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Optimum growth temperature declines with body size within fish species

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**Abstract**

According to the temperature-size rule, warming of aquatic ecosystems is generally predicted to increase individual growth rates but reduce asymptotic body sizes of ectotherms. However, we lack a comprehensive understanding of how growth and key processes affecting it, such as metabolism and consumption, depend on both temperature and body mass within species. This limits our ability to inform growth models, to link experimental data to observed growth patterns, and to advance mechanistic food web models. To resolve the combined effects of body size and temperature on growth, and examine the link between metabolism, maximum consumption and body growth, we compiled a large dataset of experimental results from studies on fishes combining body mass and temperature treatments. We estimate how these three processes scale jointly with temperature and body mass within species by fitting hierarchical models accounting for variation between species. Maximum consumption scaled exponentially with mass with an exponent smaller than that for metabolism, and is unimodal over the full temperature range. These two conditions lead to the prediction that optimal growth temperatures (*Topt*) decline with size. Analyses of an independent data set confirmed that *Topt* declined with mass. in an independent data set. Small individuals will therefore likely be able to increase growth with initial warming, whereas larger conspecific individuals could be the first to experience negative effects of warming on growth. Syntheses of existing experimental data on intra-specific scaling of key physiological rates, accounting for uncertainty at the species-level, can help overcome the mismatch between mechanistic growth models, general scaling theory, and single-species observations.

**Significance statement**

Predicting the consequences of rising temperatures requires understanding of how key physiological processes such as growth, feeding and metabolism depend on body size and temperature within species. By collating experimental data on fishes, we show how feeding rates increase slower than metabolic rate with body mass – and temperature at warmer temperatures, indicating that optimal growth temperatures decline with mass. We verify this prediction using a meta-analysis of fish growth trials. These findings suggest large individuals within populations may be the first to suffer negative consequences of warming on growth. Maintaining stable size-distribution of wild fish populations is crucial given their disproportionally large contribution to overall population resilience, fisheries yield and food web structure.

**Introduction**

Individual body growth is a fundamental process powered by metabolism, and thus depends on body size and temperature (Brown *et al.* 2004). It affects individual fitness and life history traits, such as maturation size, population growth rates (Savage *et al.* 2004) and ultimately energy transfer across trophic levels (Andersen *et al.* 2009; Barneche & Allen 2018). Therefore, understanding how growth scales with body size and temperature is important for predicting the impacts of global warming on the structure and functioning of ecosystems.

Global warming is predicted to lead to declining body sizes of organisms (Daufresne *et al.* 2009; Gardner *et al.* 2011). The temperature size-rule predicts that warmer rearing temperatures lead to faster developmental times (and larger initial size-at-age or size-at-life-stage), but smaller adult body sizes (Atkinson 1994; Ohlberger 2013). This relationship is found in numerous experimental studies (Atkinson 1994), is reflected in latitudinal gradients of insects (Horne *et al.* 2015), and is stronger in aquatic than terrestrial organisms (Forster *et al.* 2012; Horne *et al.* 2015).

In fishes, reconstructed individual growth histories often reveal positive correlations between growth rates and temperature in natural systems, in particular in young fish (Thresher *et al.* 2007; Neuheimer *et al.* 2011; Baudron *et al.* 2014; Huss *et al.* 2019; Wang *et al.* 2020). However, it is less clear if the positive effect of warming on growth is indeed limited to small individuals within a species, as predicted by the temperature size-rule. Negative correlations between maximum or asymptotic body size and temperature have been found in commercially exploited fish species (Baudron *et al.* 2014; van Rijn *et al.* 2017). However, other studies, including large scale experiments, controlled experiments and latitudinal studies, have failed to find negative relationships between maximum size or growth of old fish and temperature (Barneche *et al.* 2019; Huss *et al.* 2019; van Denderen *et al.* 2019; van Dorst *et al.* 2019), and differences between species may be related to life history traits (Wang *et al.* 2020).

