

SUPPORTING INFORMATION

of

Evolution of Size-Dependent Intraspecific Competition Predicts

Body Size Scaling of Metabolic Rate

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1 **Appendix S1: Model Parameters**

2 Body size of the consumer is expressed in grams (g) and biomass densities are expressed in milligrams
3 per liter (mg L^{-1}). Across differently-sized species, mass-specific maximum ingestion, mass-specific
4 maintenance and mortality rates are inversely proportional to the quarter power of adult body size
5 (Kleiber, 1932; Peters, 1983; Savage et al., 2004). Taking time in days and adult body weight in grams,
6 representative proportionality constants of these scaling relationships for invertebrate species are 0.1,
7 0.01 and 0.0015 for maximum ingestion, maintenance and mortality, respectively (De Roos & Persson,
8 2013). For the parameterization we take the characteristic adult body mass to equal the size at matura-
9 tion, for which we adopt a value of 1 gram. Hence $M = 0.1$, $T = 0.01$ and $\mu_c = 0.0015$. A value of
10 0.01 is adopted for the resource renewal rate δ , such that resource turn-over rate equals the mass-specific
11 maintenance rate of an individual with size s_j . Only a change in the ratios between these four rates
12 changes model predictions, as changing their absolute values all with the same factor only scales the unit
13 of time. Values for the volume related parameters are $R_{max} = 30 \text{ mg L}^{-1}$ and $H = 3 \text{ mg L}^{-1}$ (Table
14 2, main text). The value for H is derived from zooplankton grazing rates as presented by Hansen et al.
15 (1997) and R_{max} is assumed one order of magnitude larger than H (De Roos & Persson, 2013). As long
16 as the ratio of these volume-related parameters remains constant a change in these parameters is equiv-
17 alent to a scaling of the volume in which the consumer-resource interaction takes place. This does not
18 qualitatively change model predictions. Default parameters for size at birth and maximum size are 0.1
19 and 10, but these values are changed during model analysis. The scaling exponents Q and P are varied
20 throughout the analysis, but their values are limited to the range 0.4–1.3, which is the observed range of
21 intraspecific scaling exponents found by Clarke & Johnston (1999) for post-larval teleost fish.

22 Figure S1

23 We assume a juvenile-adult trade-off in both maximum ingestion rate and maintenance rate. This trade-
 24 off is implemented by parameterizing the power functions that describe these rates at the size at matura-
 25 tion. When another reference size than the size at maturation is used to fix these power functions, both
 26 exponents still evolve towards a common value. This CSS-value increases with decreasing reference
 27 size, see Figure S1 (left panel).

28 Moreover, using different scaling reference sizes for maintenance and maximum ingestion does not
 29 influence this result. Denoting the scaling reference mass for maximum ingestion by s_{r_I} , the resource
 30 ingestion function becomes:

$$I(R, s) = M \left(\frac{s}{s_{r_I}} \right)^Q \frac{R}{R + H}$$

31 Similarly denoting the scaling reference mass for maintenance by s_{r_M} , the biomass production function
 32 becomes:

$$\Omega(R, s) = \sigma I(R, s) - T \left(\frac{s}{s_{r_M}} \right)^P$$

33 Figure S1 shows how the CSS-values of Q and P change when only changing s_{r_I} (middle panel) or s_{r_M}
 34 (right panel). Although the CSS-values respond rapidly to changes in s_{r_I} and s_{r_M} , the evolved scaling
 35 exponents remain approximately identical to one another.

