. 2018), the EPA + DHA areal content at a systemic level did not show corresponding
472 decrease due to massive increase of total biomass; similar patterns have previously been observed in mesocosm
473 studies of benthic communities (Scharnweber et al. 2020). Surprisingly, EPA + DHA areal content in secondary
474 and tertiary consumers indeed increased towards more murky lakes, indicating that total biomass clearly overrode
475 the decline of quality. Changes in phytoplankton EPA + DHA areal content were highest in more eutrophic lakes,
476 even if cyanobacteria contribution to this would be bypassed highlighting the importance of biomass to
477 community EPA + DHA areal content and potentially to production as well. The total areal FA content does not
478 exhibit a 1:1 relationship with the production of phytoplankton due taxa specific production rates (Taipale et al.
479 2020). However, even with a far lower areal content to production ratio in eutrophic lakes, the system level
480 production of EPA + DHA would still be higher in more eutrophic lakes due to massive phytoplankton biomass
481 increment from oligotrophic towards eutrophic lakes. Therefore, we argue that in the studied climate and
482 productivity gradient the total production of fatty acids are higher in warm murky than cold and clear water lakes.

483 4.4 Caveats

484 While our sampling protocol did not cover all the food web components, our results from sampled organisms are
485 in general comparable to previous studies conducted from subarctic or boreal lakes. The biomass estimates of
486 fish consumers were derived from simultaneously collected echosounding and gill net CPUE data of pelagic
487 whitefish and vendace, which were collected from a subset of the same study lakes during optimal sampling
488 window using standardized protocols suitable for these two species inhabiting all lakes in current study (Malinen
489 et al. 2014). Our total fish biomass estimates of from ultra-oligotrophic to mesotrophic lakes corroborates well
490 with biomass estimates derived from subarctic Canada (Samarasin et al. 2015). In addition, results from our
491 eutrophic lakes correspond to biomass estimates derived from mark-recapture, population analysis and
492 echosounding methods of boreal eutrophic lakes (Olin et al. 2017, Rask et al. 2020). The comparison of biomass
493 results of primary producers and primary consumer values to earlier studies from boreal lakes (Leppä et al. 2003,
494 Nurminen et al. 2018) indicate broadly similar estimates, but clearly lower values than hypereutrophic and
495 warmer lakes (Jeppesen et al. 2000, Gyllström et al. 2005). Future studies should include biomass estimates of
496 benthic algae as they are very important sources of energy in oligotrophic subarctic lakes (Vadeboncoeur et al.
497 2003, Hayden et al. 2019), but could be important in other types of lakes too (Vesterinen et al. 2016,
498 Vadeboncoeur and Power 2017). Assuming a high benthic-to-pelagic production ratio (70%) in our
499 ultraoligotrophic lakes and low ratio (0%) in shallow eutrophic lakes (Vadeboncoeur et al. 2008) the increment
500 in primary producer biomass among the lake gradient would be less pronounced and this would affect also the
501 biomass pyramids. However, whole food web primary production is known to increase along phosphorous
502 gradients (Vadeboncoeur et al. 2003) and the biomass pyramids are more persistent to the changes in one trophic
503 level biomass share due to multiple trophic levels accounting the total biomass. To make future fatty acid budget
504 and production calculations more accurate we suggest analysing whole fish or creating species specific
505 conversion factors from muscle tissue to whole body.

506 4.5. Conclusions

507 While climate warming trends have been evident in the last decades in Finnish Lapland (Hayden et al. 2014b),
508 increases in lake productivity via catchment greening and especially encroachment of the treeline will likely take
509 much longer to become apparent. Historically, the treeline of Scots pine has been located in the highest latitude
510 lakes of our study with circa 2.5° C higher July air temperatures, indicating the potential for alteration of
511 catchment vegetation and lake productivity towards north (Kultti et al. 2006). While the lake productivity shifts

512 apparent in our study systems originate from intensive forestry activities, there is increasing evidence of resource
513 use related land-use in subarctic focusing on oil and gas drilling, and mining, as well as their associated
514 infrastructure such as roads, pipelines and tailing ponds; activities that are simultaneously changing catchments
515 and lake ecosystems with climate (e.g. Schindler & Smol 2006; Cott et al. 2015, Denisov et al. 2020). Under
516 current study settings, we show that increasing temperature and productivity have major impacts on lake
517 ecosystems, shifting communities towards warm and murky water adapted taxa, where especially biomass of
518 cyanobacteria and cyprinid fish are increasing. These have a major effect on lake food webs, where increasing
519 biomass of primary producers and secondary consumers shift trophic pyramid shapes towards a persistent
520 hourglass shape. Based on our findings, increasing temperature and productivity did reduce phytoplankton,
521 zooplankton and profundal benthos community EPA + DHA content, but these changes in prey quality did not
522 alter fish community EPA + DHA content. Instead, fish community areal EPA+DHA content did increase along
523 the gradient due to a massive increment in fish biomass. While we are not proposing direct predictions of near
524 future food web structure and quality, our results from a pronounced climate and productivity gradient clearly
525 showed that warmer and murkier water adapted species will likely increase their biomass share, whereas a
526 decrement in EPA+DHA content may only be observed in primary producers and consumers.

