

Appendix - Effects of habitat-specific primary production on fish size, biomass and production in northern oligotrophic lakes

The 27 lakes are situated in the western mountain region of Sweden between 501 to 998 meters above sea level in the Västerbotten (northern) and Jämtland (southern) counties (table A1, fig A1). They are all oligotrophic clear to medium colored lakes in terms of light attenuation with K_d values in the range of 0.19 – 1.47 m^{-1} , DOC in the range of 0.45 – 7.51 mg/l, total nitrogen (TN) 68 – 199 $\mu g/l$ and total phosphorous (TP) at 3.7 – 8.1 $\mu g/l$ (table A1).

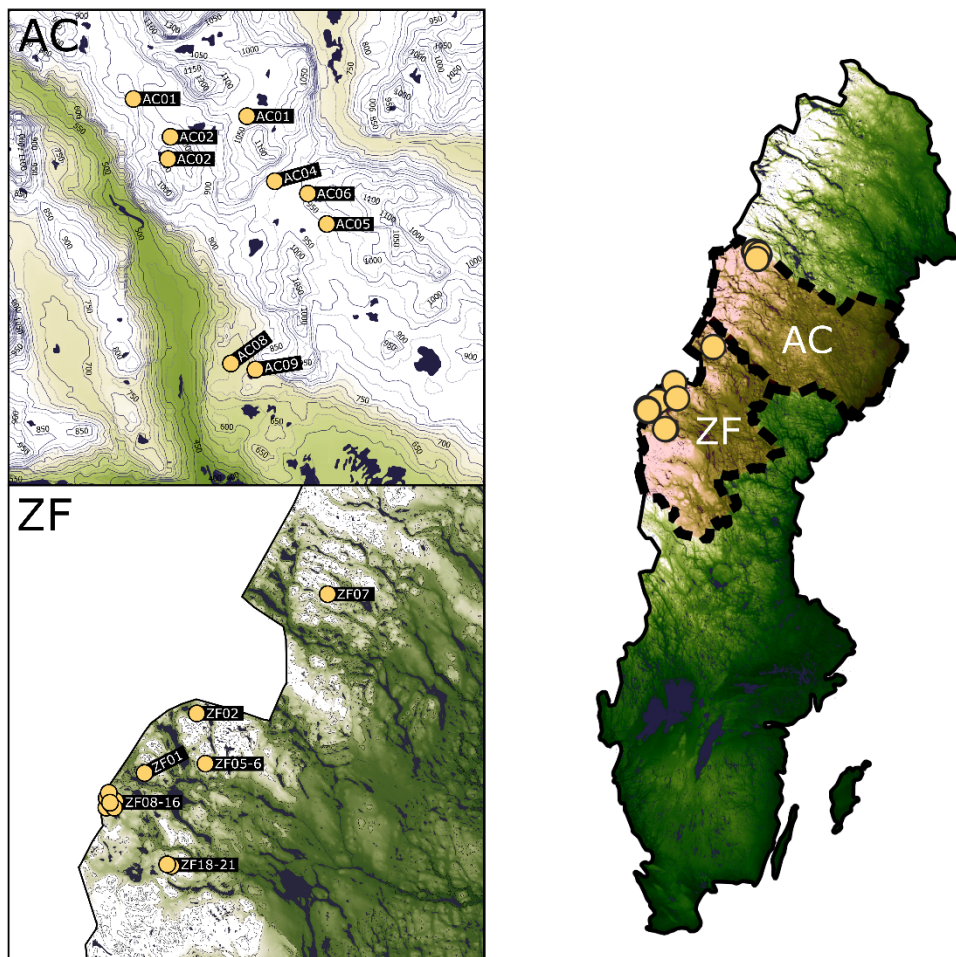


Figure A1. Locations of the sampled lakes in the Västerbotten (AC) and Jämtland (ZF) counties in Sweden. See table A1 for lake names and characteristics to corresponding lake ID's. The isoclines in the AC pane denote elevation changes of 50 meters and are shown for the sake of illustrating rough height/elevation patterns. For exact heights of the lakes, we refer to table A1. The treeline in Sweden typically ranges between 700-1000 meters above sea level (m.a.s.l.) depending on latitude and local conditions. Here the treeline is approximated and illustrated by the green color fading away at approximately 700 m.a.s.l.

The 9 lakes in Västerbotten (AC) as well as Avundtjärnen, Svartvikstjärnarna, Baulanjaure, Jille Baulanjaure and Klingervattnet in Jämtland were sampled in the summer of 2016. The 13 remaining lakes in Jämtland were sampled in the summer of 2017.

Table A1. Lake names, locations and lake data used in the analysis. Lake ID's that starts with AC are situated in the county Västerbotten and the lakes with ID that starts with ZF in the county of Jämtland, see also figure A1. Community type are either Allopatric (one species lake) or sympatric (two species). Species in the lakes is denoted by C = Arctic char and T = brown trout. Open water season averages of parameters and variables $\pm$ standard deviation are shown where applicable. Temperature corresponds to average air temperature over the open water season. GPP_{whole} estimates are missing in lake ID ZF01, ZF05-07 because no oxygen loggers could be deployed due to the remoteness of the lakes.

Lake name	Lake ID	Community type	Species	Year sampled	Coordinates		masl	Temperature	Area	Mean depth	Maximum depth	Light attenuation coefficient (K _d)	Light Climate (I _m)	Benthic proportion of GPP _{whole}	GPP _{whole}	DOC	TDN	TN	TP
					SWEREF 99 TM														
					North	East	m	°C	ha	m	m	m ⁻¹	-	-	mg O ₂ L ⁻¹ d ⁻¹	mg L ⁻¹	µg L ⁻¹	µg L ⁻¹	µg L ⁻¹
Skrapiemjåure	AC01	Allopatric	C	2016	7335091	551745	875	8.39	6.85	2.7	6	0.43 ± 0.06	0.59	0.94	0.31 ± 0.17	1.60 ± 0.21	55.9 ± 14.0	110.6 ± 23.5	5.4 ± 1.1
Aitelnastjärnen	AC02	Allopatric	T	2016	7331779	553731	913	8.81	13.95	3.8	10.8	0.30 ± 0.03	0.59	0.93	0.15 ± 0.08	1.14 ± 0.35	57.6 ± 28.0	101.2 ± 19.4	8.1 ± 1.7
Mattekjåure	AC03	Allopatric	C	2016	7332271	553367	951	7.96	12.17	10.9	27.8	0.19 ± 0.03	0.42	0.84	0.09 ± 0.07	0.46 ± 0.25	32.7 ± 24.8	67.8 ± 21.5	7.8 ± 2.5
Lisvojaure	AC04	Allopatric	T	2016	7330271	557891	899	8.32	39.8	1.8	4.7	0.59 ± 0.09	0.61	0.95	0.28 ± 0.11	1.92 ± 0.20	59.7 ± 20.0	108.6 ± 25.7	6.1 ± 3.2
Tjappisjaure	AC05	Allopatric	T	2016	7327789	561447	919	8.15	20.91	0.9	2.9	0.65 ± 0.10	0.76	0.94	0.33 ± 0.14	1.71 ± 0.39	65.8 ± 15.4	107.2 ± 15.9	5.0 ± 0.6
Ruohatajavratje	AC06	Allopatric	T	2016	7329906	559647	927	8.12	8.28	0.5	2.2	0.57 ± 0.11	0.87	0.95	0.36 ± 0.15	1.42 ± 0.34	60.0 ± 18.3	106.5 ± 18.2	6.0 ± 1.4
Båsatjaure	AC07	Allopatric	C	2016	7334060	556870	998	7.80	36.32	6.7	22.7	0.39 ± 0.07	0.35	0.87	0.09 ± 0.11	0.92 ± 0.26	37.7 ± 13.0	81.4 ± 19.2	5.4 ± 1.2
Stor-Bissitj	AC08	Sympatric	C,T	2016	7321704	556473	663	9.35	12.69	2.6	13	0.64 ± 0.07	0.49	0.92	0.15 ± 0.14	2.87 ± 0.48	95.9 ± 29.1	134.5 ± 7.2	6.6 ± 0.5
Övre Buongukjaure	AC09	Sympatric	C,T	2016	7321805	557708	708	9.17	9.75	3.5	11.2	0.32 ± 0.08	0.60	0.93	0.27 ± 0.35	2.32 ± 0.19	109.5 ± 23.5	168.0 ± 34.6	6.5 ± 0.6
Avundtjärnen	ZF01	Sympatric	C,T	2016	7070150	382107	553	8.87	26.38	4.6	16.7	0.54 ± 0.22	0.37	0.90	-	2.77 ± 0.97	97.9 ± 30.3	109.9 ± 12.8	4.3 ± 0.4
Svartvikstjärnen	ZF02	Allopatric	T	2016	7103861	410488	684	10.40	5.52	1.1	3.5	0.70 ± 0.26	0.70	0.95	0.31 ± 0.21	2.95 ± 0.64	114.6 ± 10.8	119.0 ± 32.9	4.8 ± 0.9
Baulanjaure	ZF05	Sympatric	C,T	2016	7076076	416131	696	10.69	38.51	3.9	15.5	0.52 ± 0.07	0.43	0.93	-	2.88 ± 0.19	97.6 ± 23.3	117.0 ± 29.5	4.2 ± 0.6
Jille Baulanjaure	ZF06	Sympatric	C,T	2016	7075829	415435	697	10.69	22.39	5.1	23.1	0.67 ± 0.19	0.28	0.87	-	3.13 ± 0.76	101.6 ± 24.4	126.9 ± 11.0	4.4 ± 0.4
Klingervattnet	ZF07	Allopatric	T	2016	7166334	479940	649	10.93	18.8	4.9	16.3	0.63 ± 0.07	0.31	0.84	-	3.23 ± 0.20	128.8 ± 24.4	146.2 ± 37.5	5.9 ± 3.7
Godbäckstjärnen	ZF08	Sympatric	C,T	2017	7059237	363483	501	9.40	7.06	4.8	14.5	0.65 ± 0.10	0.31	0.85	0.09 ± 0.08	3.98 ± 0.22	123.3 ± 12.6	139.5 ± 6.3	3.9 ± 1.0
Hägglidstjärnen	ZF09	Allopatric	T	2017	7058001	362474	618	8.80	4.02	2.7	8.5	0.97 ± 0.22	0.35	0.87	0.18 ± 0.26	4.51 ± 0.49	132.9 ± 23.8	143.0 ± 17.0	4.3 ± 0.8
Bergtjärnen	ZF10	Sympatric	C,T	2017	7058066	364184	573	8.93	13.64	10.2	31.2	0.40 ± 0.05	0.24	0.81	0.09 ± 0.09	2.05 ± 0.13	88.5 ± 7.1	106.4 ± 13.3	3.7 ± 1.0
Vargtjärnen	ZF11	Sympatric	C,T	2017	7057738	364649	564	9.00	11.88	3.9	14.5	1.15 ± 0.36	0.22	0.81	0.10 ± 0.10	6.23 ± 1.10	189.2 ± 15.7	194.5 ± 12.6	4.5 ± 0.2
Lång-Björnsjön	ZF12	Sympatric	C,T	2017	7055980	364401	590	8.83	13.37	3	10.3	1.00 ± 0.28	0.32	0.85	0.11 ± 0.09	5.10 ± 1.43	151.5 ± 49.9	165.0 ± 43.9	3.9 ± 0.3
Bustatjärnen	ZF13	Allopatric	T	2017	7054522	364264	588	8.84	4.27	3.7	9.7	1.43 ± 0.24	0.19	0.79	0.11 ± 0.09	7.52 ± 1.08	184.9 ± 19.3	188.4 ± 22.7	4.8 ± 0.6
Dörrstjärnen	ZF14	Allopatric	T	2017	7054747	365854	622	8.65	4.95	2.7	8.7	0.89 ± 0.17	0.38	0.89	0.14 ± 0.10	4.90 ± 1.23	152.8 ± 41.6	183.1 ± 37.0	3.8 ± 0.4
Gravatjärnen	ZF15	Allopatric	T	2017	7053633	364093	576	9.05	4.5	1.3	3.7	1.43 ± 0.53	0.46	0.89	0.27 ± 0.25	7.13 ± 1.63	187.1 ± 40.5	199.3 ± 27.9	5.3 ± 1.2
Hästbäckstjärnen	ZF16	Allopatric	T	2017	7053556	364814	582	9.00	4.68	1.8	4.8	1.47 ± 0.18	0.35	0.88	0.21 ± 0.16	7.50 ± 1.25	185.8 ± 29.6	193.9 ± 45.1	5.0 ± 0.7
Hästskotjärnen	ZF18	Sympatric	C,T	2017	7022370	394940	735	7.99	6.03	2.1	8.7	0.84 ± 0.05	0.47	0.91	0.15 ± 0.24	4.48 ± 0.26	135.8 ± 26.2	173.9 ± 52.8	4.8 ± 0.6
Högdalstjärnen	ZF19	Allopatric	C	2017	7021735	395792	812	7.52	9.15	5.7	12.7	0.60 ± 0.05	0.28	0.83	0.07 ± 0.06	3.23 ± 0.22	98.4 ± 11.4	135.9 ± 46.9	4.5 ± 0.3
Topptjärnen	ZF20	Allopatric	C	2017	7021436	396251	840	7.35	4.63	2.7	7.4	0.47 ± 0.09	0.56	0.93	0.13 ± 0.07	2.73 ± 0.08	100.7 ± 15.9	126.4 ± 12.6	4.2 ± 1.1
Valtjärnen	ZF21	Allopatric	T	2017	7022017	396945	710	8.11	4.78	3.8	11.8	0.88 ± 0.12	0.29	0.83	0.16 ± 0.28	5.31 ± 0.44	152.9 ± 28.6	166.5 ± 36.9	4.5 ± 0.6