While the underlying mechanisms of the TSR are not well understood (Ohlberger 2013; Audzijonyte *et al.* 2018; Neubauer & Andersen 2019), theoretical growth models predict similar organism responses to warming. Pütter growth models (Pütter 1920), including the von Bertalanffy growth model (VBGM) (von Bertalanffy 1938), predict declines in asymptotic body mass with temperature and declines in optimum growth temperature with body mass (Morita *et al.* 2010; Pauly & Cheung 2018b). However, the invoking of simple surface-to-volume scaling rules in favour of empirically derived parameters in these models has led to questioning of their physiological basis (Lefevre *et al.* 2017a; Marshall & White 2019a, b). Hence, despite attempting to describe growth from first principles, Pütter growth models can also be viewed as phenomenological if those principles are erroneous or overly simplified. Therefore, as empirical findings vary and theoretical predictions are questioned, it remains unclear if and how growth of large fish within populations is limited by temperature.

In more mechanistic growth models, the difference between energy acquisition and expenditure (Ursin 1967; Kitchell *et al.* 1977; Jobling 1997) is partitioned between somatic growth and gonads. Energy acquisition is normally the amount of energy extracted from consumed food and expenditure is defined as fasting, activity and feeding metabolism. Metabolic processes are in turn often assumed to be related to resting metabolism, measured as the oxygen consumption of unfed fish at rest (Jobling 1997). These components of the energetics of growth are found in dynamic energy budget models (Kitchell *et al.* 1977; Kooijman 1993; Kearney 2019), including physiologically structured population models (PSPMs) (de Roos & Persson 2001), and size-spectrum models (Hartvig *et al.* 2011; Maury & Poggiale 2013; Blanchard *et al.* 2017). In order to understand growth dynamics in changing environments and to evaluate the physiological basis of growth models, it is therefore important to understand how metabolism and consumption rates scale with body size and temperature.

The effect of body mass and temperature on growth, consumption and metabolism should ideally be evaluated at the intraspecific rather than interspecific level, as they represent individual-level processes, and because allometric and temperature relationships can differ within and between species (Glazier 2005; Rall *et al.* 2012; Jerde *et al.* 2019). Yet, despite this potential difference, body mass- and temperature scaling within species is often inferred from interspecific data. Hence, the intraspecific scaling of biological rates with mass and temperature is less understood than interspecific scaling relationships. In addition, the temperature and mass dependence of metabolism and other related rates are often (e.g., in the Arrhenius fractal supply model (AFS) appliedin the ‘metabolic theory of ecology’ (Gillooly *et al.* 2001; Brown *et al.* 2004; Downs *et al.* 2008)) assumed to scale independently with mass and temperature (Downs *et al.* 2008). However, deviations from a general ¾ mass exponent are common (Clarke & Johnston 1999; Bokma 2004; Jerde *et al.* 2019), and body mass and temperature can have interactive effects (Xie & Sun 1990; Glazier 2005; García García *et al.* 2011; Ohlberger *et al.* 2012; Lindmark *et al.* 2018) (but see Jerde *et al*. (2019)). In addition, while the AFS tends to provide good statistical fits to interspecific data (Clarke 2004) and intraspecific data with a restricted temperature range (Brown *et al.* 2004; Clarke 2004; Rall *et al.* 2012), within-species thermal response curves are generally unimodal (Dell *et al.* 2011; Englund *et al.* 2011; Rall *et al.* 2012; Uiterwaal & DeLong 2020). Alternative approaches that overcome these obstacles include fitting multiple regression models where coefficients for mass and temperature are estimated jointly (Downs *et al.* 2008), as well as fitting non-linear or polynomial models that can capture the de-activation of biological rates at higher temperatures (Schoolfield *et al.* 1981; Dell *et al.* 2011; Englund *et al.* 2011).

In this study, we analyse how maximum consumption, metabolism and growth rate of fish scale intra-specifically with mass and temperature. We performed a systematic literature review by searching the Web of Science Core Collection to compile datasets on individual growth, maximum consumption and metabolic rates of fish from experiments in which the effect of fish body mass is replicated across multiple temperatures within species. We then fit hierarchical Bayesian models to estimate general intraspecific scaling parameters while accounting for variation between species. For consumption rates, we also fit polynomial models to a subset of the data to characterize the unimodal temperature dependence seen in data. We find that the temperature dependence of growth, consumption and metabolism at below peak temperatures is close to average intraspecific predictions (activation energies approximately 0.65 ), whereas the mass exponents are larger and smaller than ¾ for metabolism and maximum consumption, respectively. Over the full temperature range, consumption rates are unimodal, suggesting declines in optimum (peak) growth temperatures with body mass. Using an independent data set on growth experiments for several fish species, we demonstrate that optimum growth temperatures indeed decline with body mass.