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535 scientific purposes were applied.

536 Author contributions

537 KKK provided the original idea for the paper. KKK, SJT and OK contributed planning the manuscript. Field
538 work was conducted mainly by KKK, SMT and BH. Fatty acid extraction and analysis was performed mostly by

539 OK, with contributions from SJT, SMT, JV, PK. OK compiled data, conducted statistical analyses and drafted
540 the first version of the manuscript. All authors contributed to subsequent revisions of the manuscript.

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545 Data sharing and data accessibility

546 Supplementary data including 7 tables and 3 figures related to this article can be found at Global Change Biology
547 web page [type URL here]. More data that support the findings of this study are available from the corresponding
548 author upon reasonable request.

549 6. References

550 Ahlgren, G., Sonesten, L., Boberg, M., Gustafsson, I.B. (1996). Fatty acid content of some freshwater fish in
551 lakes of different trophic levels—a bottom-up effect? *Ecology of Freshwater Fish* 5: 15–27.
552 <https://doi.org/10.1111/j.1600-0633.1996.tb00033.x>

553 Ahonen, S.A., Hayden, B., Leppänen, J.J., Kahilainen, K.K. (2018). Climate and productivity affect total mercury
554 concentration and bioaccumulation rate of fish along spatial gradient of subarctic lakes. *Science of the Total*
555 *Environment* 637–638: 1586–1596. <https://doi.org/10.1016/j.scitotenv.2018.04.436>

556 AMAP (1998). AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment
557 Programme (AMAP), Oslo, Norway.

558 Armstrong, J.B., Bond, M.H. (2013). Phenotype flexibility in wild fish: Dolly Varden regulate assimilative
559 capacity to capitalize on annual pulsed subsidies. *Journal of Animal Ecology* 86: 966–985.
560 <https://doi.org/10.1111/1365-2656.12066>

561 Arts, M.T., Ackmann, R.G., Holub, B.J. (2001). “Essential fatty acids” in aquatic ecosystems: a crucial link
562 between diet and human health and evolution. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 122–137.
563 <https://doi.org/10.1139/cjfas-58-1-122>

564 Baiser, B., Gravel, D., Citwill, A., Dunne, J., Fahimipour, A., Gilarranz, L.J., ... , Yakel, J. (2019).
565 Ecogeographical rules and the macroecology of food webs. *Global Ecology and Biogeography* 28: 1204–1218.
566 <https://doi.org/10.1111/geb.12925>

567 Bartrons, M., Mehner, T., Argillier, C., Beklioglu, M., Blabolil, P., Hesthagen, T., ... , Brucet, S. (2020). Energy-
568 based top-down and bottom-up relationships between fish community energy demand or production and
569 phytoplankton across lakes at a continental scale. *Limnology and Oceanography* 65: 892–902.
570 <https://doi.org/10.1002/lno.11434>

571 Bou, M., Berge, G., Baevefjord, G., Sigholt, T., Østbye, T., Ruyter, B. (2017). Low levels of very-long-chain n-
572 3 PUFA in Atlantic salmon (*Salmo salar*) diet reduce fish robustness under challenging conditions in sea cages.
573 *Journal of Nutritional Science*, 6: E32. <https://doi.org/10.1017/jns.2017.28>

574 Brown, J.H., Gillooly, J.F., Allen, A.P., Savage, V.M., West, G.B. (2004). Toward a metabolic theory of ecology.
575 *Ecology* 85: 1771–1789. <https://doi.org/10.1890/03-9000>

576 Byström, P. (2006). Recruitment pulses induce cannibalistic giants in Arctic char. *Journal of Animal Ecology* 75:
577 434–444. <https://doi.org/10.1111/j.1365-2656.2006.01064.x>

578 Carpenter, S.R., Kitchell, J.F., Hodgson, J.R. (1985). Fish predation and herbivory can regulate lake ecosystems.
579 *BioScience* 35: 634–639. <https://doi.org/10.2307/1309989>

580 Carpenter, S.R., Cole, J.J., Hodgson, J.R., Kitchell, J.F., Pace, M.L., Bade, D., ... , Schindler, D.E. (2001).
581 Trophic cascades, nutrients, and lake productivity: whole lake experiments. *Ecological Monographs* 71, 163–
582 186. <https://doi.org/10.2307/2657215>

583 Cohen, J., Screen, J.A., Furtado, J.C., Barlow, M., Whittleston, M., Whittleston, D., ... , Overland, J. (2014).
584 Recent Arctic amplification and extreme mid latitude weather. *Nature Geoscience* 7: 627–637.
585 <https://doi.org/10.1038/ngeo2234>

586 Colombo, S.M., Rodgers, T.F.M., Diamond, M.L., Bazinet, R.P., Arts, M.T. (2020). Projected declines in global
587 DHA availability for human consumption as a results of global warming. *Ambio* 49: 865–880.
588 <https://doi.org/10.1007/s13280-019-01234-6>

589 Cott, P.A, Schein, A., Hanna, B.W., Johnston, T.A., MacDonald, D.D., Gunn, J.M. (2015). Implications of linear
590 developments on northern fishes. *Environmental Reviews* 23: 177–190. <https://doi.org/10.1139/er-2014-0075>