Methods for whole-lake GPP estimation

Logger deployment

We deployed logger arrays hanging from buoys anchored at the deepest point of each lake. The logger arrays were deployed as close to ice-off as possible and was left in the lakes as close to ice-on as possible. Dissolved oxygen (*DO*) concentration was measured at 10 min intervals at 0.5 m depth using optical oxygen probes (MiniDOT, PME, Vista, CA, U.S.A.). In lakes with a maximum depth >3m, we deployed an additional logger at 0.7–7.2 m (mean 2.5 m) from the bottom to capture potential stratification effects. Probe sensors were cleaned every 1-2 months and protected from biofilms with a copper mesh. The probes were checked at nominal 0% and 100% saturation solutions of *DO* before and after field deployment. This comparison showed that 73% and 98% of all loggers were within 5% and 10% from 100% saturation, and 70% and 100% of all loggers were within 0.5% and 1% from 0% saturation respectively. We corrected for offsets by multiplying logger readings with the slope and adding the intercept of a linear regression model that relates logger readings and true concentrations in reference solutions with 0% and 100% saturation. We observed drifts larger than the certified logger accuracy (0.3 mg L⁻¹) in 6% of all loggers, with a maximum drift of 0.4 mg L⁻¹ at 100% saturation. We corrected for these changes assuming linear drifts. *DO* readings by loggers were compared with manual field measurements collected every 0.5 m (0-3 m) or 1 m (3-10 m) at 3-4 times per season using a handheld oxygen probe (ProDO, YSI, Yellow Springs, OH, U.S.A.). Median logger readings collected within ±3 hours of the field visit correlated strongly with manual measurements (mean (±sd) difference of 0.42±0.55 mg L⁻¹, *r*=0.89, *n*=172). *DO* logger data was missing for a period of 70 days in one lake (AC01, near surface) and for 12 days in another lake (AC02, near surface and near bottom). We assumed that near surface *DO* in AC01 was similar to the near bottom *DO*, supported by the fact that the lake was nearly continuously mixed (longest stratification was < 2 days). We assumed the collected data in AC02 to be representative for the whole study period, supported by the fact that the lake did not differ from the remaining dataset in terms of patterns among lakes analyzed for in this study.

We measured water temperature at 10 min intervals using thermistors (Hobo TidbiT V2, Onset Computer Corporation, Bourne, MA, U.S.A.) located at 0.5 m intervals in the upper 3 m and at 1-5 m intervals down to the lake bottom. All thermistors were within the certified accuracy of 0.2°C when kept overnight in an ice bath before and after field season. At an open location within 100 m of every lake, we measured Lux at 1m above ground every 10 min using light loggers (Hobo UA-002-64). Two Lux meters were lost during the summer (AC05 and AC06) so we used light data from the nearby AC04 to represent the three lakes. At the shore of three lakes (ZF11, ZF20, AC03) we deployed weather stations (Hobo U30-NRC) and measured wind speed, relative humidity, air temperature and air pressure every 10 s and logged averages every ten minutes. At 13 additional lakes (AC01-AC09, ZF09, ZF14, ZF15, ZF18), we deployed cup anemometers (HOBO S-WSA-M003). All anemometers were installed on islands or the main land within 1-50 m from the shoreline (average 10 m) at 1.9-2.5 m above ground. We did not *a priori* know the prevalent wind direction for every lake. We therefore placed the anemometers at accessible locations with fetches that were assumed to be as representative as possible for the

lake centroid. We verified this assumption for the lakes with weather stations (Klaus and others, 2021).

Wind speed computation

We scaled wind speed from anemometer height (z) to standard heights of 10 m above ground using law of the wall scaling, $U_{10} = U_z \left(1 + \frac{C_D^{0.5}}{K} \log \left(\frac{10}{z} \right) \right)$, where $K = 0.4$ is the von Kármán constant, and C_D is the drag coefficient computed following Klaus et al. (2021). Specifically, C_D was parameterized by a function of wind sheltering to account for lower wind drag in less sheltered lakes following Klaus and others (2021): $C_D = 2.4171 \cdot 10^{-3} - 4.304 \cdot 10^{-4} W_{str}$, where W_{str} is a shelter coefficient (Markfort and others 2010) $W_{str} = \frac{\frac{D^2}{2} \cos^{-1} \frac{x_t}{D} - \frac{x_t}{2} \sqrt{D^2 - x_t^2}}{A}$, where $D = 2 \sqrt{\frac{A}{\pi}}$ is the equivalent circular diameter of the lake, A is lake surface area, and $x_t = h_c l_c$ is the shear deficit length, here assuming $l_c = 50$ times the adjacent canopy height (h_c) (Markfort et al. 2010). The W_{str} index of a given lake is larger the smaller the lake is, and the higher the canopy. W_{str} is 1 for a fully wind exposed lake and 0 for a fully sheltered lake. We estimated h_c for 50 m wide buffers around each lake using gridded canopy height data, following Klaus et al. (2021). We computed U_{10} at time t for lakes in Jämtland *without* wind measurements (X), using U_{10} from the nearest lake (N) *with* wind measurements $U_{10X}(t) = U_{10N}(t) \frac{\overline{U_{10X}}}{\overline{U_{10N}}}$, assuming that their ratio is the same as the ratio of the respective sampling season average wind speed ($\overline{U_{10}}$). We estimated $\overline{U_{10}}$ as a function of W_{str} by the relationship $\overline{U_{10}} = 1.14 + 2.93 W_{str}$ which we found for the lakes with wind measurements ($R^2 = 0.98$, $n = 6$).

