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## In modelling effects of global warming, invalid assumptions lead to unrealistic projections

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### Abstract :

In their recent Opinion, Pauly and Cheung (2017) provide new projections of future maximum fish weight ( $W^\infty$ ). Based on criticism by Lefevre et al. (2017) they changed the scaling exponent for anabolism,  $dG$ . Here we find that changing both  $dG$  and the scaling exponent for catabolism,  $b$ , leads to the projection that fish may even become 98% smaller with a 1°C increase in temperature. This unrealistic outcome indicates that the current  $W^\infty$  is unlikely to be explained by the Gill-Oxygen Limitation Theory (GOLT) and, therefore, GOLT cannot be used as a mechanistic basis for model projections about fish size in a warmer world.

**Keywords** : climate change, fish, growth, metabolism, modelling, oxygen uptake, scaling, warming

32 In a recent Opinion paper, Pauly and Cheung (2017) argue against the criticisms we raised  
33 (Lefevre *et al.*, 2017) about the Gill-Oxygen Limitation Theory (GOLT) and its application in  
34 modelling. Rather than providing point-by-point responses to their arguments we highlight  
35 some key issues that, in our opinion, disqualify GOLT as a mechanistic basis for model  
36 projections about the future size of fishes.

37 Pauly and Cheung (2017) contend that if gill surface area scaled to body mass with an  
38 exponent larger than  $2/3$ , this would cause gill growth to outstrip body growth, such that  
39 fishes ‘run out of space’ in their head, precluding any further gill or body growth. This could  
40 only be the case, however, if it is assumed that gill surface area grows by increasing all length  
41 measures equally (Fig. 1a, Supplementary Information Table S1). This is entirely disproved  
42 by existing data, perfectly illustrated by the carp, where gill mass and surface areas have been  
43 measured over a wide range of body masses (Oikawa & Itazawa 1984; 1985). Carp gill  
44 surface area scales to body mass with an exponent of 0.79 (Fig. 1c,d), while gill volume  
45 scales with an exponent of 0.84 (Fig. 1e). That is, the gills of carp occupy a decreasing  
46 proportion of space in the head as the body grows (Fig. 1f), despite the fact that their surface  
47 area grows with an exponent larger than  $2/3$ . If carp needed a larger gill surface area, there  
48 would be no geometrical constraint hindering it - new lamellae in a growing gill are not added  
49 where oxygen depleted water flows (Fig. 1b). Pauly and Cheung seem to suggest that when  
50 the gill surface area grows, it will eventually deplete the water of oxygen and more surface  
51 area would be useless. However, an increase in body and gill size will of course coincide with  
52 a proportional increase in water and oxygen movement, so a doubling of surface area  
53 effectively doubles capacity for oxygen uptake. This is aided by the counter-current principle  
54 of gill blood flow, where blood leaving the gill lamellae meets inflowing water with the  
55 highest oxygen content (e.g. Nilsson, 2010). We know of no experimental evidence showing  
56 that large gills and large fishes are less effective at oxygenating blood. That is, a fundamental

57 pillar of the GOLT - that geometrical constraints hinder the gills and their surface area from  
58 growing at the same pace as the fish body - is not supported by existing data and knowledge.

59 Pauly and Cheung (2017) have made new calculations where they use mass exponents for gill  
60 surface area ( $d_G$ ) from 0.6 in 'small' fish to 0.9 in 'large' fish, rather than the 0.7 they  
61 previously used (Cheung et al., 2011; 2013). They find that allowing gill area to grow faster  
62 with body mass will cause fishes to be even smaller in a warmer future (Fig. 2a,b). This goes  
63 against the basic assumption of GOLT, that growth is oxygen-limited, and also makes little  
64 sense physiologically. This unrealistic outcome is, in fact, simply a result of the current  
65 maximum weight ( $W_\infty$ ) being one of few real-world parameters in the model (the others being  
66 the species-specific growth parameter  $K$  and temperature). The value of  $W_\infty$  dictates the ratio  
67 between the constants,  $H$  for anabolism and  $k$  for catabolism, in the von Bertalanffy equation  
68 ( $dW/dt = H \cdot W^{d_G} - k \cdot W^b \leftrightarrow H/k = W_\infty^b / W_\infty^{d_G}$ ; see Supplementary Information p. 3 for  
69 derivation). Thus in the original paper (Cheung et al., 2013), with  $W_\infty$  in g, the  $H/k$  ratio  
70 resolved as 1.66 in the smallest species to 101.6 in the largest species, although there is no  
71 biological foundation for such a spread in the ratio. If we test their model with more realistic  
72 values (Fig. 2c-d), by setting almost equal scaling exponents for anabolism and catabolism,  
73 the predicted effect of temperature becomes totally unrealistic, suggesting a 98-99% drop in  
74 fish body mass with a 1°C increase in temperature, while a 2°C increase will cause fishes to  
75 be 100% smaller (Supplementary Information Table S2 and S3). If the exponents are set as  
76 equal, which based on scientific evidence is probably the case in real fishes,  $W_\infty$  can never be  
77 predicted from the GOLT (or von Bertalanffy) model, as anabolism will always be larger than  
78 catabolism (Fig. 2e). Thus, with real-world data the model breaks down and cannot determine  
79  $W_\infty$  of fishes now or in any future. The most parsimonious explanation for these unrealistic  
80 predictions is that the current observed  $W_\infty$  is in fact not determined by limitations in oxygen  
81 supply; hence it cannot reliably be used to predict the future  $W_\infty$  using the von Bertalanffy