591 Creed, I.F., Bergström, A.-K., Trick, C.G., Grimm, N.B., Hessen, D.O., Karlsson, J., ... , Weyhenmeyer, G.A.
592 (2018). Global change-driven effects on dissolved organic matter composition: Implications for food webs of
593 northern lakes. *Global Change Biology* 24: 3692–3714. <https://doi.org/10.1111/gcb.14129>

594 Dai, A., Song, M., (2020). Little influence of Arctic amplification on mid-latitude climate. *Nature Climate
595 Change* 10: 231–237. <https://doi.org/10.1038/s41558-020-0694-3>

596 Denisov, D., Terentjev, P., Valkova, S., Kudryavtzeva, L. (2020). Small lakes ecosystems under the impact of
597 non-ferrous metallurgy (Russia, Murmansk Region). *Environments* 7: 29.
598 <https://doi.org/10.3390/environments7040029>.

599 Elton, C.S. (1927). *Animal ecology*. Sidgwick & Jackson, London. <https://doi.org/10.5962/bhl.title.7435>

600 Gaston, K.J. (2000). Global patterns in biodiversity. *Nature* 405: 220–227. <https://doi.org/10.1038/35012228>

601 Geay, F., Tinti, E., Mellery, J., Michaux, C., Larondelle, Y., Perpete, E., Kestemont, P. (2016). Cloning and
602 functional characterization of $\Delta 6$ fatty acid desaturase (FADS2) in Eurasian perch (*Perca fluviatilis*).
603 *Comparative Biochemistry and Physiology Part B* 191: 112–125. <https://doi.org/10.1016/j.cbpb.2015.10.004>

604 Gladyshev, M.I., Semenchenko, V.P., Dubovskaya, O.P., Fefilova, E.B., Makhutova, O.N., Buseva, Z.F., ... ,
605 Kononova, O.N. (2011). Effect of temperature on contents of essential highly unsaturated fatty acids in freshwater
606 zooplankton. *Limnologica* 41: 339–347. <https://doi.org/10.1016/j.limno.2011.03.001>

607 Grosbois, G., Mariash, H., Schneider, T., Rautio, M. (2017). Under-ice availability of phytoplankton lipids is key
608 to freshwater zooplankton winter survival. *Scientific Reports* 7: 11543. [https://doi.org/10.1038/s41598-017-
10956-0](https://doi.org/10.1038/s41598-017-
609 10956-0)

610 Gyllström, M., Hanson, L.-A., Jeppesen, E., García-Criado, F., Gross, E., Kairesalo, T., ... , Moss, B. (2005).
611 The role of climate in shaping zooplankton communities of shallow lakes. *Limnology and Oceanography* 50:
612 2008–2021. <https://doi.org/10.4319/lo.2005.50.6.2008>

613 Hairston, N.G., Smith, F.E., Slobodkin, L.B. (1960). Community structure, population control and competition.
614 *The American Naturalist* 94: 421–425. <https://doi.org/10.1086/282146>

615 Hansson, L.-A., Annadotter, H., Bergman, E., Hamrin, S.F., Jeppesen, E., Kairesalo, T., Strand, J. (1998).
616 Biomanipulation as an application of food-chain theory: constraints, synthesis, and recommendations for
617 temperate lakes. *Ecosystems* 1: 558–574. <https://doi.org/10.1007/s100219900051>

618 Hansson, L.-A., Nicolle, A., Granéli, W., Hallgren, Kritzberg, E., Persson, A., ... , Brönmark, C. (2013). Food-
619 chain length alters community responses to global change in aquatic systems. *Nature Climate Change* 3: 228–
620 233. <https://doi.org/10.1038/nclimate1689>

621 Hanson, J.M., Leggett, W.C. (1982). Empirical prediction of fish biomass and yield. *Canadian Journal of*
622 *Fisheries and Aquatic Sciences* 39: 257–263. <https://doi.org/10.1139/f82-036>

623 Hayden, B., Harrod, C., Thomas, S. M., Eloranta, A. P., Myllykangas, J.-P., Siwertsson, A., Præbel, K., Knudsen
624 R., Amundsen, P.-A., Kahilainen, K. K. (2019). From clear lakes to murky waters—tracing the functional response
625 of high-latitude lake communities to concurrent ‘greening’ and ‘browning’. *Ecology Letters* 22: 807–816.
626 <https://doi.org/10.1111/ele.13238>

627 Hayden, B., Myllykangas, J.-P., Rolls, R., Kahilainen, K.K. (2017). Climate and productivity shape fish and
628 invertebrate community structure in subarctic lakes. *Freshwater Biology* 62: 990–1003.
629 <https://doi.org/10.1111/fwb.12919>

630 Hayden, B., Harrod, C., Kahilainen, K.K. (2014a). Dual fuels: intra-annual variation in the relative importance
631 of benthic and pelagic resources to maintenance, growth and reproduction in a generalist salmonid fish. *Journal*
632 *of Animal Ecology* 83: 1501–1512. <https://doi.org/10.1111/1365-2656.12233>