Logger data treatment

We identified outliers in temperature and DO time series as readings that differed $> 1^\circ\text{C}$ and $> 3 \text{ mg L}^{-1}$ from the running median of 1 hour window length. These values were associated with reading errors or logger maintenance work and filled by linear interpolation.

We used thermistor data to calculate the depths of the actively mixing layer (z_{mix}) marking the upper boundary of the metalimnion, and the lower boundary of the metalimnion (z_{lwr}) using functions provided by the ‘rLakeAnalyzer’ package for R (Read and others 2011). We defined z_{mix} and z_{lwr} as the upper- and lowermost depths with a lake-specific vertical density gradient of 0.05 kg m^{-3} per meter. We evaluated a range of density thresholds of 0.01 - 0.10 kg m^{-3} per meter commonly used in the literature (Gray and others 2020), but did not find any notable effect on metabolism estimates.

Due to logger malfunction, overall 11% of data on LUX , z_{mix} , z_{lwr} and wind speed was missing. LUX was missing in 18 lakes on average for 33 days. Wind speed was missing for six lakes on average for 43 days. z_{mix} and z_{lwr} were missing in one lake for 26 days. We gap-filled these data using linear regressions based on available data from the nearest lake most similar in morphology. The average R^2 values of these regressions was 0.71 for LUX , 0.69 for wind speed and 0.54 for z_{mix} and z_{lwr} .

Additional measurements and calculations

During each field visit, depth profiles of photosynthetically active radiation (PAR) were measured every 0.5 m (0-3 m) or 1 m (3-10 m) using a handheld probe (LI-193 Spherical Quantum Sensor, LI-COR Bioscience, Lincoln, NE, U.S.A.). We calculated light extinction coefficients (k_d) as the slope of the linear regression between natural logarithm of PAR and depth. To match temporal resolutions with logger data, we interpolated k_d values linearly to achieve 10 min resolution.

Metabolism modeling

Estimating daily depth-specific metabolism

Separately for each DO probe, we calculated daily metabolism and assumed these estimates to be representative for the specific layer that the DO probes were located in (hereafter referred to as *DO probe footprint*, see also section *Delineation of DO probe footprints* for more details). We calculated daily GPP and ER as functions of light and temperature, respectively, using well-established functions available through the “LakeMetabolizer” package of the statistical program R (Winslow and others 2016). Specifically, $GPP = l \cdot \sum_t PAR_t$ and $ER = p \cdot \sum_t \ln(T_t)$ where l is a parameter describing GPP per unit of incoming photosynthetically active radiation (PAR , $\mu\text{mol m}^{-2} \text{s}^{-1}$) experienced by primary producers in the DO probe footprint, p is a parameter describing the average rate of respiration per natural logarithm of water temperature (T , $^{\circ}\text{C}$) as measured by the DO probe. We estimated l and p for each DO probe and sampling day (0-24 h) using a maximum likelihood approach by Solomon et al. (2013) by means of the Nelder-Mead optimization method, where the time series of DO is modeled as

$$DO_t = DO_{t-\Delta t} + l \cdot PAR_{t-\Delta t} + p \cdot \ln(T_{t-\Delta t}) + F_{t-\Delta t} + \varepsilon_t$$

where t is the sampling time, Δt is the sampling time interval, ε_t is the observation error, and $F_t = d_t \frac{k_t \Delta t}{z_{mix_t}} (DO_{sat_t} - DO_t)$ is the oxygen flux across the air-water interface, k is the air-water gas transfer velocity modeled based on measured wind speed following Cole and Caraco (1998), and DO_{sat} is the oxygen concentration at saturation, calculated from water temperature and atmospheric pressure, following Garcia and Gordon (1992) and assuming a salinity of 0. We set d_t to 1 if the oxygen probe was within the actively mixing layer ($z_{mix_t} > z_{probe}$) and to 0 if it was below.

Delineation of DO probe footprints

We set the upper and lower boundaries of the near-surface DO probe footprint to the water surface and z_{mix} , respectively, if the probe was in the epilimnion ($z_{mix_t} > z_{probe}$), and to z_{mix} and $z_{probe} + 0.5$ m, respectively, if the probe was in the metalimnion ($z_{mix_t} \leq z_{probe} < z_{lwr_t}$). We set the upper and lower boundaries of the footprint of the near-bottom DO probe to the water surface and z_{mix} , respectively, if the probe was in the epilimnion ($z_{mix_t} > z_{probe}$), to $z_{probe} - 0.5\text{m}$ and z_{lwr} , respectively, if the logger was in the metalimnion ($z_{mix_t} \leq z_{probe} < z_{lwr_t}$), and to z_{lwr} and the lake bottom, respectively, if the logger was in the hypolimnion ($z_{lwr_t} \geq z_{probe}$).

We calculated the average *PAR* within the DO probe footprint as a function of k_d and *PAR* at the water surface using Beer's law (equation 1, table A2). We approximated *PAR* at the water surface by dividing *LUX* measurements from light loggers by 54, following Thimijan and Heins (1983).

Estimating uncertainties in daily depth-specific metabolism

We estimated uncertainties in depth-specific metabolism from 10 000 daily metabolism estimates using a two-stage nested bootstrapping approach. In the *first* stage, we accounted for uncertainties in input data resulting from gap filling of *PAR*, *wind speed*, z_{mix} and z_{lmet} . We generated 100 bootstrap realizations of input data time series by randomly sampling from normal distributions defined by means and standard deviations of predictions of input data, or otherwise used raw data with standard deviations set to 0. In the *second* stage, we estimated for each input data realization the daily GPP and ER as described above. We bootstrapped the model fits of *DO* times series 100 times by adding process errors to the modelled *DO* time series and maintaining autocorrelation in residuals (Solomon and others 2013). This yielded, for each sampling day, estimates of means and standard deviations that account for uncertainties in the model fits. The result of this nested bootstrap approach was daily mean estimates (μ) of depth-specific metabolism (GPP and ER) with two independent standard deviation terms: σ_{DO} reflecting *DO* model uncertainty, and σ_{gap} , reflecting uncertainty due to gap filling of input data.

Seasonal integration of daily depth-specific metabolism

We calculated the seasonal mean $\pm$ sd GPP for the epilimnion (GPP_{EPI}) and hypolimnion (GPP_{HYP}) from daily GPP estimates for the near-surface DO probes and the near-bottom DO probes, respectively. Specifically, we calculated the weighted mean and sd of daily estimates, with weights of $1/\sqrt{\sigma_{DO}^2 + \sigma_{gap}^2}$, i.e. giving more weight to daily estimates with less uncertainty. Here, we excluded sampling days with "bad" model fits when DO dynamics were dominantly driven by processes other than the ones considered in our model. We flagged the model fit of a specific day as "bad" if $\sigma_{DO} \geq 4 \mu$ for this day was larger than the third quartile plus 1.5 times the interquartile range of all other observation days for a given DO probe. We chose this threshold as a trade-off between minimizing inclusion of bad fits and maximizing the ability to capture seasonal and day-to-day variation in metabolism. We also excluded sampling days on which the near-surface and near-bottom DO probes were not located in the epilimnion or hypolimnion, respectively. This was the case on only few days under stratified conditions ($1.5 \pm 3.5\%$ and $4.4 \pm 8.0\%$ of all days, respectively) and during these rare occasions the loggers were located in the metalimnion. Overall, and mainly due to bad model fits, we excluded $36 \pm 5\%$ of sampling days for the near-surface water probe, and $39 \pm 11\%$ for the near-bottom water probe (mean $\pm$ sd among lakes).

Depth-integrating seasonal mean metabolism

We depth-integrated the seasonal mean estimates of depth-specific GPP (GPP_{EPI} and GPP_{HYP}) to estimate whole-lake seasonal mean $\pm$ sd GPP (GPP_{whole}). Specifically, we summed

GPP_{EPI} and GPP_{HYP} and weighted these estimates by the time-averaged proportion of lake-volume that was occupied by the specific depth layer relative to the whole lake volume:

$$GPP_{Whole} = GPP_{EPI} \left(w \cdot \frac{\sum_t V_{MET_t}}{V_{TOT} \cdot n} + \frac{\sum_t V_{EPI_t}}{V_{TOT_t} \cdot n} \right) + GPP_{HYP} \left((1 - w) \cdot \frac{\sum_t V_{MET_t}}{V_{TOT} \cdot n} + \frac{\sum_t V_{HYP_t}}{V_{TOT_t} \cdot n} \right)$$

where V_{EPI_t} , V_{MET_t} and V_{HYP_t} are the volumes of the epilimnion, metalimnion and hypolimnion, respectively, at sampling time t , n is the total number of DO observations during the sampling season and w is a weighting factor set to 0.5. Our approach accounts for the change in volume of depth layers over time and assumes that volumetric metabolic rates in the metalimnion were the arithmetic means of those in the epilimnion and hypolimnion.

Estimating habitat specific contribution to GPP_{Whole}

The benthic and pelagic contributions to our measures of whole lake gross primary production were estimated using a modified version of a model first presented by Vadeboncoeur et al. (2008) named *the autotrophic structure model* in (Devlin and others 2016). The model accounts for lake morphometry, light attenuation and inherent maximum productivity of algae in different habitats (mean values estimated from reference lakes is used, see below). The model equations are summarized in table 2 and input parameters in table 3. In comparison, the two methods of estimating GPP_{Whole} in this study (free-water diel oxygen technique and the autotrophic structure model) was correlated although their estimates did not follow a 1:1 line (fig. A2).

