**Title Page**

Optimum growth temperature declines with body size within fish species

Max Lindmarka,1, Jan Ohlbergerb, Anna Gårdmarkc

a Swedish University of Agricultural Sciences, Department of Aquatic Resources, Institute of Coastal Research, Skolgatan 6, Öregrund 742 42, Sweden

b School of Aquatic and Fishery Sciences (SAFS), University of Washington, Box 355020, Seattle, WA 98195-5020, USA

c Swedish University of Agricultural Sciences, Department of Aquatic Resources, Skolgatan 6, SE-742 42 Öregrund, Sweden

1 Author to whom correspondence should be addressed. Current address:

Max Lindmark, Swedish University of Agricultural Sciences, Department of Aquatic Resources, Institute of Marine Research, Turistgatan 5, Lysekil 453 30, Sweden, Tel.: +46(0)104784137, **email**: [max.lindmark@slu.se](mailto:max.lindmark@slu.se)

**Classification**: BIOLOGICAL SCIENCES, Ecology

**Keywords**: body growth, metabolic rate, consumption rate, temperature-size rule, metabolic theory of ecology

Word count: I=1100, R=660, D=1570, M=1880; Total: 5210

**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, link experimental data to observed growth patterns, and advance mechanistic food web models. To examine the combined effects of body size and temperature on growth, and the link between metabolism, maximum consumption and body growth, we conducted a systematic review and compiled experimental data on fishes from 59 studies combining body mass and temperature treatments. By fitting hierarchical models accounting for variation between species, we estimated how these three processes scale jointly with temperature and body mass within species. We found that maximum consumption scales with a smaller mass-exponent than metabolism, and is unimodal over the full temperature range, which leads to the prediction that optimum growth temperatures declines with body size. Using an independent dataset, we confirmed this negative relationship between optimum growth temperature and size within fish species. Small individuals will therefore likely exhibit increased growth with initial warming, whereas larger conspecific individuals could be the first to experience negative impacts of warming on growth. These findings help advance mechanistic models of individual growth and food web dynamics, and improve our understanding of how climate warming affects the body growth and size structure of aquatic ectotherms.

**Significance statement**

Predicting organism responses to a warming climate requires understanding of how physiological processes such as growth, feeding and metabolism depend on body size and temperature within species. Common growth models predict declining optimum growth temperatures with body size if energetic costs increase faster than gains with body size. However, the generality of these features has not been evaluated at the within-species level. By collating data through a systematic literature review, we find support for both declining net energy gain and optimum growth temperatures with body size. These results imply that large individuals within populations may be the first to suffer negative consequences of warming on growth, with potential implications for fisheries yield and food web structure in warmer climates.

**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 in ectotherms (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). Support for the TSR exist in in fishes, where 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). However, whether the positive effect of warming on growth is indeed limited to small individuals within a species, as predicted by the temperature size-rule, remains largely untested. 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 Dorst *et al.* 2019; Denderen *et al.* 2020) and differences between species may be related to life history traits and depend on local environmental conditions (Denderen *et al.* 2020; Wang *et al.* 2020).

While the support for TSR is mixed, and the underlying mechanisms are not well understood (Ohlberger 2013; Audzijonyte *et al.* 2018; Neubauer & Andersen 2019), theoretical growth models, such as Pütter growth models (Pütter 1920), including the von Bertalanffy growth model (VBGM) (von Bertalanffy 1957), predict declines in asymptotic body mass with temperature and declines in optimum growth temperature with body mass, in line with the TSR (Morita *et al.* 2010; Pauly & Cheung 2018b). Yet, the physiological basis of these models has been questioned, as the scaling parameters (mass exponents) tend to differ from empirical estimates (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. In more mechanistic growth models, the difference between energy gain and expenditure is partitioned between somatic growth and gonads (Ursin 1967; Kitchell *et al.* 1977; Jobling 1997; Essington *et al.* 2001). Energy gain 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). Therefore, it is important to understand how metabolism and consumption rates scale with body mass and temperature in order to understand if and how growth of large fish within populations is limited by temperature, and to evaluate the physiological basis of growth models.

Moreover, in this context, the effect of body mass and temperature on growth dynamics should be evaluated over ontogeny, or at the intraspecific level (within species), which better represents the underlying process than interspecific data (among species) does (Marshall & White 2019b). Despite this, intraspecific body mass- and temperature scaling is often inferred from interspecific data, possibly because we know surprisingly little about the relationship between consumption and metabolic exponents within species (Marshall & White 2019b). Yet, how physiological rates depend on mass and temperature within species can differ from the same relationships across species (Glazier 2005; Rall *et al.* 2012; Jerde *et al.* 2019). For instance, across species, rates are often assumed (and found) to scale as power functions of mass with exponents of 3/4 for whole organism rates (-1/4 for mass-specific rates), exponentially with temperature, and with independent mass and temperature effects (e.g., in the Arrhenius fractal supply model (AFS) applied in the metabolic theory of ecology, MTE (Gillooly *et al.* 2001; Brown *et al.* 2004; Downs *et al.* 2008)). In contrast, within species deviations from a general 3/4 mass exponent are common (Clarke & Johnston 1999; Bokma 2004; Jerde *et al.* 2019), rates are typically unimodal (Dell *et al.* 2011; Englund *et al.* 2011; Rall *et al.* 2012; Uiterwaal & DeLong 2020) and the effects of mass and temperature can be interactive (Xie & Sun 1990; Glazier 2005; García García *et al.* 2011; Ohlberger *et al.* 2012; Lindmark *et al.* 2018) (but see Jerde *et al*. (2019)). 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). However, this requires intraspecific data with variation in both mass and temperature.