633 Hayden, B., Harrod, C., Kahilainen, K.K. (2014b). Lake morphometry and resource polymorphism determine
634 niche segregation between cool-and cold-water-adapted fish. *Ecology*, 95: 538–552. [https://doi.org/10.1890/13-](https://doi.org/10.1890/13-0264.1)
635 0264.1

636 Hillebrand, H., Dürselen, C.-D., Kirschtel, D., Pollingher, U., Zohary, T. (1999). Biovolume calculation for
637 pelagic and benthic microalgae. *Journal of Phycology* 35: 403–424. [https://doi.org/10.1046/j.1529-](https://doi.org/10.1046/j.1529-8817.1999.3520403.x)
638 8817.1999.3520403.x

639 Hillebrand, H. (2004). On the generality of latitudinal diversity gradient. *The American Naturalist* 163: 192–211.
640 <https://doi.org/10.1086/381004>

641 Hiltunen, M., Taipale, S.J., Strandberg, U., Kahilainen, K.K., Kankaala, P. (2016). High intraspecific variation
642 in fatty acids of *Eudiaptomus* in boreal and subarctic lakes. *Journal of Plankton Research* 38: 468–477.
643 <https://doi.org/10.1093/plankt/fbw008>

644 Hixson, S.M., Arts, M.T. (2016). Climate warming is predicted to reduce omega-3, long-chain, polyunsaturated
645 fatty acid production in phytoplankton. *Global Change Biology* 22: 2744–2755.
646 <https://doi.org/10.1111/gcb.13295>

647 Huntington, H.P., Boyle, M., Flowers, G.E., Weatherly, J.W., Hamilton, L.C., Hinzman, L., ... , Overpeck, J.
648 (2007). The influence of human activity in the Arctic on climate and climate impacts. *Climatic Change*, 82: 77–
649 92. <https://doi.org/10.1007/s10584-006-9162-y>

650 Ishikawa, A., Kabeya, N., Ikeya, K., Kakioka, R., Cech, J.N., Osada, N., ... , Kitano, J. (2019). A key metabolic
651 gene for recurrent freshwater colonization and radiation in fishes. *Science* 364: 886–889.
652 <https://doi.org/10.1126/science.aau5656>

653 IPCC (2015). Climate Change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth
654 assessment report of the intergovernmental panel on climate change. Geneva, Switzerland.

655 Jensen, H., Kahilainen, K.K., Vinni, M., Gjelland, K.Ø., Malinen, T., Harrod, C., ... , Amundsen, P.-A. (2015).
656 Food consumption rates of piscivorous brown trout (*Salmo trutta*) foraging on contrasting coregonid prey.
657 *Fisheries Management and Ecology* 22: 295–306. <https://doi.org/10.1111/fme.12126>

658 Jeppesen, E., Jensen, J., Søndergaard, M., Lauridsen, T., Landkildehus, F. (2000). Trophic structure, species
659 richness and biodiversity in Danish lakes: Changes along a phosphorus gradient. *Freshwater Biology* 45: 201–
660 218. <https://doi.org/10.1046/j.1365-2427.2000.00675.x>

661 Jeppesen, E., Meerhoff, M., Holmgren, K., Conzález-Bergonzoni, I., Teixeira-de Mello, F., Declerck, S.A.J., ...
662 , Lazzaro, X. (2010). Impacts of climate warming on lake fish community structure and potential effects on
663 ecosystem function. *Hydrobiologia* 646: 73–90. <https://doi.org/10.1007/s10750-010-0171-5>

664 Jeppesen, E., Mehner, T., Winfield, I.J., Kangur, K., Sarvala, J., Gerdeaux, D., ... , Meerhoff, M. (2012). Impacts
665 of climate warming on the long-term dynamics of key fish species in 24 European lakes. *Hydrobiologia* 694: 1–
666 39. <https://doi.org/10.1007/s10750-012-1182-1>

667 Jussila, M., Liljaniemi, P., Karvonen, L., Johansson, M. (2014). Water protection in regeneration cutting and site
668 preparation areas. Guidelines and practices in the field. Centre for Economic Development, Transport, and the
669 Environment for Lapland. *Report 72*: 1–36.

670 Jørgensen, E. H., Johansen, S. J. S., Jobling, M. (1997). Seasonal patterns of growth, lipid deposition and lipid
671 depletion in anadromous Arctic charr. *Journal of Fish Biology* 51: 312–326. [https://doi.org/10.1111/j.1095-
672 8649.1997.tb01668.x](https://doi.org/10.1111/j.1095-8649.1997.tb01668.x)

673 Kabeya, N., Fonseca, M.M., Ferrier, D.E.K., Navarro, J.C., Bay, L.K., Francis, D.S., Tocher, D.R., Castro, F.C.,
674 Monroig, Ó. (2018). Genes for de novo biosynthesis of omega-3 polyunsaturated fatty acids are widespread in
675 animals. *Science Advances* 4: eaar6849. <https://doi.org/10.1126/sciadv.aar6849>

676 Kahilainen, K., Lehtonen H. (2003). Piscivory and prey selection of four predator species in a whitefish
677 dominated subarctic lake. *Journal of Fish Biology* 63: 659–672. [https://doi.org/10.1046/j.1095-
678 8649.2003.00179.x](https://doi.org/10.1046/j.1095-8649.2003.00179.x)