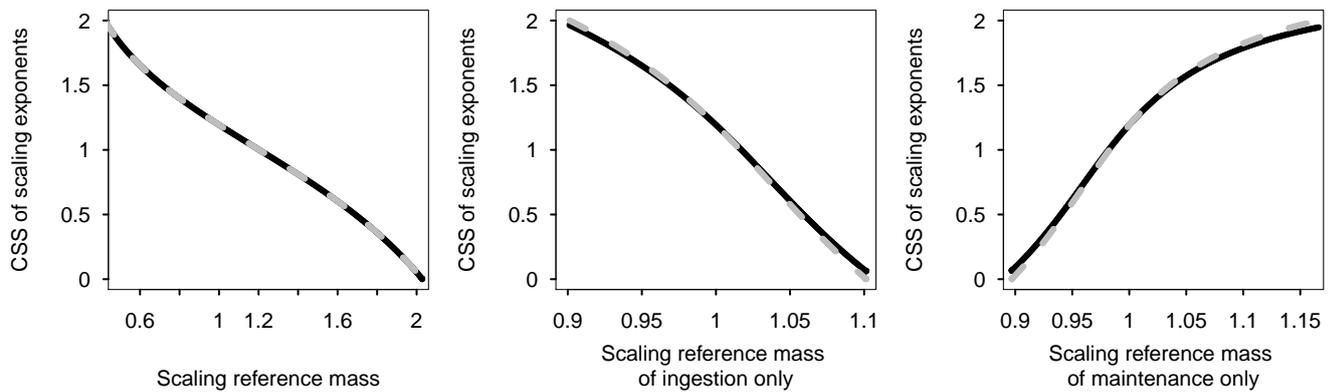


Figure S1: CSS-values of the scaling exponents of maximum ingestion Q and maintenance P , as a function of the scaling reference mass s_r (left), the separate scaling reference mass for maximum ingestion s_{r_I} (with $s_{r_M} = 1$), or the separate scaling reference mass for maintenance s_{r_M} (with $s_{r_I} = 1$). All other parameters as in Table 2 (main text)

36 **Figure S2**

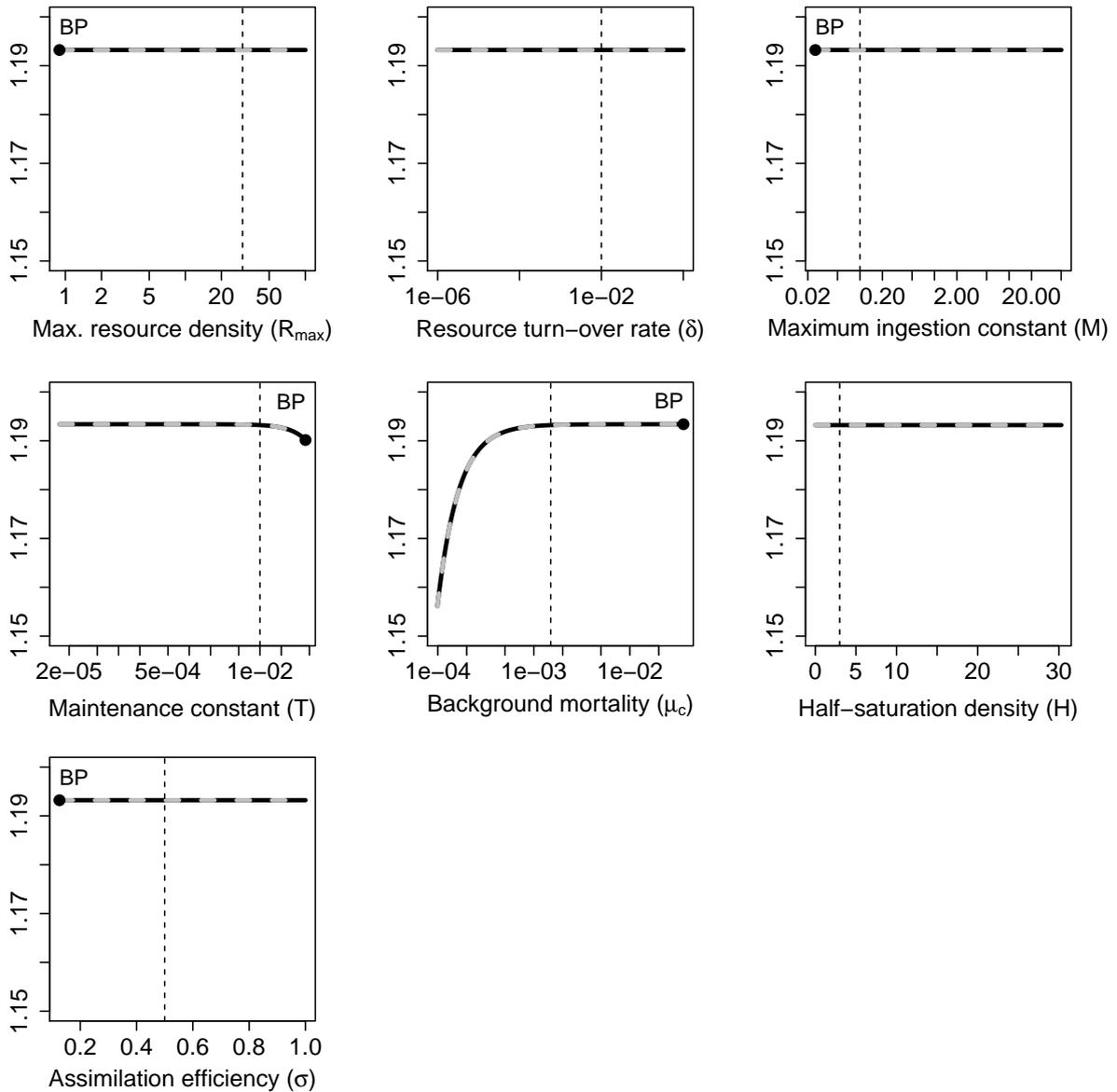


Figure S2: The CSS-values of the maintenance (P) and maximum ingestion (Q) scaling exponents as a function of seven model parameters, as indicated on each horizontal axis. The main result that these scaling exponents evolve towards the same value is independent of changes in any of these parameters. Moreover, changes in five out of seven of these parameters do not influence the CSS-values. Only the maintenance constant T and the size-independent mortality rate μ_c have a slight impact on the CSS-values of Q (solid gray lines) and P (black dashed lines). Vertical dashed lines indicate default parameter values (main text Table 2)