Parameter estimation

We used a data set from 2005 analyzed in Ask et al. (2009) to estimate the maximum productivity of epipelagic algae (BP_{maxS}) and phytoplankton (PP_{max}) in northern Scandinavian lakes, two critical parameters in the autotrophic structure model (Vadeboncoeur and others 2008; Devlin and others 2016). Ask et al. (2009) measured production at several depths in both the pelagic and the benthic habitat 5 times over the summer season in 4 lakes near Abisko, Sweden. These lakes are oligotrophic and situated below (Almberga (382 masl), Tjabrak (508 masl)) and above (Ruozut (710 masl) and Vuore (712 masl)) the tree line, and they therefore constitute reasonable reference lakes for the range of lakes in our study. In short methodological summary, Ask et al. (2009) estimated phytoplankton production by standard ^{14}C incorporation methods in 4 hour incubations during solar noon as well as benthic production by sediment core incubations over 24 hours (See Ask, J et al. 2009 for further details).

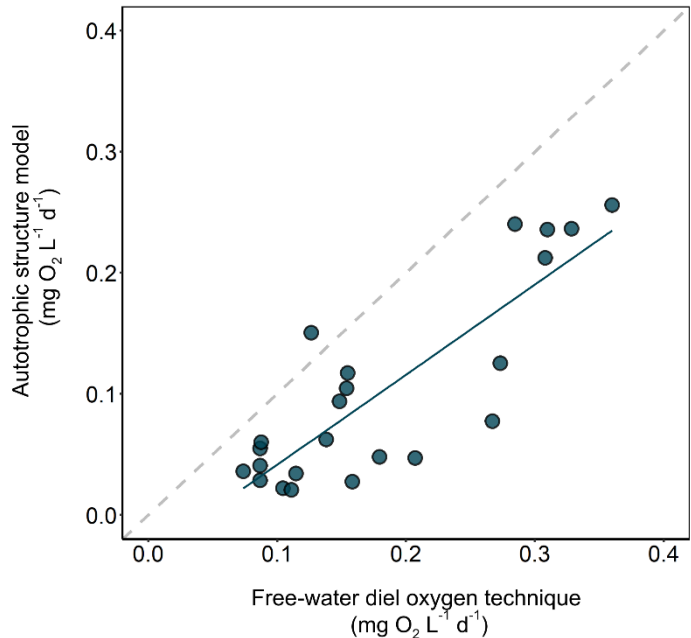


Figure A2. The correlation ($p < 0.001$ adjusted $r^2 = 0.41$) between whole lake primary production estimated by the free-water diel oxygen technique (x-axis) and by the autotrophic structure model (y-axis). The dashed grey lines denote the 1:1 relationship.

Water volumes and bottom areas were here based on bathymetric measures of 0.1 m depth increments in each lake which was obtained using QGIS and the function hypsometric curves (QGIS Development Team 2020) from integrated GPS and echo-sounding depth measurements (transects ~ 10 – 15 m apart). We further divided the benthic area into two functional habitats where the rocky shores (depth <2m) was given a literature based value of maximum productivity (BP_{max_R}) of $5 \text{ mg C m}^{-2} \text{ h}^{-1}$ corresponding to measured productivity on rocks and wood in lakes (Vadeboncoeur and others 2008). To estimate PP_{max} we divided the measured 4 hour total phytoplankton production at each depth by 4 and used the maximum value of all measured depths. We then averaged these values from all sampling dates for each reference lake, and used the average value of all four lakes to obtain a value of PP_{max} (table A3). Because Ask et al. (2009) deployed the incubations for benthic production over 24 hours we could not estimate the maximum productivity of benthic algae (BP_{max_S}) directly. Instead, we ran the model for two arbitrary BP_{max_S} using the light levels at the sampling dates (Swedish Meteorological and Hydrological Institute and others) and thus acquired a linear association between BP_{max_S} and the modelled 24 hour benthic production. We used the resulting equation: $BP_{max_S} = slope * total\ production + intercept$ to solve for BP_{max_S} using the total 24 hour benthic production that was measured by Ask et al. (2009). We thus acquired estimates of BP_{max_S} for each sampling occasion that we then averaged across sampling dates and across lakes, obtaining a value of $BP_{max_S} = 45.66 \pm 21.75$ (table A3). The parameter light at depth (z) at time (t) (I_{zt}) was estimated using the lake specific K_d , the surface light at time (t) and equation 1 (table A2).

Table A2. Equations used for estimating habitat specific production by the modified version of the autotrophic structure model (Vadeboncoeur et al., 2008). Production was calculated at 0.1 m depth intervals for every hour and day over the open water season. The daily whole lake benthic production is the sum of the production in the epilithic (0 – 2 m) and the epipelagic (2m – maximum depth) habitat. The benthic proportion of GPP_{Whole} was calculated on the seasonal sums of production in each major habitat (benthic and pelagic). See table A3 for description of symbols.

Equation		
number	Description	Equation
1	Light at depth z at time t	$I_{zt} = I_{surface\ t} \times e^{-K_d \times Z}$
2	Daily epilithic production at depth z	$PP_{R,Z} = \Delta t \sum_{t=1}^{24} BP_{max_R} \times \tanh\left(\frac{I_{zt}}{I_{kb}}\right) \times Area_z$
3	Daily epipelagic production at depth z	$PP_{S,Z} = \Delta t \sum_{t=1}^{24} BP_{max_S} \times \tanh\left(\frac{I_{zt}}{I_{kb}}\right) \times Area_z$
4	Daily phytoplankton production at depth z	$PP_{P,Z} = \Delta t \sum_{t=1}^{24} PP_{max} \times \tanh\left(\frac{I_{zt}}{I_{kp}}\right) \times Volume_z$
5	Daily whole lake benthic production	$BP_{tot} = \Delta z \sum_{Z=0.1}^{1.9} PP_{R,Z} + \Delta z \sum_{Z=2}^{Z_{max}} PP_{S,Z}$
6	Daily whole lake pelagic production	$PP_{tot} = \Delta z \sum_{Z=0.1}^{Z_{max}} PP_{P,Z}$
7	Benthic proportion of GPP_{Whole}	$BP_{GPP} = \sum_{Season\ start}^{Season\ end} BP_{tot} / \left(\sum_{Season\ start}^{Season\ end} BP_{tot} + \sum_{Season\ start}^{Season\ end} PP_{tot} \right)$

According to Vadeboncoeur et al. (2008), the maximum productivity on unconsolidated sediments is around 50 mg C m⁻² h⁻¹ in oligotrophic and mesotrophic lakes and Vander Zanden and others (2011) used a value of BPmax_s at 30 mg C m⁻² h⁻¹ as their approximation of benthic productivity in oligotrophic to mesotrophic lakes. These values corresponds well to our estimated value of 45.66 from the reference lakes (table A3). Note also that while Vadeboncoeur et al. (2008) used the level of phosphorous to estimate chlorophyll A (ChlA) which was in turn used to estimate the PPmax (2.2*ChlA), we found no correlation (Pearson, p > 0.05) between ChlA and the PPmax in our reference lakes.

Table A3. Values, units and descriptions of parameters used in the autotrophic structure model (Devlin et al. 2016; Vadeboncoeur et al. 2008). The unit of parameters I_{zt} and $I_{surface}$ is $\mu\text{mol m}^{-2} \text{s}^{-1}$. Therefore, $I_{surface}$ was converted from field measures of LUX (luminous flux m⁻²) using a conversion factor of 0.0185. For the lakes where we did not measure LUX, we acquired modelled light data (grid 2.5 x 2.5 km) from the Strång project (Swedish Meteorological and Hydrological Institute n.d.). This data is delivered as Global Irradiance (GI) in Watt m⁻² which was converted to LUX following Michael (2019) using a conversion factor of 120.

Parameter	Value	Unit	Description
$BPmax_R$	5	$\text{mg C m}^{-2} \text{h}^{-1}$	Maximum production of epilithic algae
$BPmax_S$	45.66 ($\pm$ 21.75)	$\text{mg C m}^{-2} \text{h}^{-1}$	Maximum production of epipelagic algae
$PPmax$	0.39 ($\pm$ 0.15)	$\text{mg C m}^{-3} \text{h}^{-1}$	Maximum production of phytoplankton
A_0	Lake specific	m^2	Lake area
Δz	0.1	m	Depth increment
Δt	1	hour	Time increment
Δd	1	Day	Time increment
K_d	Seasonal mean	-	Light extinction coefficient
$I_{surface,t}$	Varied	$\mu\text{mol m}^{-2} \text{s}^{-1}$	Light at lake surface at time (t)
I_{zt}	Varied	$\mu\text{mol m}^{-2} \text{s}^{-1}$	Light at depth (z) at time (t)
I_{kb}	300	$\mu\text{mol m}^{-2} \text{s}^{-1}$	Light intensity at the onset of saturation in the benthic habitat
I_{kp}	180	$\mu\text{mol m}^{-2} \text{s}^{-1}$	Light intensity at the onset of saturation in the pelagic habitat
$Area_z$	Varied	m^2	Bottom area at depth (z)
$Volume_z$	Varied	m^3	Water volume of lake segment at depth (z)

Estimating habitat specific production

For all 27 lakes (table A1) the light at depth was calculated using equation 1 (table A2). In the Jämtland lakes that were sampled in 2016 no in situ light measurements were performed and we therefore used the Strång model - a mesoscale model for solar radiation (Swedish Meteorological and Hydrological Institute and others). These data are delivered as global irradiance which was converted to Lux following (Michael 2019). In the lakes Tjappisjaur (AC05) and Ruohojavratje (AC06) the LUX loggers was lost and we therefore used the light data from the lake Lisvojaure for these as well. Those lakes all lie within 3.5 km from each other and light conditions are therefore assumed to be similar.