679 Kahilainen, K.K., Østbye, K., Harrod, C., Shikano, T., Malinen, T., Merilä, J. (2011). Species introduction
680 promotes hybridization and introgression in *Coregonus*: is there sign of selection against hybrids? *Molecular
681 Ecology* 20: 3838–3855. <https://doi.org/10.1111/j.1365-294X.2011.05209.x>

682 Kahilainen, K.K., Thomas, S.M., Nystedt, E.K.M., Keva, O., Malinen, T., Hayden, B. (2017). Ecomorphological
683 divergence drives differential mercury bioaccumulation of polymorphic European whitefish (*Coregonus
684 lavaretus*) populations of subarctic lakes. *Science of the Total Environment* 599-600: 1768–1778.
685 <https://doi.org/10.1016/j.scitotenv.2017.05.099>

686 Kahilainen, K.K., Thomas, S.M., Harrod, C., Hayden, B., Eloranta, A.P. (2019). Trophic ecology of piscivorous
687 Arctic charr (*Salvelinus alpinus* (L.)) in subarctic lakes with contrasting food-web structures. *Hydrobiologia* 840:
688 227–243. <https://doi.org/10.1007/s10750-018-3845-z>

689 Keva, O., Tang, P., Käkälä, R., Hayden, B., Harrod, C., Kahilainen, K.K. (2019). Seasonal changes in European
690 whitefish muscle and invertebrate prey fatty acid composition in a subarctic lake. *Freshwater Biology* 64: 1908–
691 1920. <https://doi.org/10.1111/fwb.13381>

692 Kosten, S., Huszar, V.L.M., Bécares, E., Costa, L.S., van Don, E., Hansson, L.-A., ... , Scheffer, M. (2012).
693 Warmer climates boost cyanobacterial dominance in shallow lakes. *Global Change Biology* 18: 118–126.
694 <https://doi.org/10.1111/j.1365-2486.2011.02488.x>

695 Kultti, S., Mikkola, K., Virtanen, T., Timonen, M., Eronen, M. (2006). Past changes in the Scots pine forest line
696 and climate in Finnish Lapland: A study based on megafossils, lake sediments, and GIS-based vegetation and
697 climate data. *The Holocene*, 16: 381–391. <https://doi.org/10.1191/0959683606hl934rp>

698 Lappalainen, J., Tarkan, A.S., Harrod, C. (2008). A meta-analysis of latitudinal variations in life-history traits of
699 roach, *Rutilus rutilus*, over its geographical range: linear or non-linear relationships? *Freshwater Biology*, 53:
700 1491-1501. <https://doi.org/10.1111/j.1365-2427.2008.01977.x>

701 Laske, S. Amundsen, P.-A., Christoffersen, K.S., Erkinaro, J. ,Guðbergsson, G., Hayden, B., ... , Zimmerman,
702 C.E. (2020). Circumpolar patterns of Arctic freshwater fish biodiversity: A baseline for monitoring. *Freshwater*
703 *Biology*, <https://doi.org/10.1111/fwb.13405>

704 Lau D.C.P., Christoffersen, K.S., Erkinaro, J., Hayden, B., Heino, J., Hellsten, S., ... , Goedkoop, W. (2020).
705 Multitrophic biodiversity patterns and environmental descriptors of sub-Arctic lakes in northern Europe.
706 *Freshwater Biology* 00: 1-19. <https://doi.org/10.1111/fwb.13477>

707 Leppä, M., Hämäläinen, H., Karjalainen, J. (2003). The response of benthic macroinvertebrates to whole-lake
708 biomanipulation. *Hydrobiologia* 498: 97–105. <https://doi.org/10.1023/A:1026224923481>

709 Makhutova, O.N., Shulepina, S.P., Sharapova, T.A., Dubovskaya, O.P., Sushchik, N.N., Baturina, M.A., ...
710 Gladyshev, M.I. (2016). Content of polyunsaturated fatty acids essential for fish nutrition in zoobenthos species.
711 *Freshwater Science* 35: 1222–1234. <https://doi.org/10.1086/688760>

712 Malinen, T., Tuomaala, A., Lehtonen, H., Kahilainen, K.K. (2014). Hydroacoustic assessment of mono- and
713 polymorphic *Coregonus* density and biomass in subarctic lakes. *Ecology of Freshwater Fish*, 23: 424–437.
714 <https://doi.org/10.1111/eff.12096>

715 McCauley, E. (1984). The estimation of the abundance and biomass of zooplankton samples. In: *A manual on*
716 *methods for the assessment of secondary productivity in freshwaters*, Downing, L.A., Rigler, F.H. Blackwell,
717 Oxford, 228–265.