**Results**

We identified that within species of fish, metabolic rates increase faster with body mass than maximum consumption rates, and neither of these rates conform to the commonly predicted 3/4 scaling with body mass (Fig. 2-3).

We also find that consumption rate is unimodal over the full temperature range. Based on this scaling of rates, growth models predict a decrease in optimal growth temperature with body size (Fig. 4). The prediction of declining optimal growth temperatures with size is corroborated by our analysis of experimental growth rate data, where we find that within species, the optimum growth temperature declines with body size by 0.31 per unit increase in the natural log of relative body mass (Fig. 5). Below we present the underlying results in more detail.

At below peak temperatures, the intraspecific mass- and temperature dependence of specific growth (% increase in size day-1) can be described by the equation: (Fig. 1), based on posterior medians of the global parameters (representing an average, unmeasured fish) of the models fit to XXX temperature experiments. The estimated temperature-mass interaction coefficient is both small and uncertain, and only leads to marginally better fits to growth data compared to the model without the interaction (WAIC without interaction, M5, is 2.4; Table 2). The estimated interaction coefficient is 0.0046 [-0.064, 0.075], where Bayesian 95% credible intervals are indicated in square brackets. The mass exponent of growth is estimated to be -0.36 [-0.5, -0.23] and the activation energy (-) of growth 0.74 [0.95, 0.53].

We find that the global intraspecific scaling of mass-specific maximum consumption rate can be described by the equation (Fig. 2). For mass-specific metabolic rate, the relationship is: . In the models for consumption and metabolic, all coefficients vary by species (M5 and M1, respectively) (*SI Appendix*, Table S4). Maximum consumption rate scales with a smaller mass exponent (-0.38 [-0.45, -0.30) than metabolic rate (-0.21 [-0.26, -0.16]), based on the non-overlapping Bayesian 95% credible intervals (Fig. 3). It is also probable that the mass-specific scaling exponents differ from -0.25 (predicted by the 3/4 scaling scaling in AFS and ‘Metabolic Theory of Ecology’ (‘MTE’)). 99.7% of the posterior distribution of the mass exponent of maximum consumption is below -0.25 whereas 95.5% of the posterior distribution of the mass exponent of metabolic rate is above -0.25.Activation energies of maximum consumption rate and metabolism are both similar (0.69 [0.54, 0.84] and 0.62 [0.57, 0.67] respectively; Fig. 3) and largely fall within the prediction from the ‘MTE’ (0.6-0.7 eV) (Brown *et al.* 2004)). For maximum consumption, the model with a global interaction term, , (M2) has a WAIC of 1.3 compared to the best model (M5) without an interaction term, meaning that WAIC offers little support for one of these models over the other (Table 2). In contrast, we find statistical support for a species-varying interaction between the effect of body mass and temperature for metabolic rate. 98.3% of the posterior distribution of the global interaction coefficient is above 0 (Fig. S12). The estimated coefficient is 0.018 [0.0011, 0.0364] on the Arrhenius temperature scale, which corresponds to a decline in the mass scaling exponent of metabolic rate by 0.0026 .

Based on WAIC and visual inspection of residual patterns we chose a model for maximum consumption rate fitted to data including beyond peak temperature with a cubic temperature variable and an increasing (rather than constant) standard deviation ( with temperature (see *SI Appendix*, Table S5 for details). The equation for rescaled mass-specific consumption rate over the full temperature range in the data is therefore: (Fig. S13).