We ran our model for the entirety of the season using the equations in table A2 and parameters in table A3. Equations 3-4 describes the depth- and lake-specific production in each habitat which depends on the the maximum productivity (BP_{maxR} , BP_{maxS} , PP_{max}), the light at depth (I_{zt}), the light intensity at onset of saturation (I_{kb}), and the area or volume of each 0.1 m depth increment (expressed as $Area_z$ and $Volume_z$). The model was run for 24 hrs per day where each hour had a different light at the surface — based on measurements made at each lake (see above) – resulting in different light at depth for each hour and each lake. Then the production in all depth and volume increments were summed up over the whole day for each habitat (equation 5-6). Finally, the benthic proportion of the total production was calculated by summing up all days over the season, where season lengths differed because of differences in the length of ice cover.

Model output for our 27 lakes estimated benthic contribution to GPP_{whole} to range between 79 – 95 % (table A1), much in line with the estimates from the reference lakes (84 – 95%) (Ask and others 2009) and similar lakes from the same region (70 – 83 %, (Björk-ramberg and Ånell 1985).

(Devlin and others 2016) tested the *autotrophic structure model*'s performance and sensitivity to different ways of simplifying input parameter estimation for production in the benthic habitat. They conclude and suggest that one should, for optimal performance of the model, (1) use actual sediment surface area in calculations, (2) account for depth specific variation in the maximum periphyton productivity (BP_{max}) and (3) incorporate depth specific saturating light intensity (I_k). The first criteria is met. However, we do not have measures of BP_{max} or I_k for the benthic or the pelagic habitats at a depth gradient. We therefore simplified the hump shaped relationship of BP_{max} over depth (Ask and others 2009) by setting the maximum productivity of epilithic algae in shallow benthic areas (< 2 m deep) to $5 \text{ mg C m}^{-2} \text{ h}^{-1}$ as suggested in Vadeboncoeur (2008) for rocky habitats and the epipelagic algae (> 2 m deep) maximum production to $45.66 \text{ mg C m}^{-2} \text{ h}^{-1}$ as was the average maximum value from our reference lakes studied by Ask et al. (2009). We chose to use the values for I_k for benthic and pelagic habitats of 300 (I_{kb}) and 180 (I_{kp}) as suggested in (Vadeboncoeur and others 2008) although (Devlin and others 2016) in their study noted a risk of underestimating benthic production using the average value of $I_{kb} = 300$. Still, our estimated contributions of benthic production to GPP_{whole} were high (78-95%) and we are therefore confident that even with our conservative approach we capture the main patterns and the importance of benthic production for GPP_{whole} over the range of lakes in watercolor and bathymetry that we studied.

Additional figures and tables

Figure A3 shows the bathymetric maps of the lakes. Figure A4 and A5 shows the size structure of the fish populations in our studied lakes. Figure A6 (Arctic char) and A7 (brown trout) shows the growth trajectories of fish in each lake. Table A5-A8 show model summaries of ordinary least squares regression models that is presented in less detail in main paper (table 2 and 3). Table A9 lists R-packages that we used in analysis and for producing figures.

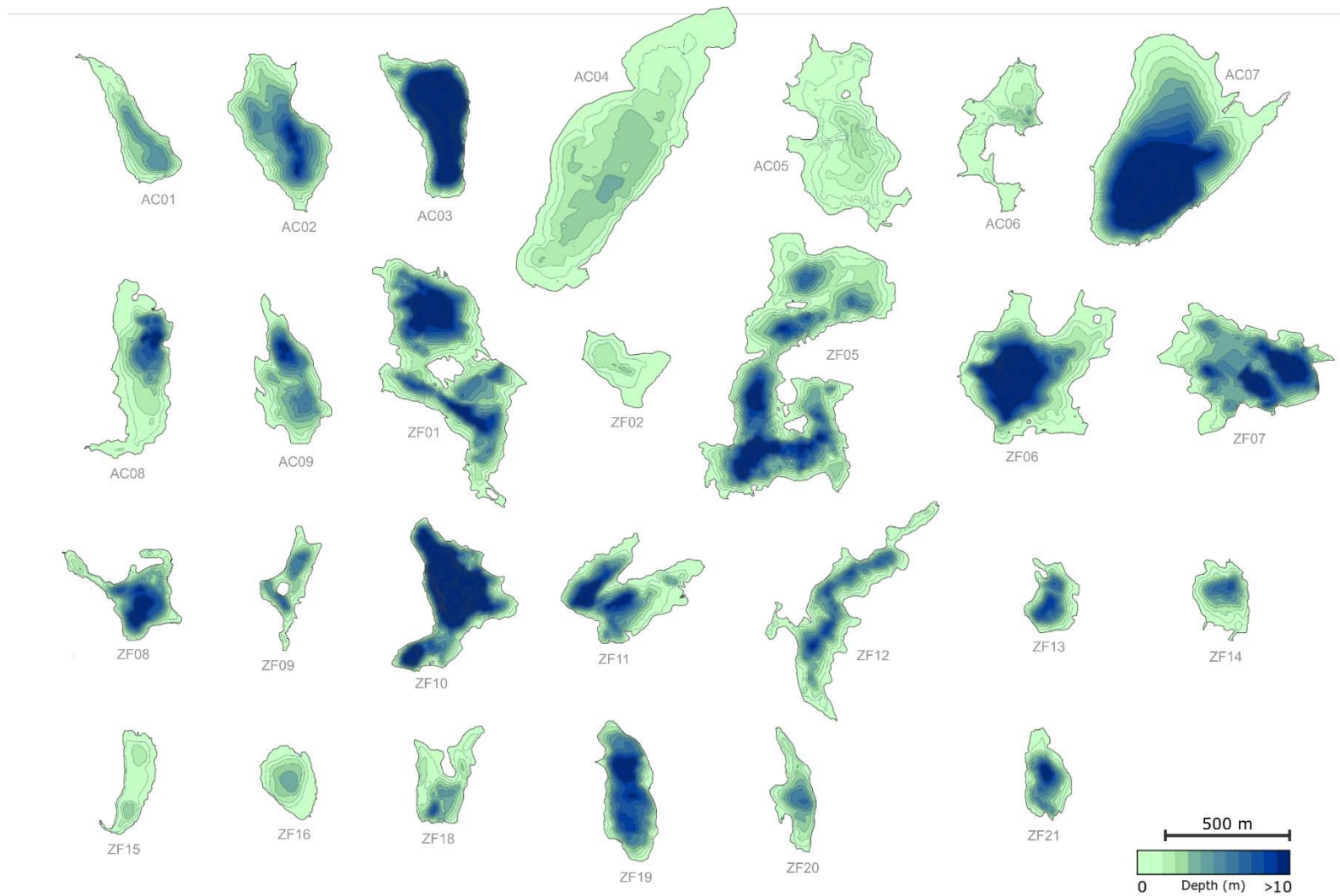


Figure A3. North aligned depth maps of the lakes in the study. The darkest blue corresponds to all depths > 10m.

Size structures

Allopatric lakes

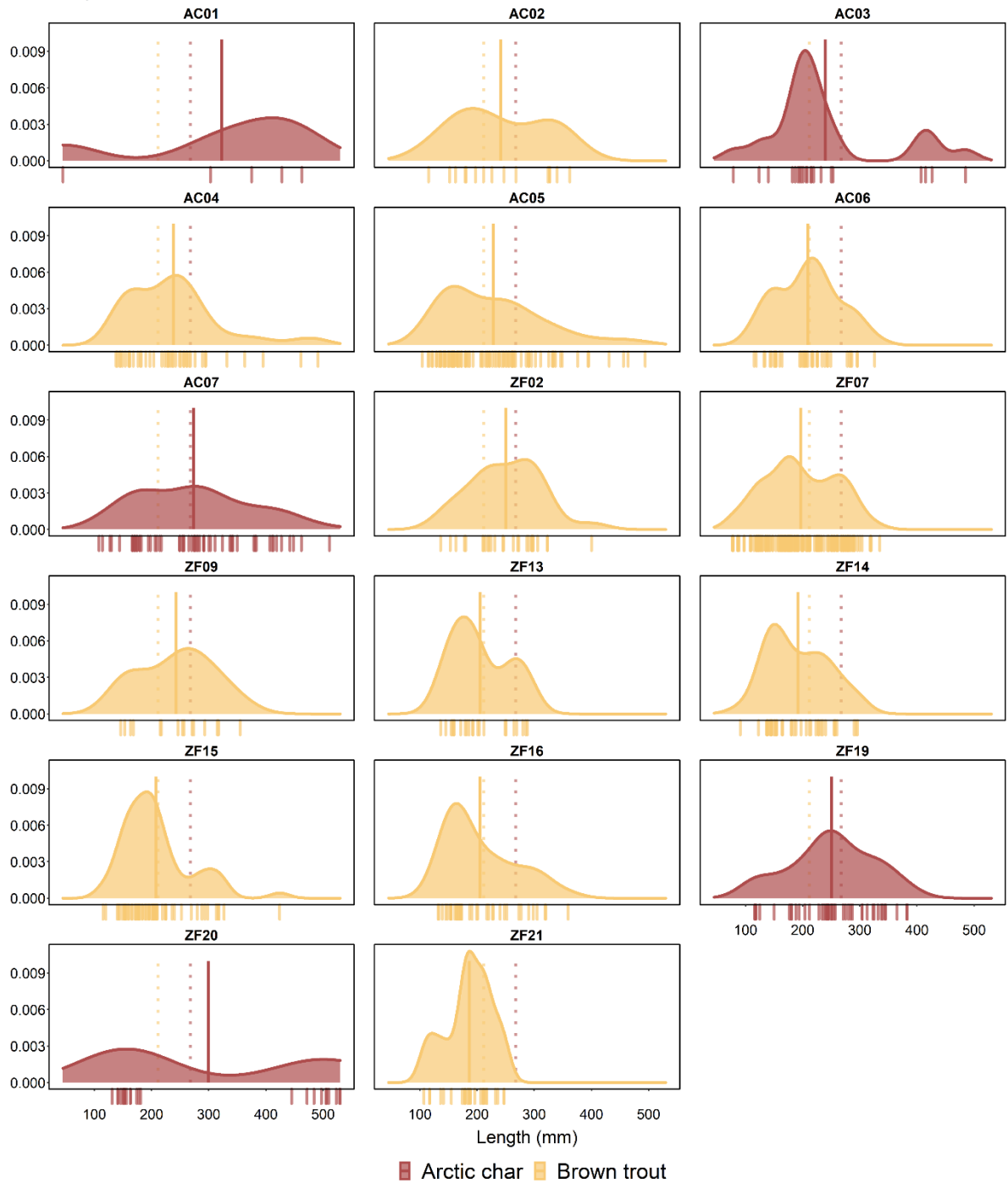


Figure A4. Density plots of each population representing the length distribution for allopatric populations of Arctic char and brown trout. The rug below each plot shows the length of each fish that was caught. The mean length for all allopatric populations is shown as dotted lines while the mean length within a population is shown as a solid line.