718 McCauley, D.J., Gellner, C., Martinez, N.D., Williams, R.J., Sandin, S.A., Micheli, F., ... , McCann, K.S. (2018).
719 On the prevalence and dynamics of inverted trophic pyramids and otherwise top-heavy communities. *Ecology*
720 *Letters* 439–454. <https://doi.org/10.1111/ele.12900>

721 Menden-Deuer, S., Lessard, E.J. (2000). Carbon to volume relationships for dinoflagellates, diatoms, and other
722 protist plankton. *Limnology and Oceanography* 45: 569–579. <https://doi.org/10.4319/lo.2000.45.3.0569>

723 Müller-Navarra, D.C., Brett, M.T., Liston, A.M., Goldman, C.R. (2000). A highly unsaturated fatty acid predicts
724 carbon transfer between primary producers and consumers. *Nature* 403: 74–77. <https://doi.org/10.1038/47469>

725 Müller-Navarra, D.C., Brett, M.T., Park, S., Chandra, S., Ballantyne, A.P., Zorita, E., Goldman, C.R. (2004).
726 Unsaturated fatty acid content in seston and tropho-dynamic coupling in lakes. *Nature* 427: 69–72.
727 <https://doi.org/10.1038/nature02210>

728 Nieminen, M., Koskinen, M., Sarkkola, S., Laurén, A., Kaila, A., Kiikkilä, O., Nieminen, T.M., Ukonmaanaho,
729 L. (2015). Dissolved organic carbon export from harvested peatland forests with differing site characteristics.
730 *Water, Air & Soil Pollution* 226: 181. <https://doi.org/10.1007/s11270-015-2444-0>

731 Nurminen, L., Héllen, N., Olin, M., Tiainen, J., Vinni, M., Grönroos, M., Estlander, S., Horppila, J., Rask, M.,
732 Lehtonen, H. (2018). Fishing-induced changes in predation pressure by perch (*Perca fluviatilis*) regulate littoral
733 benthic macroinvertebrate biomass, density, and community structure. *Aquatic Ecology* 52: 1–16.
734 <https://doi.org/10.1007/s10452-017-9641-4>

735 Nürnberg, G. (1996). Trophic state of clear and colored, soft- and hardwater lakes with special consideration of
736 nutrients, anoxia, phytoplankton and fish. *Lake and Reservoir Management* 12: 432–447.
737 <https://doi.org/10.1080/07438149609354283>

738 Olin, M., Tiainen, J., Rask, M., Vinni, M., Nyberg, K., Lehtonen, H. (2017). Effects of non-selective and size-
739 selective fishing on perch populations in a small lake. *Boreal Environment Research* 22: 137–155.

740 Oksanen, L., Fretwell, S.D., Arruda, J., Niemelä, P. (1981). Exploitation ecosystems in gradients of primary
741 production. *American Naturalist* 118: 240–260. <https://doi.org/10.1086/283817>

742 Paine, R.T. (1980). Food webs: Linkage, interaction strength and community infrastructure. *Journal of Animal*
743 *Ecology* 49: 667–685. <https://doi.org/110.2307/4220>

744 Post, D.M., Pace, M.L., Hairston Jr., N.G. (2000). Ecosystem size determines food-chain length in lakes. *Nature*
745 405: 1047–1049. <https://doi.org/10.1038/35016565>

746 Przytulska, A., Bartosiewicz, M., Vincent, W.F. (2017). Increased risk of cyanobacterial blooms in northern high-
747 latitude lakes through climate warming and phosphorus enrichment. *Freshwater Biology*, 62: 1986–1996.
748 <https://doi.org/10.1111/fwb.13043>

749 Rask, M., Malinen, T., Olin, M., Peltonen, H., Ruuhijärvi, J., Vesala, S., Hietala, J. (2020). Responses of the fish
750 community in a eutrophicated lake to long-term food web management assessed by multiple sampling methods.
751 *Hydrobiologia*, in press. <https://doi.org/10.1007/s10750-020-04243-9>.

752 R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical
753 Computing, Vienna, Austria. <https://www.R-project.org/>.

754 Rolls, R.J., Hayden, B., Kahilainen, K.K. (2017). Conceptualising the interactive effects of climate change and
755 biological invasions on subarctic freshwater fish. *Ecology and Evolution* 7: 4109–4128.
756 <https://doi.org/10.1002/ece3.2982>

757 Samarsin, P., Minns, C.K., Shuter, B.J., Tonn, W.M., Rennie, M.D. (2015). Fish diversity and biomass in northern
758 Canadian lakes: northern lakes are more diverse and have greater biomass than expected based on species–energy
759 theory. *Journal of Canadian Fisheries and Aquatic Sciences* 72: 226–237. <https://doi.org/10.1139/cjfas-2014->
760 0104

761 Senar, O.E., Creed, I.F., Strandberg, U., Arts, M.T. (2019). Browning reduces the availability but not the transfer
762 of essential fatty acids in temperate lakes. *Freshwater Biology* 64: 2107–2119. <https://doi.org/10.1111/fwb.13399>

763 Scharnweber K., Chaguaceda, F., Dalman, E., Tranvik, L., Eklöv, P. (2020). The emergence of fatty acids—
764 Aquatic insects as vectors along a productivity gradient. *Freshwater Biology* 65: 567–578.
765 <https://doi.org/10.1111/fwb.13454>

766 Scheffer, M., Carpenter, S.R. (2003). Catastrophic regime shifts in ecosystems: linking theory to observation.
767 *Trends in Ecology & Evolution* 18: 648–656. <https://doi.org/10.1016/j.tree.2003.09.002>