Statistical support for the predicted decline in optimum growth temperature with body mass is strong in the growth rate data from XXX temperature experiments on fish. 92% of the posterior density of the global slope estimate () is below 0. The models with and without species-varying slopes were indistinguishable in terms of WAIC (*SI Appendix*, Table S6), and we present the results for the species-varying intercept and slope model, due to slightly better model diagnostics (*SI Appendix*, Fig. S31-34). The global relationship is given by the model: , where is the natural log of the rescaled body mass.

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**Fig. 1**. *Effects of temperature and body mass on body growth below optimum temperature. Panel A) shows the natural log of specific growth rate as a function of body mass on a logarithmic x-axis (for readability, note the model is fitted with ln(mass) as a predictor), such that the slope corresponds to the mass-scaling exponent. Colors indicate species. The line in panel A is the global prediction from model M1 at the mean temperature (14, but note the model is fitted using Arrhenius temperature). Shaded areas correspond to 80% and 95% credible intervals. Point colours indicate species. The bottom row shows the posterior distributions for (B) the global mass-scaling exponent, , (C) the global temperature coefficient, and (D) the global mass-temperature interaction, . Dashed white line shows the posterior median and red vertical line in (D) indicates zero.*

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***Fig. 2****. Natural log of mass-specific maximum consumption rate (A) and metabolic rate (B) against body mass on a logarithmic x-axis. Lines are global predictions at the average temperature in each data set (both 19, but note the model is fitted using mean-centred Arrhenius temperature). Shaded areas correspond to 80% and 95% credible intervals. Species are grouped by colour (legend not shown, n=20 for consumption and n=34 for metabolism, respectively).*

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***Fig. 3****. Global and species-level effects of mass- and temperature on specific maximum consumption rate and metabolic rate. Vertical lines show the posterior medians of the global activation energies and mass exponents of maximum consumption and metabolism ( and in Eqs. 6-8 for the mass and temperature coefficients, respectively). The shaded vertical bars correspond to the posterior median standard deviations. Points and triangles show the posterior medians for each species-level coefficient (for maximum consumption rate and metabolic rate, respectively), and the horizontal bars show their 80% and 95% credible interval.*

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***Fig. 4.*** *Illustration of predicted whole-organism maximum consumption rate (green), metabolic rate (purple) and the difference between them (orange) for two body sizes (top = 2g , bottom = 200g). Vertical arrows indicate the temperature where the difference in net energy acquisition – and hence, energy available for growth – is maximized for the two body sizes, which occurs at different temperatures despite that consumption peaks at the same temperature for both body sizes.*

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**Fig. 5**. *Experimental data demonstrating optimum growth temperature declines with body mass. The plot shows the optimum temperature within species (rescaled by subtracting the mean optimum temperature from each observation, by species) as a function of the natural log of rescaled body mass (ratio of mass to maturation mass within species). Probability bands represent 80% and 95% credible intervals and the solid line shows the global prediction ( and ). Colours indicate species and the area of the circle corresponds to body mass in unit .*

**Discussion**

Individual growth, consumption and metabolism represent fundamental processes in ecology, and their scaling with body mass and temperature has been used to predict the effects of warming on body size and size structure, and population and community dynamics (Vasseur & McCann 2005; Rall *et al.* 2010; Cheung *et al.* 2013). How biological rates scale with temperature and/or mass is commonly inferred from either meta-analysis of single-species studies (Bokma 2004; Glazier 2005) or interspecific relationships (Brown *et al.* 2004; Killen *et al.* 2010). However, the former can result in large variation in intraspecific scaling parameters due to variation between species, and the latter relies on the assumption that rates scale identically within as between species, which is often not the case (Glazier 2005; Rall *et al.* 2012; Jerde *et al.* 2019). As growth, consumption and metabolism represent individual-level processes, it is important to understand how these rates depend on temperature and mass within species, ideally over ontogeny. At temperatures below those that maximize the rates (‘peak temperatures’), we find that temperature sensitivities of metabolism, consumption and growth are close to predictions from the ‘Metabolic theory of ecology’ , i.e. with an activation energy of ~0.65 . This means that a “metabolic mismatch” (e.g. metabolism being more temperature sensitive than consumption) does not occur in this temperature range. However, over a larger temperature range, the relationship between maximum consumption rate and temperature is typically unimodal within species (Englund *et al.* 2011; Rall *et al.* 2012; Jutfelt *et al.* 2020) (Fig. 4), and a mismatch can therefore occur at higher temperatures. This likely contributes to growth rates reaching an optimum over temperature (Jobling 1997). Importantly, a larger exponent of intraspecific mass-scaling for metabolism than for consumption, as we find in fish (Fig. 3), leads to a decline in optimum growth temperature with body size in Pütter-type growth models such as the von Bertalanffy growth model (Morita *et al.* 2010).