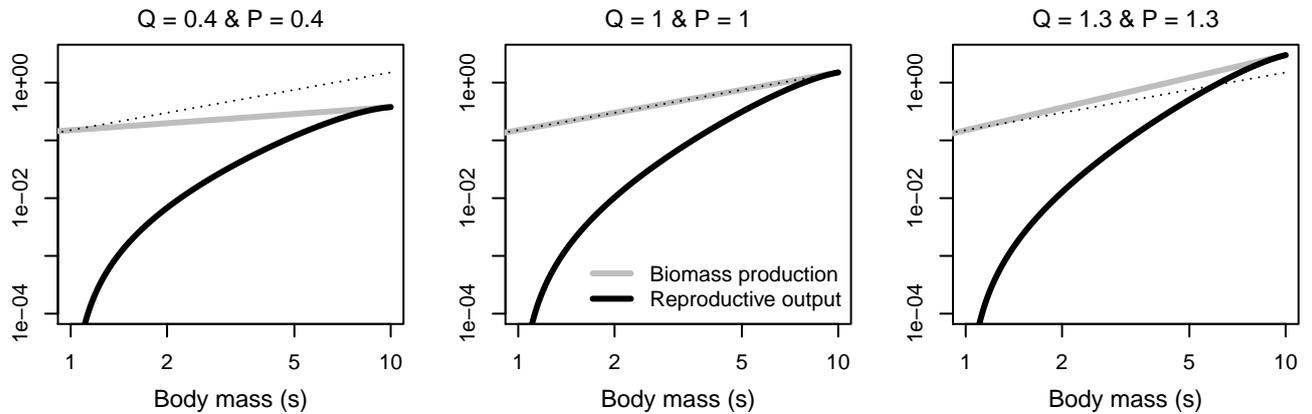
37 **Figure S3**

Figure S3: The scaling of the biomass production rate $\Omega^+(R, s)$ and the reproductive output in terms of biomass: $(1 - \kappa(s))\Omega^+(R, s)$, as a function of the adult body-mass range s_j to s_m , plotted on a log-log scale. Reproductive output scales more steeply with body mass compared to the biomass production rate, due to the increasing allocation towards reproduction with increasing size. For the range of scaling exponents considered (0.4 – 1.3), reproductive output scales approximately hyperallometrically with body mass. The thin dashed line shows an isometric scaling of biomass production: $\Omega^+(R, s)$ with $Q = P = 1$. All other parameters at default values (main text Table 2) and $R = 3$.

38 **Appendix S2: Data Collection and Analysis**

39 *Data collection*

40 Data on the relationship between metabolic rate and body mass were taken from the supporting infor-
41 mation of Killen, Atkinson, & Glazier (2010). This dataset provides estimates on metabolic scaling
42 exponents (b) and metabolic activity level (L), defined as “the mass-specific metabolic rate estimated at
43 the body mass corresponding to the midpoint of the allometric relationship” (Killen et al., 2010) for 89
44 species of Teleost fish. These data are an extension of the data provided by Clarke & Johnston (1999)
45 and selection criteria handled by both Killen et al. (2010) and Clarke & Johnston (1999) were aimed
46 at selecting rates of standard or routine metabolism. Only data on resting, post-larval, fasted animals
47 measured in absence of additional stressors and after a 24h acclimation period were accepted (Killen
48 et al., 2010). Additionally, the temperature (T) at which metabolism was measured should be within the
49 natural temperature range of the species and the metabolism should be measured over a suitable body-
50 mass range (see Clarke & Johnston (1999) and Killen et al. (2010) for a more detailed description of
51 acceptance criteria).

52 To test the hypothesis that the scaling of metabolic rate changes with the ratio between size at birth
53 and size at maturation we collected data on egg diameter (l_{egg}) and length at maturation (l_{mat}) for the
54 species in the dataset of Killen et al. (2010). Length instead of mass estimates were used since the for-
55 mer are more readily available for fish. Furthermore, any pattern in the length ratios will remain intact
56 after a non-linear transformation to mass ratios. Data collection was carried out at the species level and
57 the estimates for l_{mat} and l_{egg} are generally not from the same source, nor is any of the two directly
58 derived from populations or individuals that were used for the metabolic rates measurements. There is
59 considerable variation in both size at maturation and egg size between individuals of the same popula-
60 tion, between different populations of the same species and with size and age of the parents (Bagenal,
61 1971; Bøhn, Sandlund, Amundsen, & Primicerio, 2004; Bonislawska, Formicki, Korzelecka-Orkisz, &
62 Winnicki, 2001; Kamler, 2005; Wallace & Aasjord, 1984). This variation could not be controlled for and
63 is taken for granted since estimates on our variables of interest (l_{egg} , l_{mat} and b) are not available for the
64 same individuals.