Size structures

Sympatric lakes

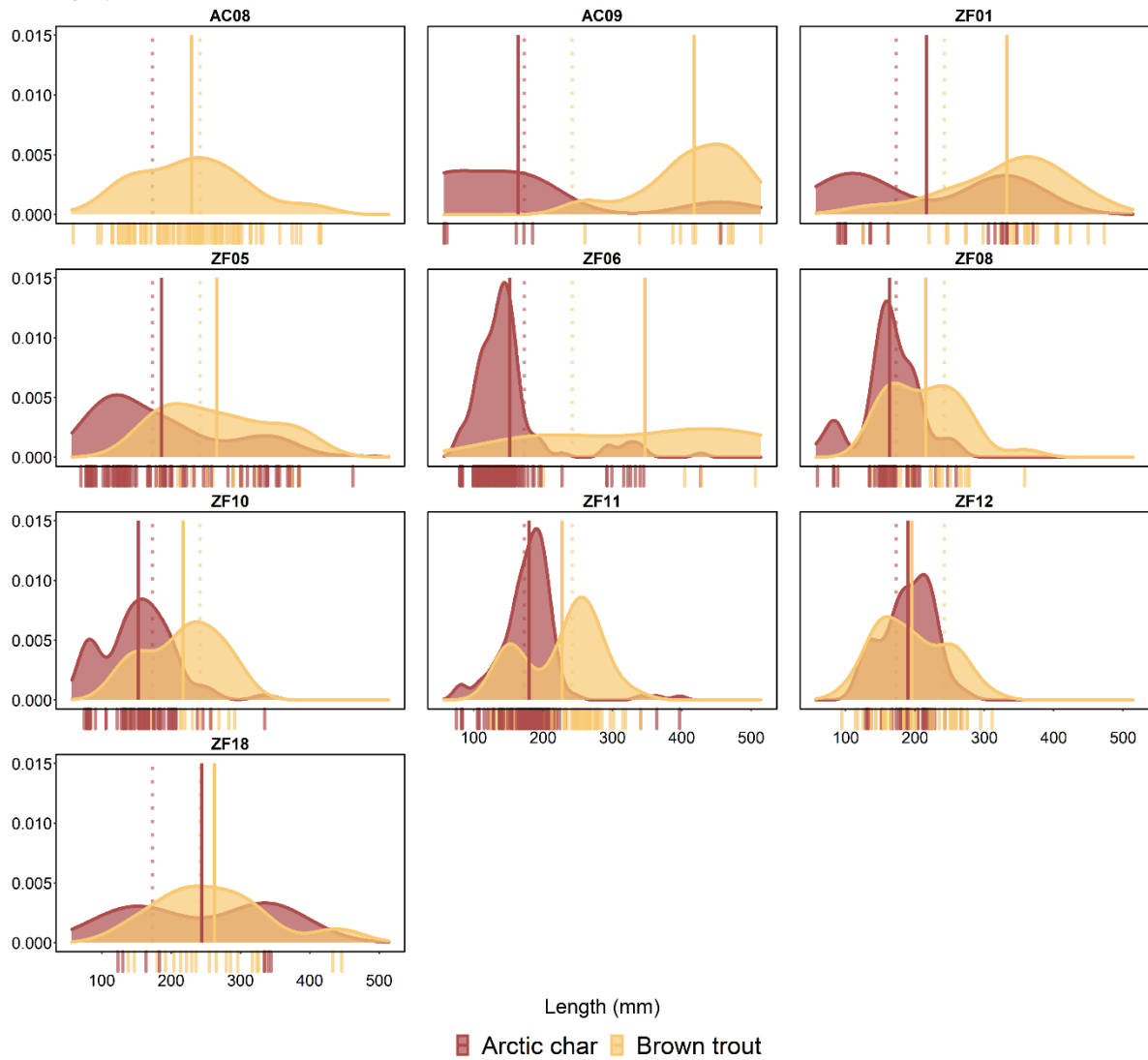


Figure A5. Density plots of each population representing the length distribution for sympatric populations of Arctic char and brown trout. The rug below each plot shows the length of each individual fish that was caught. The mean length of all sympatric populations of both species is shown as dotted line while the mean length within the population is shown as a solid line. Note that no Arctic char density or rug is shown for the lake AC08 because only one Arctic char was caught (length = 396 mm).

Arctic char

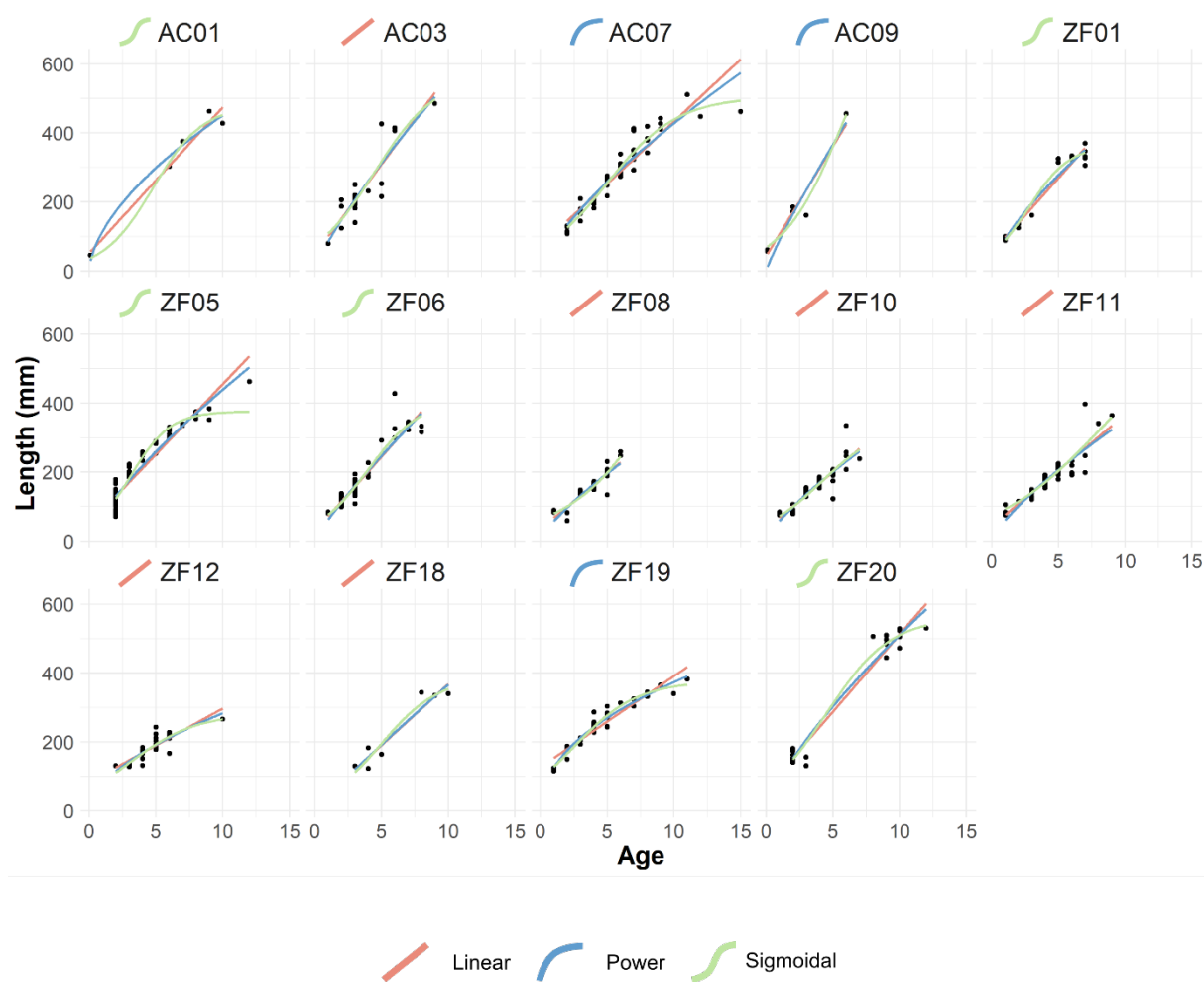


Figure A6. Growth trajectories of Arctic char in each lake. The lines are fitted functions of different shapes corresponding to linear (red), power (blue) and sigmoidal (green). The selected function (AICc procedure) used in individual growth estimations is shown as symbol to the left of the lake ID.