In this study, we analyse how maximum consumption, metabolism and growth rate of fish scale intraspecifically 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 (total n=3672, with data from 13, 20 and 34 species for each rate, respectively). We then fit hierarchical Bayesian models to estimate general intraspecific scaling parameters while accounting for variation between species. The estimated mass dependence and temperature sensitivity of mass-specific growth, consumption and metabolism, are used to quantify average changes in net energy gain (growth) over temperature and body mass. Lastly, we compare our predicted changes in optimum growth temperature over body mass with an independently compiled experimental data set on optimum growth temperatures across individuals of different sizes within species.

**Results**

We identified that within species of fish, mass-specific metabolic rates increase faster with body mass than maximum consumption rates, and neither of these rates conform to the commonly predicted -1/4 scaling with body mass (Fig. 1). We also quantified the unimodal relationship of consumption rate over the full temperature range (Fig. 2). Combined, these scaling relationships lead to the prediction from Pütter-type growth models that optimum growth temperature declines with body size (Fig. 3) (Morita *et al.* 2010). The prediction of declining optimum growth temperatures with size was confirmed by our analysis of independent 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. 4). Below we present the underlying results in more detail.

We find that the global intraspecific scaling of mass-specific maximum consumption rate can be described by the equation (Fig. 1). For mass-specific metabolic rate, the relationship is: . In the models for consumption and metabolic rate, all coefficients vary by species (M5 and M1, respectively) (*SI Appendix*, Table S4). Consumption 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. 1). It is also probable that the mass-specific scaling exponents differ from -1/4 (predicted by the MTE). 99.7% of the posterior distribution of the mass exponent of maximum consumption is below -1/4, whereas 95.5% of the posterior distribution of the mass exponent of metabolic rate is above -1/4. 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. 1) 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 S4). In contrast, we find statistical support for a species-varying mass and temperature interaction for metabolic rate. 98.3% of the posterior distribution of the global interaction coefficient is above 0 (Fig. S5). 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 .

We estimate the parameters of the Sharpe-Schoolfield equation (Eq. 4) for temperature-dependence of consumption including data beyond peak temperature to: = 0.58 [0.45, 0.74], = 0.70 [0.52, 0.89], = 4.03 [2.81, 4.98], and = 2.64 [2.17, 3.22]. This shows that the relationship between consumption rate and temperature is unimodal and asymmetric, where the decline in consumption rate at high temperatures is steeper than the increase at low temperatures (Fig. 2).

The above results confirm the criteria outlined in Morita et al., (2010) for declining optimum temperature declines size – smaller whole organism mass exponent for consumption than metabolism and that growth reaches an optimum over temperature. In our case, because consumption reaches a peak, whereas Morita et al., (2010) et al assumed a linear temperature dependence of energy gain. We illustrate these findings in Fig. 3, which shows that the optimum temperature for net energy gain is reached at a lower temperature for a smaller fish.

Next, we investigate if this result also can be seen in experimental growth data. We find a strong statistical support for a decline in optimum growth temperature with body mass, as 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 S5), and we present the results for the species-varying intercept and slope model, due to slightly better model diagnostics (*SI Appendix*, Fig. S23-26). The global relationship is given by the model: , where is the natural log of the rescaled body mass.

**Discussion**

In this study, we systematically analysed the intraspecific scaling of growth, consumption and metabolism with body mass and temperature. We found strong evidence from two independent approaches for declining optimum growth temperatures as individuals grow in size. Specifically, we predict it using a Pütter growth model based on the differences in the mass-scaling of consumption and metabolism that we identify at the intraspecific level together with the unimodal temperature dependence of consumption, and in addition confirm it from growth rate data. These results are dependent on the use of intraspecific data and by characterizing temperature dependence by the response to increasing temperatures rather than inferring it from latitudinal gradients within species. Hence, our analysis shows the importance of understanding intraspecific scaling relationships in order to predict responses of fish populations to climate warming – and in particular how size affects the ability to increase growth rates with warming.

Recently, the prediction of shrinking of large fish has been questioned (Lefevre *et al.* 2017b), partly due to assumptions of the von Bertalanffy growth model – a special case of the Pütter growth model. Specifically, the allometric exponent of energy gains ( is assumed to be smaller than that of energetic costs (). This is based on the arguments that anabolism scales with the same power as surfaces to volumes () and catabolism, or maintenance metabolism, is assumed proportional to body mass (), as spontaneous denaturation occurs in every cell (von Bertalanffy 1957; Pauly & Cheung 2018a). The criticism concerning this assumption comes mainly from empiricists, as maintenance costs are thought to be proportional to standard metabolic rate, which in turn often is proportional to intake rates (Lefevre *et al.* 2017a; Marshall & White 2019b). In this case, is close to , which results in unrealistic growth trajectories and temperature dependences of growth dynamics (Lefevre *et al.* 2017a; Marshall & White 2019b). However, until now, we have not had a good understanding of the relationship between the *intraspecific* exponents for energy gains and costs, and instead rely on interspecific estimates (Peters 1983; Marshall & White 2019b). Similar to how 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 model predictions on growth dynamics within species. By collating experimental data with intraspecific variation in both size and temperature, we have shown that the mass scaling exponent of metabolism is larger than that of maximum consumption, which implies that on average within species of fish, maintenance costs increase faster with body mass than energy gains.