65 Various sources report different estimates of l_{egg} and l_{mat} for the same species and these data were
66 averaged to arrive at a species-specific prediction. Main sources for size at maturation estimates were
67 Winemiller & Rose (1992), King & McFarlane (2003) and Fishbase (Froese & Pauly, 2016). Fishbase
68 estimates were collected using R (R Core Team, 2015) with the package ‘rfishbase’ (Boettiger, Cham-

berlain, Temple Lang, & Wainwright, 2016; Boettiger, Lang, & Wainwright, 2012). Single estimates for l_{mat} were preferred over range estimates and the latter were only used when both minimum and maximum values were reported. Estimates of l_{egg} were mainly derived from Winemiller & Rose (1992), King & McFarlane (2003) and Russel (1976). Additional searches for egg size were performed for species if size at maturation estimates were provided in the sources mentioned above. This resulted in a total of 41 species with estimates of l_{egg} , l_{mat} and b . All data and data source are deposited in Dryad Digital Repository (Hin & De Roos, 2018).

Data analysis

Killen et al. (2010) show an effect of the temperature (T) at which the metabolic measurements were performed on both the scaling of metabolism with body size (b) and on the metabolic level (L). Furthermore, the authors show an effect of $\log(L)$ on b . To correct for these dependencies in our analysis we calculate the effect of T on the $\log(L)$ for the original 89 species described in Killen et al. (2010). This analysis is identical to the one described in the Figure S1 of the supporting information of Killen et al. (2010) and gives an ordinary least squares (OLS) regression of $\log(L) = 0.0653T + 3.17$ (slope $P < 0.0001$ and $R^2 = 0.510$). We used the residuals of the regression of $\log(L)$ against T relative to the prediction for $\log(L)$ at $T = 15^\circ\text{C}$ to calculate temperature-corrected estimates of $\log(L)$. These temperature-corrected values are referred to as $\log(L_{Tcorr})$. We related $\log(L_{Tcorr})$ to the scaling exponents of metabolic rate of the original dataset of Killen et al. (2010). Contrary to the values of L the temperature-corrected values do not show a clear relationship with b (slope = -0.0300 , $P = 0.176$, $R^2 = 0.0212$), indicating that the original effect of $\log(L)$ on b as reported by Killen et al. (2010) was mediated by temperature and not through an effect of $\log(L)$ directly. Due to the lack of a clear correspondence between the temperature-corrected values of $\log(L)$ on b we refrained from correcting estimates of b to the metabolic level L . Instead, we only controlled for a direct effect of T on b . This was done by recalculating the OLS regression between b and T as reported in Figure S1b of Killen et al. (2010) and using the residuals of this regression equation ($b = -0.005872T + 0.875878$, slope $P < 0.0001$, $R^2 = 0.198$) relative to the predicted scaling exponent at 15°C . These temperature-corrected values were calculated with the full dataset as reported by Killen et al. (2010) and used to test the hypothesis that the scaling of maintenance metabolism is negatively related with the ratio between size at maturation and size at birth for species for which these latter estimates were available.

We used ranged major axis (RMA) regression to calculate the correlation between $\log(l_{mat}/l_{egg})$ and the temperature-corrected scaling exponent b_{Tcorr} (main text Figure 5). Since RMA regression is

100 sensitive to the presence of outliers (Legendre, 2014), Cook's distance was calculated from an OLS
101 regression of b_{Tcorr} on $\log(l_{mat}/l_{egg})$. The estimates for the eel (*Anguilla anguilla*) had a Cook's distance
102 of 0.697, which was 6.2 times the value of the second highest Cook's distance. Therefore, we decided
103 to exclude the eel from further analysis, since it has a disproportionately large effect on the estimates of
104 the OLS regression. The RMA regression line relating the temperature-corrected scaling exponent of
105 metabolism to the juvenile size-range is: $b_{Tcorr} = -0.19 \log(l_{mat}/l_{egg}) + 1.72$, with $n = 40$, $R^2 = 0.357$
106 and a one-tailed permutation test of the slope of $P < 0.01$ (main text Figure 5). This negative correlation
107 supports the evolutionary prediction that an increased juvenile size-range through either a smaller size at
108 birth (measured as egg diameter) or a larger size at maturation should result in a lower scaling exponent
109 of metabolism with body size.

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