82 equation. There is simply no scientific evidence or known mechanism to support the claim by  
83 Cheung and Pauly (2017) that “*fish with a higher  $d_G$  tend to have a lower ratio of the*  
84 *anabolic to catabolic rate constant, suggesting that the fish would spend relatively more*  
85 *energy for catabolic activities than anabolic activities*”. This claim is based on the fact that,  
86 when using the von Bertalanffy equation, the H/k ratio is forced to fit a certain observed  
87 maximum size.

88 Pauly and Cheung (2017) reaffirm their belief that the oxygen demand of maintenance  
89 metabolism is dictated by denaturation of proteins and that it is therefore constant relative to  
90 body mass because it ‘occurs in all cells’. We must stress that this idea is not supported by  
91 scientific evidence. As we explained (Lefevre et al., 2017), all evidence indicates that  
92 maintenance oxygen demand decreases with mass ( $b-1 = -0.13$ ) in essentially the same  
93 manner as maximum capacity for oxygen supply ( $d-1 = -0.12$ ). When it comes to the  
94 exponent  $b$  (for maintenance metabolism or ‘catabolism’), von Bertalanffy (1957) contended  
95 that using  $b < 1$  would have little impact on the model, while Pauly and Cheung (2017)  
96 suggest that “*the shrinkage of body size under warming may be lower with  $b < 1$* ”. Our  
97 calculations based on GOLT (Fig. 2d-f, Supplementary Information Table S2 and S3),  
98 however, indicates the opposite: reducing  $b$  and hence bringing the exponents closer to each  
99 other actually results in an exaggerated effect of even a very minor increase in temperature,  
100 regardless of the value of the input parameters  $W_\infty$  and  $K$  (Supplementary Information Table  
101 S2 and S3).

102 Finally, Cheung and Pauly (2017) dismiss the fact that the existence of extremely large  
103 tropical fishes goes against GOLT, arguing that sunfish and large groupers are very sluggish.  
104 They do not consider marlins, which are very large and anything but sluggish, and which  
105 prefer warm tropical surface waters (see Lefevre et al., 2017). Their comment about whale  
106 sharks spending much time in the cold is also inaccurate; depth and temperature loggers

107 reveal that whale sharks prefer warm water and, if they dive into cold waters, they  
108 subsequently remain near the surface to warm up (Thums *et al.*, 2013).

109 We urge our colleagues to accept that the GOLT is not a valid explanation for why some  
110 fishes may become smaller as the world warms. We must develop new models, based upon  
111 sound physiological principles, to project how such a phenomenon may affect fish  
112 populations in the future.

### 113 **Supplementary Information**

114 Supplementary Information is available online at  
115 [http://onlinelibrary.wiley.com/journal/10.1111/\(ISSN\)1365-2486](http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1365-2486).

### 116 **Conflicts of Interest**

117 The authors declare that no conflict of interests exists.

### 118 **References**

119 Cheung WWL, Dunne J, Sarmiento JL, Pauly D (2011) Integrating ecophysiology and  
120 plankton dynamics into projected maximum fisheries catch potential under climate  
121 change in the Northeast Atlantic. *ICES Journal of Marine Science: Journal du Conseil*,  
122 68, 1008-1018.

123 Cheung WWL, Sarmiento JL, Dunne J et al. (2013) Shrinking of fishes exacerbates impacts  
124 of global ocean changes on marine ecosystems. *Nature Climate Change*, 3, 254-258.

125 Cheung WWL, Pauly D (2017) Projecting the shrinking fish body size under ocean warming:  
126 tuna as an illustrative example ([http://www.nereusprogram.org/wp-](http://www.nereusprogram.org/wp-content/uploads/2017/08/Short-notes-on-body-size-calculation.pdf)  
127 [content/uploads/2017/08/Short-notes-on-body-size-calculation.pdf](http://www.nereusprogram.org/wp-content/uploads/2017/08/Short-notes-on-body-size-calculation.pdf)).

128 Lefevre S, Mckenzie DJ, Nilsson GE (2017) Models projecting the fate of fish populations  
129 under climate change need to be based on valid physiological mechanisms. *Global*  
130 *change biology*, **23**, 3449-3459.

131 Oikawa S, Itazawa Y (1984) Relative Growth of Organs and Parts of the Carp, *Cyprinus*  
132 *carpio*, with Special Reference to the Metabolism-Size Relationship. *Copeia*, 1984,  
133 800-803.