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.* 2010a; Lemoine & Burkepile 2012; Fussmann *et al.* 2014; Lindmark *et al.* 2019). We find that when using sub-peak temperatures, 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 (all else equal). This is in contrast to other studies, e.g. Lemoine & Burkepile (2012) and Rall *et al.* (2010b)*.* 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 gain. Our analysis instead suggest that the mismatch occurs when accounting for unimodal consumption rates over temperature. The reason for the unimodal thermal response of consumption is not well understood, it may be a mechanism to protect aerobic scope by not overshooting post-meal oxygen consumption (Jutfelt *et al.* 2020). Importantly, the unimodal thermal response of consumption leads to a unimodal thermal response of net energy gain that peaks at temperatures below the peak for consumption. And in addition, the peak temperature is a function of size, which illustrates the importance accounting for the unimodality of consumption also at below peak temperatures (Fig. 4). Therefore, the mass and temperature dependence of metabolism and consumption also constitutes a relatively simple mechanism that may contribute to the temperature-size rule (Ohlberger 2013), assuming a supply-demand type growth model like the Pütter. Specifically, the TSR states that warming increase growth rates but reduce maximum body size, which is also what would be expected if optimum growth temperatures decline over ontogeny.

Though 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), others have not (Brett *et al.* 1969; Elliott & Hurley 1995), hence we do not know if this is a general pattern. Using systematically collated growth data from experiments with variation in both size and temperature treatments (13 species), we find that for an average fish, the optimum growth temperature declines as it grows in size. This is despite the small range of body sizes used in the experiments (only 10% of observations are larger than 50% of maturation size) (Fig. S1). Individuals of such small relative size likely invest little energy in reproduction, which suggests that physiological constraints contribute to reduced growth performance of large compared to small fish, in addition to increasing investment into reproduction (Barneche *et al.* 2018).

Translating results from experimental data to natural systems is challenging because unlimited food supply, lack of predation, and constant temperatures do not reflect natural conditions, yet affect growth rates (Brett *et al.* 1969; Lorenzen 1996; Huey & Kingsolver 2019). Moreover, effects in experiments reflect responses on shorter time scales than that of natural warming. In fact, the relationship between growth and temperature along latitudinal gradients in a snapshot of time in natural populations tends to be weaker than predicted from metabolic theory, likely a result of acclimation, adaptation and thermal plasticity of life history traits (Denderen *et al.* 2020). That said, ample evidence exist for positive associations between *warming* and reconstructed growth rates in time series studies (Thresher *et al.* 2007; Neuheimer *et al.* 2011; Baudron *et al.* 2014; Huss *et al.* 2019; van Dorst *et al.* 2019). This probably reflects that species generally live in temperatures cooler than those maximizing growth, such that initial warming can be beneficial, which would be in line with experimental predictions from the studies compiled here, all else equal (Fig. S6) (Bernhardt *et al.* 2018). These somewhat varying results from gradient studies, time series and experiments highlight the importance of understanding the time scale of environmental change in relation to that of immediate physiological responses, acclimation, adaptation and community reorganization for the specific prediction about climate change impacts.

In natural systems, climate warming may also result in stronger food limitation (Huey & Kingsolver 2019). Hence, as optimum growth temperatures decline not only with size but also food availability (Brett *et al.* 1969; Brett 1971), and realized consumption rates are a fraction of the maximum consumption rate (20-70%) (Kitchell *et al.* 1977; Neuenfeldt *et al.* 2019), species may be negatively impacted by warming even when controlled experiments show they can maintain growth capacity at these temperatures. Supporting this point is the observation that warming already has negative or lack of positive effects on body growth (Huss *et al.* 2019) in populations living at the edge of their physiological tolerance in terms of growth (Neuheimer *et al.* 2011).

Whether or not the negative effects of warming will be first experienced by the largest fish, as suggested by our finding that optimum growth temperature declines with body size, depends on whether they typically occupy lower environmental temperatures compared to smaller conspecifics. They may for instance inhabit colder temperatures compared to small fish due to ontogenetic habitat shifts (Werner & Hall 1988), see also Heincke’s law (Heincke 1913; Audzijonyte & Pecl 2018)). That said, there is already empirical evidence of the largest individuals in natural populations being the first to suffer from negative impacts of warming from heatwaves (Pörtner & Knust 2007), or not being able to benefit from warming (Huss *et al.* 2019; van Dorst *et al.* 2019). Hence, assuming that warming can lead to increased growth rate for individuals of all sizes in a population is a simplification that can bias predictions of the biological impacts of climate change.

Growth, consumption and metabolism represent fundamental processes in ecology, and their interspecific scaling with body mass and temperature has been used to predict the effects of warming on body size, size structure, and population and community dynamics (Vasseur & McCann 2005; Cheung *et al.* 2013). We argue that a contributing factor to the discrepancy between mechanistic growth models, general scaling theory, and data is the lack of data synthesis at the intraspecific level. The approach presented here can help overcome limitations of small data sets by incorporating prior knowledge and borrowing information across species in a single modelling framework. In order to predict the impacts of climate warming on individuals, populations and food webs, it is important to improve our understanding of the intraspecific scaling of key physiological rates such as growth, metabolism and consumption with body mass and temperature. In conclusion, accounting for 1) the smaller whole-organism mass-exponent of consumption rates compared to metabolic rates and 2) the unimodal thermal response of consumption, could improve predictions on the impacts of warming on body growth of fishes.