Some previous studies have found declines in optimum growth temperatures with body size in particular species of fishes and other aquatic ectotherms (Wyban *et al.* 1995; Panov & McQueen 1998; Steinarsson & Imsland 2003; Björnsson *et al.* 2007; Handeland *et al.* 2008), while others have not (Brett *et al.* 1969; Elliott & Hurley 1995). We find that for an average fish, the optimum growth temperature declines as it grows in size, despite the small range of body sizes used in the experiments (only 10% of observations are larger than 50% of maturation size). Individuals of such small relative size likely invest little energy in reproduction. This suggests that reduced growth performance of large fish with warming cannot only be explained by earlier maturation and changes in energy allocation from somatic growth to gonads, but may also represent physiological constraints.

In the von Bertalanffy growth model, the difference in allometric exponents of net energy gains vs costs ( and ) stems from the assumption that anabolism scales with an exponent of and catabolism or maintenance metabolism is proportional to body mass (). The latter stems from the argument that spontaneous denaturation occurs in every cell (von Bertalanffy 1957; Pauly & Cheung 2018a) – and likely also for mathematical convenience (Ursin 1967). However, this assumption has been criticized by empiricists, as maintenance costs are thought of as proportional to standard metabolic rate, i.e. with an interspecific exponent of ~0.8 (Ursin 1967; Jobling 1997; Lefevre *et al.* 2017a). In this case when is close to , growth trajectories are not asymptotic and the effect of temperature on asymptotic size can become unrealistic (Lefevre *et al.* 2017a; Marshall & White 2019b). Hence, the prediction of shrinking of large fish has been questioned (Lefevre *et al.* 2017b). However, we do not have a good understanding of the relationship between the exponents (e.g. ) at the intraspecific level, because these models and their parameters are typically evaluated using interspecific data. Just as the existence of large fishes in tropical waters does not invalidate the hypothesis that large fish may shrink with warming, interspecific parameters cannot reject or support these models. By collating experimental data with intraspecific variation in both size and temperature, we are able to show that the mass scaling exponent of metabolism is larger than that of maximum consumption, which implies that maintenance costs increase faster with body mass than energy gains. There may thus be purely physiological constraints to growing large in warm waters that cause declining optimal growth temperatures.

result instronger effects on body growth in (as suggested by our finding that growth temperature optimum declines with intra-specific body size) whether compared to smaller conspecifics in natural populationss

In addition to resolving the scaling of net energy gain with body mass within species, it is important to understand how the balance between energy gains and costs is affected by temperature. The match, or mismatch, between the temperature dependence of feeding vs. metabolic rates is a central question in ecology that extends from experiments to meta-analyses to food web models (Vasseur & McCann 2005; Rall *et al.* 2010; Lemoine & Burkepile 2012; Fussmann *et al.* 2014; Lindmark *et al.* 2019). We find that when using temperatures below peak, the global (average intraspecific) predictions about the activation energy of metabolism and consumption do not differ substantially and the 95% credible intervals largely overlap, meaning there is no clear loss or gain of energetic efficiency with warming within species. This is in contrast to other studies, e.g. (Lemoine & Burkepile 2012; Rall *et al.* 2012). However, it is in line with the finding that growth rates increase with temperature (Angilletta & Dunham 2003), which is difficult to reconcile from a bioenergetics perspective if warming always reduced net energy gains. However, we do find clear mismatches at higher temperatures, due to consumption rates reaching a peak whereas metabolic rates increase exponentially over much wider temperature ranges. A recent hypothesis suggests that the reason for unimodal consumption curves is to protect aerobic scope by not overshooting post-meal oxygen consumption (Jutfelt *et al.* 2020). This would causally explain why also growth curves are unimodal, as has been argued from a conceptual point of view (Jobling 1997). Thus, unimodal thermal responses are likely important for understanding impacts of climate change (Neuheimer *et al.* 2011). Therefore, a priority should be to identify generalized approaches and parameters for characterizing the unimodal shape of consumption rate, which would require more data and experiments with combined mass and temperature treatments.