768 Schindler, D.W., Smol, J.P. (2006). Cumulative effects of climate warming and other human activities on
769 freshwaters of Arctic and subarctic North America. *Ambio* 35: 160–168. [https://doi.org/10.1579/0044-
770 7447\(2006\)35\[160:CEOCWA\]2.0.CO;2](https://doi.org/10.1579/0044-7447(2006)35[160:CEOCWA]2.0.CO;2)

771 Smit, H., van Heel E.D., Wiersma S. (1993). Biovolume as a tool in biomass determination of Oligochaeta and
772 Chironomidae. *Freshwater Biology* 29: 37–46. <https://doi.org/10.1111/j.1365-2427.1993.tb00742.x>

773 Strandberg, U., Hiltunen, M., Jelkänen, E., Taipale, S.J., Kainz, M.J., Brett, M.T., Kankaala, P. (2015). Selective
774 transfer of polyunsaturated fatty acids from phytoplankton to planktivorous fish in large boreal lakes. *Science of
775 the Total Environment* 536: 858–865. <https://doi.org/10.1016/j.scitotenv.2015.07.010>

776 Taipale, S.J., Strandberg, U., Peltomaa, E., Galloway, A., Ojala, A., Brett, M.T. (2013). Fatty acid composition
777 as biomarkers of freshwater microalgae: Analysis of 37 strains of microalgae in 22 genera and in seven classes.
778 *Aquatic Microbial Ecology* 71: 165–178 <https://doi.org/10.3354/ame01671>

779 Taipale, S.J., Vuorio, K., Strandberg, U., Kahilainen, K.K., Järvinen, M., Hiltunen, M., Peltomaa, E., Kankaala,
780 P. (2016). Lake eutrophication and brownification downgrade availability and transfer of essential fatty acids for
781 human consumption. *Environment International* 96: 156–166. <https://doi.org/10.1016/j.envint.2016.08.018>

782 Taipale, S.J., Peltomaa, E.J., Salmi, P. (2020). Variation in ω -3 and ω -6 polyunsaturated fatty acids produced by
783 different phytoplankton taxa at early and late growth phase. *Biomolecules* 10: 559.
784 <https://doi.org/10.3390/biom10040559>

785 Twining, C.W., Brenna, J.T., Hairston, N.G., Flecker, A.S. (2016). Highly unsaturated fatty acids in nature: what
786 we know and what we need to learn. *Oikos* 125: 749–760. <https://doi.org/10.1111/oik.02910>

787 Takimoto, G., Post, D.M., Spiller, D.A., Holt, R.D. (2012). Effects of productivity, disturbance, and ecosystem
788 size on food-chain length: insights from a metacommunity model of intraguild predation. *Ecological Research*
789 27: 481–493. <https://doi.org/10.1007/s11284-012-0943-7>

790 Takimoto, G., Post, D.M. (2013). Environmental determinants of food-chain length: A meta-analysis. *Ecological*
791 *Research* 28: 675–681. <https://doi.org/10.1111/1365-2656.12326>

792 Thomas, S.M., Crowther, T.W. (2015). Predicting rates of isotopic turnover across the animal kingdom: a
793 synthesis of existing data. *Journal of Animal Ecology* 84, 861–870.

794 Thomas, S.M., Harrod, C., Hayden, B., Malinen, T., Kahilainen, K.K. (2017). Ecological speciation in a
795 generalist consumer expands the trophic niche of a dominant predator. *Scientific Reports* 7: 8765.
796 <https://doi.org/10.1038/s41598-017-08263-9>

797 Thomas, S.M., Kainz, M., Amundsen, P.-A., Hayden, B., Taipale, S.J., Kahilainen, K.K. (2019). Resource
798 polymorphism in European whitefish: Analysis of fatty acid profiles provides more detailed evidence than
799 traditional methods alone. *PloSOne* 14: e0221338. <https://doi.org/10.1371/journal.pone.0221338>

800 Utermöhl, H. (1958). Zur Vervollkommnung der quantitativen Phytoplankton-Methodik. *Verhandlungen der*
801 *Internationalen Vereinigung für Theoretische und Angewandte Limnologie* 9: 1–38.

802 Vadeboncoeur, Y., Jeppesen, E., Vander Zanden, M.J., Schierup, H.-H. Cristoffersen, K., Lodge, D. M. (2003).
803 From Greenland to green lakes: Cultural eutrophication and the loss of benthic pathways in lakes. *Limnology and*
804 *Oceanography* 48: 1408–1418. <https://doi.org/10.4319/lo.2003.48.4.1408>

805 Vadeboncoeur, Y., Återson, G., Vander Zanden, M.J., Kalff, J. (2008). Benthic algal production across lake size
806 gradients: interactions among morphometry, nutrients and light. *Ecology* 89: 2542–2552.
807 <https://doi.org/10.1890/07-1058.1>

808 Vadeboncoeur, Y., Power, M. (2017). Attached algae: the cryptic base of inverted trophic pyramids in
809 freshwaters. *Annual Review of Ecology, Evolution, and Systematics* 48: 255–279.
810 <https://doi.org/10.1146/annurev-ecolsys-121415-032340>

811 Vesterinen, J., Devlin, S.P., Syväranta, J., Jones, R.I. (2016). Accounting for littoral primary production by
812 periphyton shifts a highly humic boreal lake towards net autotrophy. *Freshwater Biology* 61: 256–276.
813 <https://doi.org/10.1111/fwb.12700>

814 Vesterinen, J., Keva, O., Kahilainen, K.K., Strandberg, U., Hiltunen, M., Kankaala, P., Taipale, S.J. (2020).
815 Nutritional quality of littoral macroinvertebrates and pelagic zooplankton in subarctic lakes. *Limnology and*
816 *Oceanography*. Early view, <https://doi.org/10.1002/lno.11563>

817 Ward, C.L., McCann, K.S. (2017). A mechanistic theory for aquatic food chain length. *Nature Communications*
818 8: 2028. <https://doi.org/10.1038/s41467-017-02157-0>

819 Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York.