**Materials and methods**

**Data acquisition**

We searched the literature for experimental studies evaluating the temperature response 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), across individuals of different sizes within species. 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 that experimentally varied both body size and temperature (at least two temperature treatments and at least two body masses; average of unique temperatures rounded to nearest is 7.2 for growth and 4.3 for consumption and metabolism data,; average of unique body masses rounded to nearest for growth, consumption and metabolism is 3.4, 20 and 47, respectively). The criteria for both mass and temperature variation in the experiments reduces the number of potential data sets, 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, which represents a life stage exhibiting different constraints and scaling relationships (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 studied (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*). We ensured that the experiments were conducted at ecologically relevant temperatures (*SI Appendix* Fig S2-S3). A more detailed description of the search protocol, data selection, acquisition, quality control, collation of additional information and standardizing of 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 a total of 227 measurements of growth rate (45 optimum temperatures), 746 measurements of maximum consumption rate (of which 666 are below peak) and 2699 measurements of metabolic rate from published articles for each rate, from 13, 20 and 34 species, respectively, from different taxonomic groups, habitats and lifestyles (Table S1-S2). We requested original data from all corresponding authors of each article. In cases where we did not hear from the corresponding author, we extracted data 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). Predictors are mean centred to improve interpretability (Schielzeth 2010). 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). We used a mix of flat, weakly informative and non-informative priors to facilitate convergence (see *SI Appendix*, Table S3). Weakly informative priors were given mean values around average prediction from the MTE (Brown *et al.* 2004), with large standard deviations to make them less informative. 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) refer to the temperature at which the rate was maximized, by size group. For data below peak temperatures, we assumed that mass-specific growth, maximum consumption rate and metabolism scale allometrically (as a power function of the form ) with mass, and exponentially with temperature. Hence, after log-log transformation of mass and the rate, and temperature in Arrhenius temperature ( in unit , where is Boltzmann’s constant [8.6210-5 ]), the relationship between the rate and its predictors becomes linear. This is similar to the MTE, except that we estimate all coefficients instead of correcting rates, and allow not only the intercepts but also slopes to vary across species.

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. 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 large temperature range, many biological rates are unimodal. We identified such tendencies in 10 out of 20 species in the consumption data set. To characterize the decline in rescaled consumption rates () beyond peak temperature, we fit a mixed-effects version of the Sharpe Schoolfield equation (Schoolfield *et al.* 1981), as parameterized in (Padfield *et al.* 2018). Specifically, we model in Eq. 1 as:

(4)

(5)

(6)

where the right-hand side of Eq. 4 is the Sharpe-Schoolfield equation, is the rate at a reference temperature (here set to -10 on a centred scale), [] is the activation energy, [] characterises the decline in the rate past the peak temperature and [] is the temperature at which half the rate is reduced due to high temperatures. We assume and vary across species according to a normal distribution with means and , and standard deviations and (Eq. 5-6). Prior to rescaling maximum consumption (in unit ) by dividing with the mean within species , we mass-normalize it by dividing it with where is mass in and is the mass-exponent estimated with the log-linear model fitted to data below peak temperature. Temperature, , is centred by subtracting the peak temperature estimated separately for each species using a linear model with a quadratic temperature term. 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 such that data can be pooled.

*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 over “ontogenetic size”, and because we do not expect an interspecific relationship between optimum growth temperature and body mass because species are adapted to different thermal regimes. 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 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 () (*SI Appendix*). compares chain variance with the pooled variance, and values <1.1 suggest all three chains converged to a common distribution (Gelman *et al.* 2003). 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 S4-S5), 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 (5 and 1000 g, which roughly correspond to the 25th percentile of both datasets and the maximum mass in the consumption data, respectively), 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 factors for consumption and for metabolism. is based on the Sharpe Schoolfield model and is given by the temperature dependence of metabolic rate from the log-linear model. Because and are fitted to data on different scales, we divide these functions by their maximum. Lastly, we rescale the product between the allometric function and and such that the rate at 19 (mean temperature in both data sets) equals the temperature-independent rate.

**Acknowledgements**

We thank Hiroki Yamanaka, Dennis Tomalá Solano, Vanessa Messmer, Björn Björnsson, Albert Imsland, Tomas Árnasson, Yiping Luo, Takeshi Tomiyama and Myron Peck for generously providing data, Magnus Huss and Ken Haste Andersen for providing useful comments on earlier versions of the manuscript and Matthew Low and Malin Aronson for an introduction to Bayesian inference. This study was supported by grants from the Swedish Research Council FORMAS (no. 217‐2013‐1315) and the Swedish Research Council (no. 2015‐03752) (both to AG).