We find that body mass can affect the temperature dependence of physiological rates (here metabolism), something which is overlooked by the ‘Metabolic Theory of Ecology’ and previously has been reported only for single species studies (Beamish 1964; Xie & Sun 1990; Ohlberger *et al.* 2012; Lindmark *et al.* 2018; Fossen *et al.* 2019; Christensen *et al.* 2020) and between species size variation (Killen *et al.* 2010). This finding is in line with the metabolic boundary-level hypothesis, which predicts a negative relationship between mass scaling exponents of resting metabolism and temperature (Glazier 2010). However, this interaction was not found in a recent study on the intraspecific mass scaling exponent of metabolic rate in fishes (Jerde *et al.* 2019), possibly due to different data collection protocols. We specifically used studies with temperature replicates within species and hence evaluate within-species interactive effects of mass and temperature. The effect size of the interaction is, however, relatively small. We do not find strong evidence for temperature-body size interactions in growth or consumption, although it has been reported for some species (García García *et al.* 2011). A possible explanation is that we strictly exclude temperatures beyond those at which rates peak for the log-linear model, and inclusion of these could lead to significant negative interactions if rates for large fish peak at lower temperature. The ecological implications of temperature-size interactions at sub peak temperatures could therefore be small, although larger estimates have been reported in single species studies (Ohlberger *et al.* 2012). It could also be that the overall effect is masked by variation between species, as studies have found both positive and negative interactions between mass and temperature (Ohlberger *et al.* 2012; Messmer *et al.* 2017; Lindmark *et al.* 2018). Given the between-species variation, one approach forward could be to control for taxonomic structure at multiple levels when assessing intraspecific mass- and temperature scaling of these rates.

While the numbers of temperature-replicates per size range within species in our dataset is relatively small due to strict selection criteria, our approach allows for jointly estimating the effects of mass- and temperature, which is particularly important when scaling coefficients differ from general predictions. In addition, the hierarchical Bayesian model with literature-informed priors helps overcome limitations of small data sets by incorporating prior knowledge and borrowing information across species.

We argue that one contributing factor to the discrepancy between mechanistic models, general scaling theory, and data is the lack of data synthesis at the intraspecific level. Systematic analysis of existing experimental data, as presented in this study, can improve our understanding of the intraspecific scaling of rates such as growth, metabolism and consumption, which is crucial for predicting the impacts of climate warming on individuals, populations and food webs.

**Materials and methods**

**Data acquisition**

We searched the literature for experimental studies measuring the temperature- and mass dependence of individual growth rate, maximum consumption rate (feeding rate at unlimited food supply, *ad libitum*) and resting, routine and standard oxygen consumption rate as a proxy for metabolic rate (Nelson 2016). We used three different searches on the Web of Science Core Collection (see *SI Appendix*, for details). In order to estimate how these rates depend on both body size and temperature within species, we selected studies with a combination of body mass-temperature setup (at least two temperature treatments and a size range). This reduces the number of data sets available in the literature, as most experimental studies use either size or temperature treatments, not both. However, this criterion allows us to fit multiple regression models and estimate the effects of mass and temperature jointly, and to evaluate the probability of interactive mass- and temperature effects within species. Following common practice we excluded larval studies, because larvae can exhibit different isometric scaling and do not feed independently (Glazier 2005).

Studies were included if (i) a unique experimental temperature was recorded for each trial (1), (ii) fish were provided food at *ad libitum* (consumption and growth data) or if they were unfed (resting, standard or routine metabolic rate), and (iii) fish exhibited normal behaviour during the experiments. We used only one study per species and rate to ensure that all data within a given species are comparable as measurements of these rates can vary between studies due to e.g. measurement bias, differences in experimental protocols, or because different populations were used (Armstrong & Hawkins 2008; Jerde *et al.* 2019). In cases where we found more than one study for a given rate and species, we selected the most suitable study based on our pre-defined criteria (for details, see *SI Appendix*). A more detailed description of the search protocol, data selection, acquisition, quality control, collation of additional information and standardizing rates to common units can be found in *SI Appendix*.