820 Winfield, I.J., Nelson, J.S. (1991). *Cyprinid fishes: Systematics, biology and exploitation* Cambridge University
821 Press, Cambridge.

822 Yeşilayer, N., Kaymak, I.E. (2020). Effect of partial replacement of dietary fish meal by soybean meal with
823 betaine attractant supplementation on growth performance and fatty acid profiles of juvenile rainbow trout
824 (*Oncorhynchus mykiss*). *Aquaculture Research* 51: 1533-1541. <https://doi.org/10.1111/are.14501>

825 Zubova, E.M., Kashulin, N.A., Dauvalter, V.A., Denisov, D.B., Valkova, S.A., Vandysh, O.I., ... , Cherepanov,
826 A.A. (2020). Long-term environmental monitoring in an Arctic lake polluted by metals under climate change.
827 *Environments* 7: 35. <https://doi.org/10.3390/environments7050034>

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829 7. Figure legends

830 Fig. 1. Map of the study region (a) in northern Fennoscandia and boxplot figures of the basic lake chemistry (b–d) and
831 physics (e–f) of the sampled lakes. The study lakes are marked with grey shade shapes (a) or boxes (b–f) indicating different
832 lake types (light grey = ultraoligotrophic, grey = oligotrophic, dark grey = mesotrophic, black = eutrophic). Abbreviations
833 in x-axes labels are named as following: TotP=total phosphorous (B), TotN = total nitrogen (c), DOC = dissolved organic
834 carbon (d), Temp = average air temperature in June–September 1981–2010 (e), CompD = compensation depth i.e. water
835 depth where 1% surface light is left (f).

836 Fig. 2. Community structure (a), biomass (b) and computed community quality (FA content, c) across different lake types
837 (x-axis). Food web community compartments: phytoplankton (1), zooplankton (2), littoral benthos (3), profundal benthos
838 (4), invertivorous fish (5) and piscivorous fish (6) are presented in different columns. The coloured bars indicate average
839 taxa values of different lake types as following: normalized relative community composition (a: biomass %), lake type
840 average biomass (b1: g dw m⁻³, b2: mg dw m⁻³, b3–b6: kg dw ha⁻¹) and lake type average community EPA and DHA content
841 (c: mg FA g⁻¹ dw). Lake specific community bulk FA content is derived from the FA analysed bulk sample (c2: zooplankton)
842 and calculated for other food web community compartments (c1, c3–c6) from taxa specific biomass contribution and fatty
843 acid content. Whiskers on top of the lake type average (b and c rows) represents + SD.

844 Fig. 3. Linear regression models showing (a–b): Community biomass (kg dw ha⁻¹) and quality (mg EPA+DHA g⁻¹ dw)
845 against climate-productivity index (CPi) and (c): EPA + DHA areal content (kg EPA+DHA ha⁻¹) against total food web
846 biomass (kg dw ha⁻¹). Food web community compartments: phytoplankton (1), zooplankton (2), littoral benthos (3),
847 profundal benthos (4), invertivorous fish (5) and piscivorous fish (6) are presented in different columns. The grey shaded
848 shapes indicate different lake trophy corresponding to Fig. 1: light grey square = ultraoligotrophic, grey dot = oligotrophic,
849 dark grey triangle = mesotrophic, black diamond = eutrophic. Linear regressions fits (bolded line), 95% confidence limit
850 (grey shaded areas) and adjusted coefficient of determination (r^2) are presented in the figures if the model was statistically
851 significant ($p < 0.05$). Linear regression equations, F statistics, adjusted r^2 and p values are presented for each model in Table
852 S6.

853 Fig. 4. Relative biomass (a) and FA stock (b) pyramids by food web compartments for the lake types. The pyramid steps
854 represent lake type averages of relative biomass or EPA+DHA areal content and are ordered with trophic level from bottom-
855 up order: 1) phytoplankton, 2) invertebrates, 3) invertivorous fish and 4) piscivorous fish. The second trophic level
856 (invertebrates) are divided among profundal benthos, littoral benthos and zooplankton with patterns: transparent, spots,
857 stripes respectively. Different lake types, ultraoligotrophic, oligotrophic, mesotrophic and eutrophic respectively, are
858 separated into different columns delineated with dashed lines and additionally with light grey, grey, dark grey, black
859 respectively. The lake specific data is presented at Fig. S2. Abbreviations in legend are BMI = benthic macroinvertebrates
860 and ZPL = zooplankton.

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