**Author contributions**

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

**Data accessibility statement**

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

**Figure texts**

**Figure 1.** *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). C) Global and species-level effects of mass- and temperature on specific maximum consumption rate and metabolic rate. Horizontal 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 horizontal rectangles 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 vertical bars show their 80% and 95% credible interval*

**Figure 2.** *Mass-specific maximum consumption rate increase until a maximum is reached, after which it declines steeper than the initial rate of increase. Maximum consumption rates are relative to the average maximum consumption rates within species and temperature is the difference between the experimental temperature and the temperature where maximum consumption peaks (also by species species). Lines show posterior median of predictions from the Sharpe-Schoolfield model (using the average intercept across species and the common coefficients), grey bands show 95% and 80% credible intervals. Colors indicate species.*

**Figure 3.** *Illustration of predicted whole-organism maximum consumption rate (green), metabolic rate (purple) and the difference between them (orange) for two body sizes (top=1000g, bottom=5g) (see ´Materials and Methods´). Vertical arrows indicate the temperature where the difference in net energy gain (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.*

**Figure 4**. *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 .*

**Figures**

**Figure 1**

Chart

Description automatically generated

**Figure 2**

Chart, scatter chart

Description automatically generated

**Figure 3**

A picture containing diagram

Description automatically generated

**Figure 4**

Chart, scatter chart

Description automatically generated

**References**

Andersen, K.H., Beyer, J.E. & Lundberg, P. (2009). Trophic and individual efficiencies of size-structured communities. *Proceedings of the Royal Society B: Biological Sciences*, 276, 109–114.

Angilletta, M.J. & Dunham, A.E. (2003). The temperature-size rule in ectotherms: simple evolutionary explanations may not be general. *The American Naturalist*, 162, 332–342.

Armstrong, J.D. & Hawkins, L.A. (2008). Standard metabolic rate of pike, Esox lucius: variation among studies and implications for energy flow modelling. *Hydrobiologia*, 601, 83–90.

Atkinson, D. (1994). Temperature and Organism Size—A Biological Law for Ectotherms? In: *Advances in Ecological Research*. Elsevier, pp. 1–58.

Audzijonyte, A., Barneche, D.R., Baudron, A.R., Belmaker, J., Clark, T.D., Marshall, C.T., *et al.* (2018). Is oxygen limitation in warming waters a valid mechanism to explain decreased body sizes in aquatic ectotherms? *Global Ecology and Biogeography*.

Audzijonyte, A. & Pecl, G.T. (2018). Deep impact of fisheries. *Nature Ecology & Evolution*, 2, 1348–1349.

Barneche, D.R. & Allen, A.P. (2018). The energetics of fish growth and how it constrains food-web trophic structure. *Ecology Letters*, 21, 836–844.

Barneche, D.R., Jahn, M. & Seebacher, F. (2019). Warming increases the cost of growth in a model vertebrate. *Functional Ecology*, 33, 1256–1266.

Barneche, D.R., Robertson, D.R., White, C.R. & Marshall, D.J. (2018). Fish reproductive-energy output increases disproportionately with body size. *Science*, 360, 642–645.

Baudron, A.R., Needle, C.L., Rijnsdorp, A.D. & Marshall, C.T. (2014). Warming temperatures and smaller body sizes: synchronous changes in growth of North Sea fishes. *Global Change Biology*, 20, 1023–1031.

Beamish, F.W.H. (1964). Respiration of fishes with special emphasis on standard oxygen consumption II. Influence of weight and temperature on respiration of several species’. *Canadian Journal of Zoology/Revue Canadienne de Zoologie*, 42, 177–188.

Bernhardt, J.R., Sunday, J.M., Thompson, P.L. & O’Connor, M.I. (2018). Nonlinear averaging of thermal experience predicts population growth rates in a thermally variable environment. *Proceedings of the Royal Society B: Biological Sciences*, 285, 20181076.

von Bertalanffy, L. (1957). Laws in metabolism and growth. *The quarterly review of biology*, 32, 217–231.

Björnsson, B., Steinarsson, A. & Árnason, T. (2007). Growth model for Atlantic cod (Gadus morhua): Effects of temperature and body weight on growth rate. *Aquaculture*, 271, 216–226.

Blanchard, J.L., Heneghan, R.F., Everett, J.D., Trebilco, R. & Richardson, A.J. (2017). From Bacteria to Whales: Using Functional Size Spectra to Model Marine Ecosystems. *Trends in Ecology & Evolution*, 32, 174–186.

Bokma, F. (2004). Evidence against universal metabolic allometry. *Functional Ecology*, 18, 184–187.

Brett, J.R. (1971). Energetic Responses of Salmon to Temperature. A Study of Some Thermal Relations in the Physiology and Freshwater Ecology of Sockeye Salmon (Oncorhynchus nerkd). *Integr Comp Biol*, 11, 99–113.

Brett, J.R., Shelbourn, J.E. & Shoop, C.T. (1969). Growth Rate and Body Composition of Fingerling Sockeye Salmon, Oncorhynchus nerka, in relation to Temperature and Ration Size. *J. Fish. Res. Bd. Can.*, 26, 2363–2394.

Brown, J.H., Gillooly, J.F., Allen, A.P., Savage, V.M. & West, G.B. (2004). Toward a metabolic theory of ecology. *Ecology*, 85, 1771–1789.

Cheung, W.W.L., Sarmiento, J.L., Dunne, J., Frölicher, T.L., Lam, V.W.Y., Deng Palomares, M.L., *et al.* (2013). Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nature Climate Change*, 3, 254–258.

Clarke, A. & Johnston, N.M. (1999). Scaling of metabolic rate with body mass and temperature in teleost fish. *Journal of Animal Ecology*, 68, 893–905.