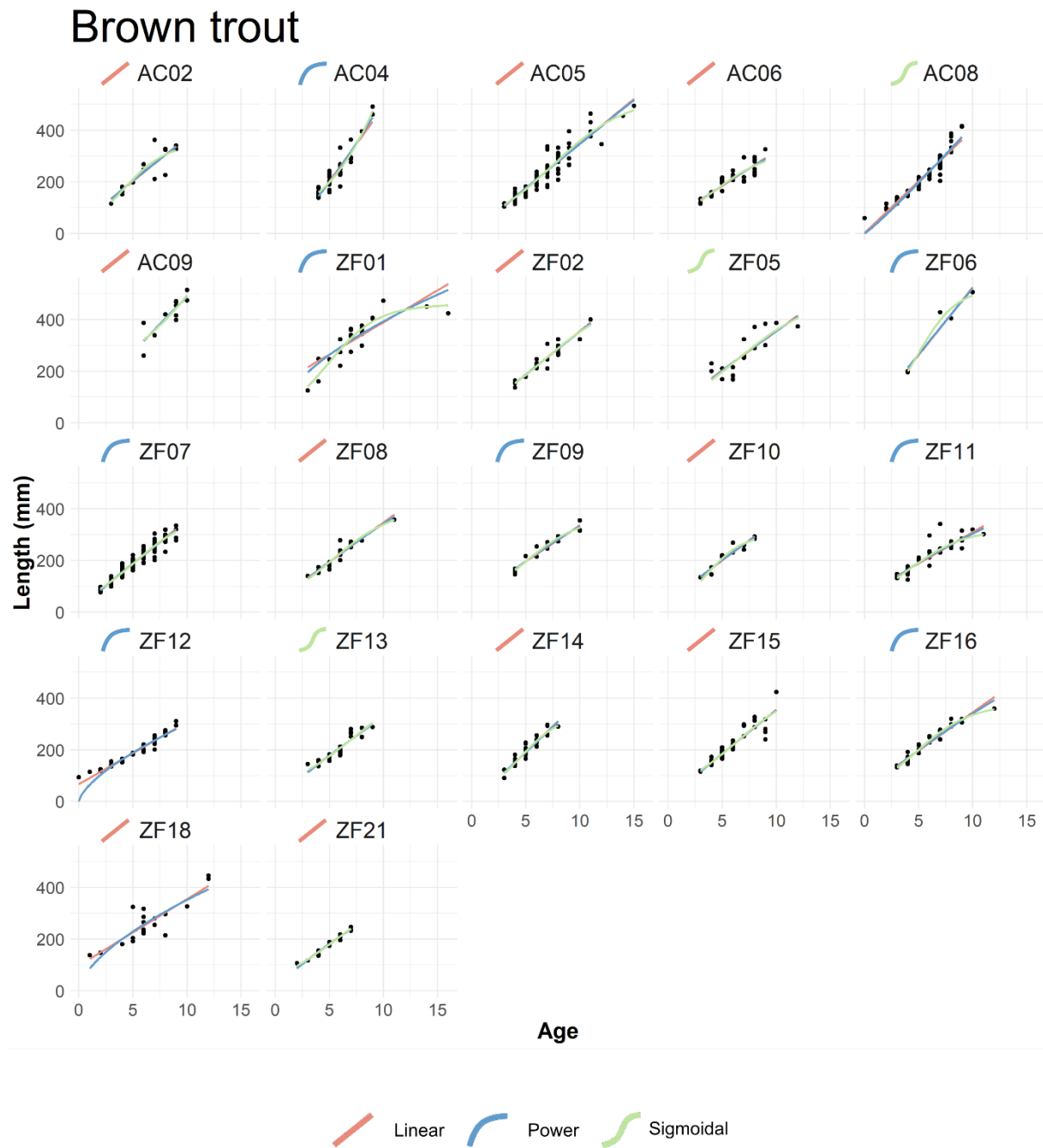


Figure A7. Growth trajectories of brown trout in each lake. The lines are fitted functions of different shapes corresponding to linear (red), power (blue) and sigmoidal (green). The selected function (AICc procedure) used in lake specific individual growth estimations is shown as symbol to the left of the lake ID.

Table A4. Retained explanatory variables after stepwise variable selection using step() in R. Function and overall model significance for growth estimates. The full model was fitted as BP * Temperature + BP * lake type. Where BP is the benthic proportion of GPP_{Whole}, and lake type corresponds to allopatric or sympatric lake types.

Response variables	Arctic char		Brown trout	
	Retained explanatory variables	Model significance level	Retained explanatory variables	Model significance level
Ratio of specific growth rates	BP*Lake type	N.S.	BP	p = 0.01
Specific growth rate - small (150 mm)	BP*Lake type	N.S.	BP * Temperature	N.S.
Specific growth rate - large (300 mm)	BP*Lake type	N.S.	BP	p = 0.05

Table A5. Model summaries from ordinary least squares regression analysis of whole lake GPP measures and habitat specific GPP estimates as functions of I_m, DOC, TN and TP.

GPP _{Whole}					GPP _{Pelagic}				GPP _{Benthic}			
Intercept I _m	F(1,21) = 44.91083 R ² = 0.68139 p = 0.00000				F(1,21) = 0.81615 R ² = 0.03741 p = 0.37656				F(1,21) = 55.63307 R ² = 0.72597 p = 0.00000			
	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p
	-0.00732	0.03009	-0.24313	0.81026	0.01990	0.00321	6.20530	0.00000	-0.02722	0.02743	-0.99229	0.33236
Intercept DOC	F(1,21) = 0.67165 R ² = 0.03099 p = 0.42168				F(1,21) = 16.76665, R ² = 0.44395 p = 0.00052				F(1,21) = 1.07531 R ² = 0.04871 p = 0.31154			
	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p
	0.20692	0.03762	5.49979	0.00002	0.01105	0.00175	6.32316	0.00000	0.19587	0.03663	5.34676	0.00003
Intercept TN	F(1,21) = 0.14090 R ² = 0.00666 p = 0.71115				F(1,21) = 10.86187 R ² = 0.34090 p = 0.00344				F(1,21) = 0.30421 R ² = 0.01428 p = 0.58708			
	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p
	0.20740	0.07451	2.78336	0.01114	0.00536	0.00372	1.44119	0.16428	0.20204	0.07295	2.76969	0.01148
Intercept TP	F(1,21) = 1.30660 R ² = 0.05857 p = 0.26588				F(1,21) = 0.53055 R ² = 0.02464 p = 0.47442				F(1,21) = 1.47362 R ² = 0.06557 p = 0.23825			
	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p
	0.01849	0.01618	1.14307	0.26588	-0.00074	0.00101	-0.72839	0.47442	0.01923	0.01584	1.21393	0.23825

Table A6. Model summaries from ordinary least squares regression analysis of fish community biomass and production as functions of seasonal air temperature, I_m , benthic proportion of GPP_{Whole} , GPP_{Whole} , $GPP_{Pelagic}$ and $GPP_{Benthic}$.

Biomass					Production				
F(1,25) = 0.370 R ² = 0.015					F(1,25) = 0.201 R ² = 0.008				
	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	
Intercept	1489.097	1020.297	1.459	0.157	173.298	431.009	0.402	0.691	
Temperature	-69.254	113.839	-0.608	0.548	21.566	48.090	0.448	0.658	
F(1,25) = 8.794 R ² = 0.260					F(1,25) = 4.931 R ² = 0.165				
	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	
Intercept	147.804	261.940	0.564	0.578	122.877	117.185	1.049	0.304	
I_m	1657.899	559.068	2.965	0.007	555.381	250.112	2.221	0.036	
F(1,25) = 7.994 R ² = 0.242					F(1,25) = 5.632 R ² = 0.184				
	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	
Intercept	-4100.592	1761.352	-2.328	0.028	-1458.350	769.629	-1.895	0.070	
GPP_{Benthic}:GPP_{Whole}	5613.089	1985.284	2.827	0.009	2058.746	867.477	2.373	0.026	
F(1,21) = 3.293 R ² = 0.136					F(1,21) = 3.082 R ² = 0.128 Adj. R ² = 0.086				
	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	
Intercept	435.720	266.247	1.637	0.117	179.547	111.495	1.610	0.122	
GPP_{Whole}	2400.187	1322.649	1.815	0.084	972.403	553.879	1.756	0.094	
F(1,21) = 2.182 R ² = 0.094					F(1,21) = 1.504 R ² = 0.067				
	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	
Intercept	1429.954	398.706	3.586	0.002	552.158	168.723	3.273	0.004	
GPP_{Pelagic}	-32626.165	22085.708	-1.477	0.154	-11463.085	9346.171	-1.227	0.234	
F(1,21) = 3.854 R ² = 0.155					F(1,21) = 3.548 R ² = 0.145				
	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	
Intercept	442.397	246.568	1.794	0.087	183.366	103.444	1.773	0.091	
GPP_{Benthic}	2612.271	1330.618	1.963	0.063	1051.496	558.243	1.884	0.074	

Table A7. Model summaries from ordinary least squares regression analysis of Arctic char biomass and production as functions of seasonal air temperature, I_m , benthic proportion of GPP_{Whole}, GPP_{Whole}, GPP_{Pelagic} and GPP_{Benthic}.