We compiled four datasets: growth rate, maximum consumption rate, metabolic rate and the optimum growth temperature for each combination of body mass group and species. We compiled in total 227 (growth rate) (and 45 optimum temperatures), 746 (maximum consumption rate) and 2699 (metabolic rate) data points from published articles for each rate, from 13, 20 and 34 species, respectively, from different taxonomic groups, habitats and lifestyles (*SI Appendix*). We asked all the corresponding authors of each article to share data, and in case data were not shared, we extracted them from tables or figures using Web Plot Digitizer (Rohatgi 2012).

**Model fitting**

*Model description*

To each dataset, we fit hierarchical models with different combinations of species-varying coefficients, meaning they are estimated with shrinkage. This reduces the influence of outliers which could occur in species with small samples sizes (Gelman & Hill 2007; Harrison *et al.* 2018). The general form of the model is:

(1)

(2)

(3)

where is the th observation for species for rate *y*, is a species-varying intercept, is a predictor and is its coefficient, with , where is the number of predictors considered in the model (mass, temperature, and their interaction). Species-level intercepts follow a normal distribution with hyperparameters (global intercept) and (between-species standard deviation). For most models we also allow the effects of predictor(s) tovary between species, such that becomes and , where . For each dataset, we evaluate multiple combinations of species-varying coefficients (from varying intercept to varying coefficients). The models are completed with priors for parameters (*SI Appendix*, Table S3). Below we describe how the model in Eqns. 1-3 is applied to each data set.

*Mass- and temperature dependence of growth, consumption and metabolism below peak temperatures*

Peak temperatures (optimum in the case of growth), refers to the temperature at which the rate was maximized, by size group. For data below peak temperatures, we assumed that individual growth, maximum consumption rate and metabolism scale as a generalized version of the Arrhenius fractal supply model (Gillooly *et al.* 2001; Brown *et al.* 2004), such that the mass exponent was not assumed a priori. On a linear scale, this more general scaling relationship is , where is a rate (growth, maximum consumption or metabolism), is mass and is temperature. After log-transformation it becomes: , where is the intercept, is the mass scaling exponent (on a linear scale) when () and is the interaction coefficient.

When applied to Eqns. 1-3, is the th observation for species of the natural log of the rate (growth, consumption or metabolism), and the predictors are (natural log of body mass), (Arrhenius temperature, in unit ), both of which were mean-centred, and their interaction (in that order). Body mass is in , specific growth rate has unit , consumption rate , and metabolic rate . We use resting or routine metabolism (mean oxygen uptake of a resting unfed fish only showing some spontaneous activity) and standard metabolism (resting unfed and no activity, usually inferred from extrapolation or from low quantiles of routine metabolism, e.g. lowest 10 % of measurements) to represent metabolic rate (Beamish 1964; Ohlberger *et al.* 2007). Routine and resting metabolism constitute 58% of the data used and standard metabolism constitutes 42%. We accounted for potential differences between these metabolic rate measurements by allowing the intercept and slopes to vary between species and used a single study per species.

*Mass- and temperature dependence of consumption including beyond peak temperatures*

Over a larger temperature range, many biological rates are unimodal. We identified such tendencies in 11 species in the consumption data set. To characterize the decline in consumption rates beyond peak temperature, we fit second and third-degree polynomial regressions to a subset of these data containing only species with data points extending beyond such a peak temperature. For these data, in Eqn. 1 refers to the th observation of mass-specific consumption rates for species divided by the mean value for species (). We consider the following predictors (in Eqn. 2): mean-centred body mass (), standardized temperature (, where is the median temperature in the environment of species ), as well as the square and cube of this temperature-variable. The rescaling is done to control for differences between species with respect to the experimental temperatures relative to the temperature that maximizes their consumption rate. We only consider the intercept to be vary between species.