Daufresne, M., Lengfellner, K. & Sommer, U. (2009). Global warming benefits the small in aquatic ecosystems. *Proceedings of the National Academy of Sciences, USA*, 106, 12788–12793.

Dell, A.I., Pawar, S. & Savage, V.M. (2011). Systematic variation in the temperature dependence of physiological and ecological traits. *Proceedings of the National Academy of Sciences*, 108, 10591–10596.

Denderen, D. van, Gislason, H., Heuvel, J. van den & Andersen, K.H. (2020). Global analysis of fish growth rates shows weaker responses to temperature than metabolic predictions. *Global Ecology and Biogeography*, 29, 2203–2213.

van Dorst, R.M., Gårdmark, A., Svanbäck, R., Beier, U., Weyhenmeyer, G.A. & Huss, M. (2019). Warmer and browner waters decrease fish biomass production. *Global Change Biology*, 25, 1395–1408.

Downs, C.J., Hayes, J.P. & Tracy, C.R. (2008). Scaling metabolic rate with body mass and inverse body temperature: A test of the Arrhenius fractal supply model. *Functional Ecology*, 22, 239–244.

Elliott, J.M. & Hurley, M.A. (1995). The Functional Relationship between Body Size and Growth Rate in Fish. *Functional Ecology*, 9, 625.

Englund, G., Öhlund, G., Hein, C.L. & Diehl, S. (2011). Temperature dependence of the functional response. *Ecology Letters*, 14, 914–921.

Essington, T.E., Kitchell, J.F. & Walters, C.J. (2001). The von Bertalanffy growth function, bioenergetics, and the consumption rates of fish. *Canadian Journal of Fisheries and Aquatic Sciences*, 58, 2129–2138.

Fernández-i-Marín, X. (2016). ggmcmc: Analysis of MCMC Samples and Bayesian Inference. *Journal of Statistical Software*, 70, 1–20.

Forster, J., Hirst, A.G. & Atkinson, D. (2012). Warming-induced reductions in body size are greater in aquatic than terrestrial species. *PNAS*, 109, 19310–19314.

Fussmann, K.E., Schwarzmüller, F., Brose, U., Jousset, A. & Rall, B.C. (2014). Ecological stability in response to warming. *Nature Climate Change*, 4, 206–210.

Gabry, J., Simpson, D., Vehtari, A., Betancourt, M. & Gelman, A. (2019). Visualization in Bayesian workflow. *J. R. Stat. Soc. A*, 182, 389–402.

García García, B., Cerezo Valverde, J., Aguado-Giménez, F., García García, J. & Hernández, M.D. (2011). Effect of the interaction between body weight and temperature on growth and maximum daily food intake in sharpsnout sea bream (Diplodus puntazzo). *Aquaculture International*, 19, 131–141.

Gardner, J.L., Peters, A., Kearney, M.R., Joseph, L. & Heinsohn, R. (2011). Declining body size: a third universal response to warming? *Trends in Ecology & Evolution*, 26, 285–291.

Gelman, A., Carlin, J., Stern, H. & Rubin, D. (2003). *Bayesian Data Analysis. 2nd edition*. Chapman and Hall/CRC, Boca Raton.

Gelman, A. & Hill, J. (2007). *Data Analysis Using Regression and Multilevel/Hierarchical Models*. Cambridge University Press.

Gillooly, J.F., Brown, J.H., West, G.B., Savage, V.M. & Charnov, E.L. (2001). Effects of size and temperature on metabolic rate. *Science*, 2248–2251.

Glazier, D.S. (2005). Beyond the “3/4-power law”: variation in the intra- and interspecific scaling of metabolic rate in animals. *Biological Reviews of the Cambridge Philosophical Society*, 80, 611–662.

Handeland, S.O., Imsland, A.K. & Stefansson, S.O. (2008). The effect of temperature and fish size on growth, feed intake, food conversion efficiency and stomach evacuation rate of Atlantic salmon post-smolts. *Aquaculture*, 283, 36–42.

Harrison, X.A., Donaldson, L., Correa-Cano, M.E., Evans, J., Fisher, D.N., Goodwin, C.E.D., *et al.* (2018). A brief introduction to mixed effects modelling and multi-model inference in ecology. *PeerJ*, 6, e4794.

Hartvig, M., Andersen, K.H. & Beyer, J.E. (2011). Food web framework for size-structured populations. *Journal of Theoretical Biology*, 272, 113–122.

Heincke, F. (1913). Rapp. Proc. Verb. Réun. ICES 16, 1–70.

Hepher, B. (1988). *Nutrition of Pond Fishes*. Cambridge University Press.

Horne, C.R., Hirst, Andrew.G. & Atkinson, D. (2015). Temperature-size responses match latitudinal-size clines in arthropods, revealing critical differences between aquatic and terrestrial species. *Ecology Letters*, 18, 327–335.

Huey, R.B. & Kingsolver, J.G. (2019). Climate Warming, Resource Availability, and the Metabolic Meltdown of Ectotherms. *The American Naturalist*, 194, E140–E150.

Huss, M., Lindmark, M., Jacobson, P., van Dorst, R.M. & Gårdmark, A. (2019). Experimental evidence of gradual size‐dependent shifts in body size and growth of fish in response to warming. *Glob Change Biol*, 25, 2285–2295.