		Allopatric				Sympatric											
		Biomass		Production		Biomass		Production									
		F(1,3) = 1.350 R ² = 0.310		p = 0.329		F(1,3) = 1.008 R ² = 0.252		p = 0.389		F(1,7) = 5.487 R ² = 0.439		p = 0.052		F(1,7) = 13.332 R ² = 0.656		p = 0.008	
		Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p
Intercept		8352.815	6329.753	1.320	0.279	2118.022	1790.723	1.183	0.322	-898.337	510.004	-1.761	0.122	-794.305	266.224	-2.984	0.020
Temperature		-941.160	810.095	-1.162	0.329	-230.141	229.181	-1.004	0.389	128.163	54.711	2.343	0.052	104.279	28.559	3.651	0.008
		F(1,3) = 0.732 R ² = 0.196		p = 0.455		F(1,3) = 0.246 R ² = 0.076		p = 0.654		F(1,7) = 0.123 R ² = 0.017		p = 0.736		F(1,7) = 0.126 R ² = 0.018		p = 0.733	
		Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p
Intercept		-4.491	1223.792	-0.004	0.997	150.884	356.361	0.423	0.701	358.158	199.195	1.798	0.115	218.763	132.651	1.649	0.143
I _{in}		2288.471	2674.058	0.856	0.455	386.583	778.670	0.496	0.654	-185.075	527.756	-0.351	0.736	-124.798	351.451	-0.355	0.733
		F(1,3) = 1.655 R ² = 0.355		p = 0.289		F(1,3) = 0.686 R ² = 0.186		p = 0.468		F(1,7) = 0.014 R ² = 0.002		p = 0.910		F(1,7) = 0.021 R ² = 0.003		p = 0.888	
		Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p
Intercept		-5616.584	5157.230	-1.089	0.356	-980.122	1573.797	-0.623	0.578	146.787	1233.041	0.119	0.909	53.761	820.857	0.065	0.950
GPP ^{Benthic} :GPP ^{Whole}		7503.111	5833.208	1.286	0.289	1474.748	1780.081	0.828	0.468	165.187	1404.948	0.118	0.910	137.024	935.299	0.147	0.888
		F(1,3) = 0.010 R ² = 0.003		p = 0.927		F(1,3) = 0.161 R ² = 0.051		p = 0.715		F(1,4) = 0.039 R ² = 0.010		p = 0.854		F(1,4) = 0.018 R ² = 0.004		p = 0.900	
		Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p
Intercept		1062.206	655.473	1.621	0.204	380.428	173.708	2.190	0.116	270.999	137.522	1.971	0.120	126.256	90.166	1.400	0.234
GPP ^{Whole}		-404.938	4042.644	-0.100	0.927	-429.954	1071.346	-0.401	0.715	-179.716	914.128	-0.197	0.854	80.402	599.341	0.134	0.900
		F(1,3) = 5.687 R ² = 0.655		p = 0.097		F(1,3) = 6.692 R ² = 0.690		p = 0.081		F(1,4) = 8.535 R ² = 0.681		p = 0.043		F(1,4) = 8.199 R ² = 0.672		p = 0.046	
		Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p
Intercept		3133.837	915.871	3.422	0.042	914.952	235.479	3.885	0.030	-358.840	209.950	-1.709	0.163	-256.204	139.179	-1.841	0.139
GPP ^{Benthic}		-167021.978	70038.072	-2.385	0.097	-46583.856	18007.437	-2.587	0.081	37783.673	12932.784	2.922	0.043	24549.086	8573.300	2.863	0.046
		F(1,3) = 0.003 R ² = 0.001		p = 0.961		F(1,3) = 0.127 R ² = 0.041		p = 0.745		F(1,4) = 0.072 R ² = 0.018		p = 0.802		F(1,4) = 0.005 R ² = 0.001		p = 0.948	
		Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p	Est.	S.E.	t val.	p
Intercept		1034.316	622.239	1.662	0.195	370.302	165.592	2.236	0.111	276.129	125.170	2.206	0.092	132.151	82.537	1.601	0.185
GPP ^{Benthic}		-221.258	4133.690	-0.054	0.961	-392.375	1100.072	-0.357	0.745	-246.627	921.884	-0.268	0.802	41.922	607.886	0.069	0.948

Table A8. Model summaries from ordinary least squares regression analysis of brown trout biomass and production as functions of seasonal air temperature, I_m , benthic proportion of GPP_{Whole} , GPP_{Whole} , $GPP_{Pelagic}$ and $GPP_{Benthic}$.

Allopatric								Sympatric																							
Biomass				Production				Biomass				Production																			
F(1,10) = 0.019 R ² = 0.002				p = 0.892				F(1,10) = 0.029 R ² = 0.003				p = 0.867				F(1,8) = 0.380 R ² = 0.045				p = 0.554				F(1,8) = 0.047 R ² = 0.006				p = 0.834			
	Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		
Intercept	1040.620	1745.219	0.596	0.564		490.846	792.530	0.619	0.550		1955.736	2136.090	0.916	0.387		467.586	1046.546	0.447	0.667		467.586	1046.546	0.447	0.667		467.586	1046.546	0.447	0.667		
Temperature	-26.603	191.746	-0.139	0.892		-14.905	87.075	-0.171	0.867		-141.303	229.078	-0.617	0.554		-24.242	112.233	-0.216	0.834		-24.242	112.233	-0.216	0.834		-24.242	112.233	-0.216	0.834		
F(1,10) = 5.116 R ² = 0.338				p = 0.047				F(1,10) = 3.074 R ² = 0.235				p = 0.110				F(1,8) = 8.149 R ² = 0.505				p = 0.021				F(1,8) = 3.837 R ² = 0.324				p = 0.086			
	Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		
Intercept	20.622	373.315	0.055	0.957		60.827	182.376	0.334	0.746		-562.618	441.987	-1.273	0.239		-221.512	247.834	-0.894	0.398		-221.512	247.834	-0.894	0.398		-221.512	247.834	-0.894	0.398		
I _m	1595.799	705.520	2.262	0.047		604.341	344.669	1.753	0.110		3236.119	1133.663	2.855	0.021		1245.241	635.674	1.959	0.086		1245.241	635.674	1.959	0.086		1245.241	635.674	1.959	0.086		
F(1,10) = 3.060 R ² = 0.234				p = 0.111				F(1,10) = 2.743 R ² = 0.215				p = 0.129				F(1,8) = 2.447 R ² = 0.234				p = 0.156				F(1,8) = 1.673 R ² = 0.173				p = 0.232			
	Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		
Intercept	-3875.140	2676.829	-1.448	0.178		-1679.909	1231.240	-1.364	0.202		-4568.253	3334.997	-1.370	0.208		-1907.090	1663.942	-1.146	0.285		-1907.090	1663.942	-1.146	0.285		-1907.090	1663.942	-1.146	0.285		
GPP _{Benthic} :GPP _{Whole}	5243.727	2997.526	1.749	0.111		2283.512	1378.749	1.656	0.129		5917.076	3782.311	1.564	0.156		2440.629	1887.122	1.293	0.232		2440.629	1887.122	1.293	0.232		2440.629	1887.122	1.293	0.232		
F(1,9) = 13.140 R ² = 0.594				p = 0.006				F(1,9) = 9.089 R ² = 0.502				p = 0.015				F(1,5) = 8.553 R ² = 0.631				p = 0.033				F(1,5) = 1.483 R ² = 0.229				p = 0.278			
	Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		
Intercept	-444.691	350.359	-1.269	0.236		-163.856	174.633	-0.938	0.373		-267.654	385.296	-0.695	0.518		-11.128	277.048	-0.040	0.970		-11.128	277.048	-0.040	0.970		-11.128	277.048	-0.040	0.970		
GPP _{Whole}	5260.993	1451.328	3.625	0.006		2180.849	723.398	3.015	0.015		7464.858	2552.549	2.924	0.033		2235.106	1835.416	1.218	0.278		2235.106	1835.416	1.218	0.278		2235.106	1835.416	1.218	0.278		
F(1,9) = 0.864 R ² = 0.088				p = 0.377				F(1,9) = 1.199 R ² = 0.118				p = 0.302				F(1,5) = 0.100 R ² = 0.020				p = 0.765				F(1,5) = 0.171 R ² = 0.033				p = 0.696			
	Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		
Intercept	1327.663	646.300	2.054	0.070		632.883	286.354	2.210	0.054		304.632	1478.160	0.206	0.845		595.715	730.035	0.816	0.452		595.715	730.035	0.816	0.452		595.715	730.035	0.816	0.452		
GPP _{Pelagic}	-28463.039	30624.604	-0.929	0.377		-14856.806	13568.748	-1.095	0.302		29618.702	93713.907	0.316	0.765		-19149.259	46283.506	-0.414	0.696		-19149.259	46283.506	-0.414	0.696		-19149.259	46283.506	-0.414	0.696		
F(1,9) = 14.210 R ² = 0.612				p = 0.004				F(1,9) = 9.966 R ² = 0.525				p = 0.012				F(1,5) = 8.656 R ² = 0.634				p = 0.032				F(1,5) = 1.591 R ² = 0.241				p = 0.263			
	Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		Est.	S.E.	t val.	p		
Intercept	-342.509	312.204	-1.097	0.301		-124.616	155.601	-0.801	0.444		-162.955	350.804	-0.465	0.662		13.299	251.133	0.053	0.960		13.299	251.133	0.053	0.960		13.299	251.133	0.053	0.960		
GPP _{Benthic}	5283.028	1401.461	3.770	0.004		2205.052	698.480	3.157	0.012		7557.141	2568.566	2.942	0.032		2319.098	1838.779	1.261	0.263		2319.098	1838.779	1.261	0.263		2319.098	1838.779	1.261	0.263		

Table A9. R packages that were used in analysis and for producing figures.

Package	Functions used	Reference
MuMin	AICc() - Akaike's information criterion corrected for small sample sizes	Kamil Barton (2020). MuMin: Multi-Model Inference. R package version 1.43.17. https://CRAN.R-project.org/package=MuMin
GGplot2	ggplot() - figures	H. Wickham. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2016.
patchwork	for combining figures	Thomas Lin Pedersen (2020). patchwork: The Composer of Plots. R package version 1.1.1. https://CRAN.R-project.org/package=patchwork
rLakeAnalyzer	Lake metabolism modeling	Luke Winslow, Jordan Read, Richard Woolway, Jennifer Brenttrup, Taylor Leach, Jake Zwart, Sam Albers and Doug Collinge (2019). rLakeAnalyzer: Lake Physics Tools. R package version 1.11.4.1. https://CRAN.R-project.org/package=rLakeAnalyzer

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