*Mass-dependence of optimum growth temperature*

To evaluate how the optimum temperature (, in degrees Celsius) for individual growth depends on body mass, we fit Eqns. 1-3 with as the mean-centred optimum growth temperature within species (), to account for species being adapted to different thermal regimes. , the predictor variable for this model, is the natural log of the ratio between mass and mass at maturation within species: . This rescaling is done because we are interested in examining relationships within species while accounting for variation in relative body masses between experiments, and because we do not expect an interspecific relationship between optimum growth temperature and body mass. We consider both the intercept and the effect of mass to potentially vary between species.

*Parameter estimation*

We fit the models in a Bayesian framework, using R version 4.0.2 (R Core Team 2020) and JAGS (Plummer 2003) through the R-package ‘*rjags*’ (Plummer 2019). We used a mix of flat, weakly informative and non-informative priors to facilitate convergence (Table 1). Weakly informative priors were given mean values around average prediction from the ‘Metabolic theory of ecology’ (Brown *et al.* 2004), with large variances to make them less informative. We used 3 Markov chains with 5000 iterations for adaptation, followed by 15000 iterations burn-in and 15000 iterations sampling where every 5th iteration saved. Model convergence was assessed by visually inspecting trace plots and potential scale reduction factors () (Gelman *et al.* 2003) (*SI Appendix*). compares chain variance with the pooled variance, and values <1.1 suggest all three chains converged to a common distribution. We relied heavily on the R packages within ‘*tidyverse’* (Wickham 2017) for data processing, as well as ‘*ggmcmc*’ (Fernández-i-Marín 2016), ‘*mcmcviz*’ (Youngflesh 2018) and ‘*bayesplot*’ (Gabry *et al.* 2019) for visualization.

*Model comparison*

We compared the parsimony of models with different hierarchical structures, and with or without mass-temperature interactions, using the Watanabe-Akaike information criterion (WAIC) (Watanabe 2013; Vehtari *et al.* 2017), which is based on the posterior predictive distribution. We report WAIC for each model descried above (Table 2), and examine models with WAIC values < 2, where WAIC is each models difference to the lowest WAIC across models, in line with other studies (Olmos *et al.* 2019).

*Net energy gain*

The effect of temperature and mass dependence of maximum consumption and metabolism (proportional to biomass gain and losses, respectively) (Ursin 1967; Kitchell *et al.* 1977; Essington *et al.* 2001) on growth is illustrated by visualizing the net energy gain. The model for the net energy gain (growth) can be viewed as a Pütter-type model, which is the result of two antagonistic allometric processes: , where is body mass and is temperature. We convert metabolism from oxygen consumption [] to by assuming 1 = 295 (based on an oxycaloric coefficient of 14.2 ) (Hepher 1988), 1 = 4184 and an energy content of 5600 (Rijnsdorp & Ibelings 1989). Consumption and metabolic rate are calculated for two sizes (2 and 200 g, which roughly correspond to the 25th and 75th percentile in the datasets), using the global allometric relationships found in the log-log models fit to sub-peak temperatures. These allometric functions are further scaled with the temperature correction factor , (subscript for consumption and for metabolism). Because maximum consumption reaches a peak over temperature, is based on the polynomial model (but without a mass-coefficient and an intercept, because the mass-coefficent is applied through the allometric function and is rescaled to become a multiplier). It can be written as: , where is temperature in and is a constant that scales the term to 1 at the mean temperature in the data (19). is defined as where , is in unit K and is a constant that scales the term to 1 at the mean temperature in the data (19). Note that when estimating these parameters, temperature () is centred to the median temperature in the environment for species in the polynomial, whereas for the log-log model it is centred to the overall mean in the data ().

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**Author contributions**

ML conceived the study; ML, JO, AG designed research; ML performed research; ML analysed data; ML, JO, AG wrote the paper and contributed to revisions of the manuscript.

**Data accessibility statement**

All data and R code (data manipulation, analyses and figures) can be downloaded from a GitHub repository (<https://github.com/maxlindmark/scaling>) and will be archived on Zenodo upon publication.

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