Jerde, C.L., Kraskura, K., Eliason, E.J., Csik, S.R., Stier, A.C. & Taper, M.L. (2019). Strong Evidence for an Intraspecific Metabolic Scaling Coefficient Near 0.89 in Fish. *Front. Physiol.*, 10, 1166.

Jobling, M. (1997). Temperature and growth: modulation of growth rate via temperature change. In: *Global Warming: Implications for Freshwater and Marine Fish* (eds. Wood, C.M. & McDonald, D.G.). Cambridge University Press, Cambridge, pp. 225–254.

Jutfelt, F., Norin, T., Åsheim, E.R., Rowsey, L.E., Andreassen, A.H., Morgan, R., *et al.* (2020). *The aerobic scope protection hypothesis: a mechanism explaining reduced growth of ectotherms in warming environments?* (preprint). EcoEvoRxiv.

Kearney, M. (2019). Reproductive Hyperallometry Does Not Challenge Mechanistic Growth Models. *Trends in Ecology & Evolution*, 34, 275–276.

Kitchell, J.F., Stewart, D.J. & Weininger, D. (1977). Applications of a bioenergetics model to yellow perch (Perca flavescens) and walleye (Stizostedion vitreum vitreum). *Journal of the Fisheries Board of Canada*, 34, 1922–1935.

Kooijman, S.A.L.M. (1993). *Dynamic energy budgets in biological systems*. Cambridge University Press.

Lefevre, S., McKenzie, D.J. & Nilsson, G.E. (2017a). Models projecting the fate of fish populations under climate change need to be based on valid physiological mechanisms. *Global Change Biology*, 23, 3449–3459.

Lefevre, S., McKenzie, D.J. & Nilsson, G.E. (2017b). Models projecting the fate of fish populations under climate change need to be based on valid physiological mechanisms. *Global Change Biology*, 23, 3449–3459.

Lemoine, N.P. & Burkepile, D.E. (2012). Temperature-induced mismatches between consumption and metabolism reduce consumer fitness. *Ecology*, 93, 2483–2489.

Lindmark, M., Huss, M., Ohlberger, J. & Gårdmark, A. (2018). Temperature-dependent body size effects determine population responses to climate warming. *Ecology Letters*, 21, 181–189.

Lindmark, M., Ohlberger, J., Huss, M. & Gårdmark, A. (2019). Size‐based ecological interactions drive food web responses to climate warming. *Ecology Letters*, 22, 778–786.

Lorenzen, K. (1996). The relationship between body weight and natural mortality in juvenile and adult fish: a comparison of natural ecosystems and aquaculture. *Journal of Fish Biology*, 49, 627–642.

Marshall, D.J. & White, C.R. (2019a). Aquatic Life History Trajectories Are Shaped by Selection, Not Oxygen Limitation. *Trends in Ecology & Evolution*, 34, 182–184.

Marshall, D.J. & White, C.R. (2019b). Have We Outgrown the Existing Models of Growth? *Trends in Ecology & Evolution*, 34, 102–111.

Maury, O. & Poggiale, J.-C. (2013). From individuals to populations to communities: A dynamic energy budget model of marine ecosystem size-spectrum including life history diversity. *Journal of Theoretical Biology*, 324, 52–71.

Morita, K., Fukuwaka, M., Tanimata, N. & Yamamura, O. (2010). Size-dependent thermal preferences in a pelagic fish. *Oikos*, 119, 1265–1272.

Nelson, J.A. (2016). Oxygen consumption rate v. rate of energy utilization of fishes: a comparison and brief history of the two measurements. *Journal of Fish Biology*, 88, 10–25.

Neubauer, P. & Andersen, K.H. (2019). Thermal performance of fish is explained by an interplay between physiology, behaviour and ecology. *Conserv Physiol*, 7.

Neuheimer, A.B., Thresher, R.E., Lyle, J.M. & Semmens, J.M. (2011). Tolerance limit for fish growth exceeded by warming waters. *Nature Climate Change*, 1, 110–113.

Ohlberger, J. (2013). Climate warming and ectotherm body size – from individual physiology to community ecology. *Functional Ecology*, 27, 991–1001.

Ohlberger, J., Mehner, Thomas., Staaks, Georg. & Hölker, Franz. (2012). Intraspecific temperature dependence of the scaling of metabolic rate with body mass in fishes and its ecological implications. *Oikos*, 121, 245–251.

Ohlberger, J., Staaks, G. & Hölker, F. (2007). Effects of temperature, swimming speed and body mass on standard and active metabolic rate in vendace (Coregonus albula). *Journal of Comparative Physiology, B*, 177, 905–916.

Olmos, M., Payne, M.R., Nevoux, M., Prévost, E., Chaput, G., Pontavice, H.D., *et al.* (2019). Spatial synchrony in the response of a long range migratory species (Salmo salar) to climate change in the North Atlantic Ocean. *Global Change Biology*, 26, 1319–1337.

Padfield, D., Buckling, A., Warfield, R., Lowe, C. & Yvon‐Durocher, G. (2018). Linking phytoplankton community metabolism to the individual size distribution. *Ecology Letters*, 21, 1152–1161.

Panov, V.E. & McQueen, D.J. (1998). Effects of temperature on individual growth rate and body size of a freshwater amphipod, 76, 10.

Pauly, D. & Cheung, W.W.L. (2018a). On confusing cause and effect in the oxygen limitation of fish. *Global Change Biology*, 24, e743–e744.

Pauly, D. & Cheung, W.W.L. (2018b). Sound physiological knowledge and principles in modeling shrinking of fishes under climate change. *Global Change Biology*, 24, e15–e26.

Peters, R.H. (1983). *The ecological implications of body size*. Cambridge University Press.

Plummer, M. (2003). JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. *Working Papers*, 8.

Plummer, M. (2019). *rjags*.

Pörtner, H.O. & Knust, R. (2007). Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science*, 315, 95–97.

Pütter, A. (1920). Studien über physiologische Ähnlichkeit VI. Wachstumsähnlichkeiten. *Pflügers Arch.*, 180, 298–340.

R Core Team. (2020). *R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing*. Vienna, Austria.

Rall, B.C., Brose, U., Hartvig, M., Kalinkat, G., Schwarzmuller, F., Vucic-Pestic, O., *et al.* (2012). Universal temperature and body-mass scaling of feeding rates. *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences*, 367, 2923–2934.

Rall, B.C., Vucic-Pestic, O., Ehnes, R.B., Emmerson, M. & Brose, U. (2010a). Temperature, predator-prey interaction strength and population stability. *Global Change Biology*, 16, 2145–2157.

Rall, B.C., Vucic‐Pestic, O., Ehnes, R.B., Emmerson, M. & Brose, U. (2010b). Temperature, predator–prey interaction strength and population stability. *Global Change Biology*, 16, 2145–2157.

van Rijn, I., Buba, Y., DeLong, J., Kiflawi, M. & Belmaker, J. (2017). Large but uneven reduction in fish size across species in relation to changing sea temperatures. *Global Change Biology*, 23, 3667–3674.

Rijnsdorp, A.D. & Ibelings, B. (1989). Sexual dimorphism in the energetics of reproduction and growth of North Sea plaice, Pleuronectes platessa L. *Journal of Fish Biology*, 35, 401–415.

Rohatgi, A. (2012). *WebPlotDigitalizer: HTML5 based online tool to extract numerical data from plot images. Version 4.1. [WWW document] URL https://automeris.io/WebPlotDigitizer (accessed on January 2019).*

de Roos, A.M. & Persson, L. (2001). Physiologically structured models – from versatile technique to ecological theory. *Oikos*, 94, 51–71.

Savage, V.M., Gillooly, J.F., Brown, J.H., West, G.B. & Charnov, E.L. (2004). Effects of body size and temperature on population growth. *The American Naturalist*, 163, 429–441.

Schielzeth, H. (2010). Simple means to improve the interpretability of regression coefficients: Interpretation of regression coefficients. *Methods in Ecology and Evolution*, 1, 103–113.

Schoolfield, R.M., Sharpe, P.J.H. & Magnuson, C.E. (1981). Non-linear regression of biological temperature-dependent rate models based on absolute reaction-rate theory. *Journal of Theoretical Biology*, 88, 719–731.

Steinarsson, A. & Imsland, A.K. (2003). Size dependent variation in optimum growth temperature of red abalone (Haliotis rufescens). *Aquaculture*, 224, 353–362.

Thresher, R.E., Koslow, J.A., Morison, A.K. & Smith, D.C. (2007). Depth-mediated reversal of the effects of climate change on long-term growth rates of exploited marine fish. *Proceedings of the National Academy of Sciences, USA*, 104, 7461–7465.

Uiterwaal, S.F. & DeLong, J.P. (2020). Functional responses are maximized at intermediate temperatures. *Ecology*, n/a.

Ursin, E. (1967). A Mathematical Model of Some Aspects of Fish Growth, Respiration, and Mortality. *Journal of the Fisheries Research Board of Canada*, 24, 2355–2453.

Vasseur, D.A. & McCann, K.S. (2005). A mechanistic approach for modelling temperature-dependent consumer-resource dynamics. *The American Naturalist*, 166, 184–198.

Vehtari, A., Gelman, A. & Gabry, J. (2017). Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. *Stat Comput*, 27, 1413–1432.

Wang, H.-Y., Shen, S.-F., Chen, Y.-S., Kiang, Y.-K. & Heino, M. (2020). Life histories determine divergent population trends for fishes under climate warming. *Nature Communications*, 11, 4088.

Watanabe, S. (2013). A Widely Applicable Bayesian Information Criterion. *Journal of Machine Learning Research*, 14, 867–897.

Werner, E.E. & Hall, D.J. (1988). Ontogenetic Habitat Shifts in Bluegill: The Foraging Rate-Predation Risk Trade-off. *Ecology*, 69, 1352–1366.

Wickham, H. (2017). *tidyverse: Easily Install and Load the “Tidyverse.”*

Wyban, J., Walsh, W.A. & Godin, D.M. (1995). Temperature effects on growth, feeding rate and feed conversion of the Pacific white shrimp (Penaeus vannamei). *Aquaculture*, 138, 267–279.

Xie, Xiaojun. & Sun, Ruyung. (1990). The Bioenergetics of the Southern Catfish (Silurus meridionalis Chen). I. Resting Metabolic Rate as a Function of Body Weight and Temperature. *Physiological Zoology*, 63, 1181–1195.

Youngflesh, C. (2018). MCMCvis: Tools to Visualize, Manipulate, and Summarize MCMC Output. *Journal of Open Source Software*, 3, 640.