134 Oikawa S, Itazawa Y (1985) Gill and Body Surface Areas of the Carp in relation to Body  
135 Mass, With Special Reference To The Metabolism-Size Relationship. *Journal of*  
136 *Experimental Biology*, 117, 14.

137 Pauly D, Cheung WWL (2017) Sound physiological knowledge and principles in modeling  
138 shrinking of fishes under climate change. *Global Change Biology*.

139 Nilsson GE (2010) *Respiratory Physiology of Vertebrates: Life With and Without Oxygen*.  
140 Cambridge University Press.

141 Thums M, Meekan M, Stevens J, Wilson S, Polovina J (2013) Evidence for behavioural  
142 thermoregulation by the world's largest fish. *Journal of the Royal Society Interface*, **10**,  
143 20120477.

144 Von Bertalanffy L (1957) Quantitative laws in metabolism and growth. *Quarterly review of*  
145 *Biology*, 217-231.

146 **Fig. 1: Isometric vs ‘hyper-allometric’ growth of gill surface area in relation to body**  
147 **mass.** In panel (a) it is hypothetically assumed that all dimensions of the gill grows  
148 isometrically, and therefore all one-dimensional measures (lengths, widths, heights) increase  
149 with an exponent of  $1/3$ , hence the number of lamellae per length of filament (as well as  
150 number of filaments per length of gill arch) will have to decrease with  $1/3$ , and the surface  
151 area of each lamellae can increase with only  $2/3$ . Panel (b) shows the situation supported by  
152 existing morphometric evidence (Lefevre et al., 2017), where the thickness of the lamellae,  
153 and therefore distance between, and thus the number of lamellae per length of filament, can  
154 remain constant regardless of body mass, hence the total number of lamellae can be increased  
155 when the fish grows. Note also that other ‘hyper-allometric’ scaling exponents [defined by  
156 Pauly and Cheung (2017) as anywhere between  $2/3$  and 1] can be obtained by changing other  
157 parameters in addition to the lamellae number and thickness, such as the length of the  
158 filament and height and length of the lamellae – this is in fact how fish adjust their respiratory  
159 surface area to their needs. The isometric growth of the gills in (a) leads to a scaling exponent  
160 for the total gill surface area with body mass of  $2/3$ , while the growth of the gills in (b) have a  
161 scaling exponent for the surface area of 1 (c) or a constant gill surface area relative to body  
162 mass (d). In both scenarios, however, the total gill volume (mass) will increase in direct  
163 proportion to body mass (e) and thus occupy the same amount of space in relation to body  
164 mass (f). That is, ‘hyper-allometric’ growth of the gills does not cause them to take up more  
165 and more relative space. A large body of evidence shows that gill surface area in fishes scales  
166 in relation to body mass in direct proportion to their oxygen needs (basal and maximal),  
167 which scales with an exponent between  $2/3$  and 1 [average 0.86-0.87 (Lefevre et al., 2017)],  
168 as here exemplified by the carp [data from Oikawa & Itazawa (1984; 1985)]. Further details  
169 on the calculations are presented in Supplementary Information Table S1.

170

171 **Fig. 2: Models for anabolism and catabolism in small-spotted catshark as a function of**  
172 **body mass, revealing unrealistic consequences of GOLT-based models.** The graphs show  
173 weight-specific anabolism ( $H \cdot W^{d_G}/W$ ; solid lines) and catabolism ( $k \cdot W^b/W$ ; dashed lines) at  
174 current temperature (dark / black and blue) and current temperature +1°C (bright / purple and  
175 orange), based on von Bertalanffy's equation ( $dW/dT = H \cdot W^{d_G} - k \cdot W^b$ ). In (a), anabolism and  
176 catabolism have been calculated with the original exponents used by Cheung et al. (2013),  $d_G$   
177 = 0.7 and  $b = 1$ , respectively. In (b), anabolism and catabolism has been calculated with the  
178 exponents now used by Pauly and Cheung (2017) for fish larger than 60cm,  $d_G = 0.9$  and  $b =$   
179 1, respectively. Similar to their new calculations for tuna, a 1°C increase in temperature leads  
180 to a 35% reduction in maximum body mass ( $W_\infty$ ) of small-spotted catshark, as opposed to the  
181 13% in (a). To obtain the same current  $W_\infty$  when  $d_G$  increases from 0.7 to 0.9,  $H/k$  has to be  
182 reduced. In (c),  $d_G$  has been increased from 0.9 to 0.961 to reflect the actual measured scaling  
183 exponent for gill surface area of small-spotted catshark [from Wegner, 2016 (Fish Physiology  
184 Vol 34A, Chapter 3, pp. 101-151)], while  $b$  has been maintained at 1. A 1°C increase in  
185 temperature now leads to a 65% reduction in  $W_\infty$ , illustrating that the decreasing difference  
186 between the exponents is exacerbating the effect of elevated temperature. In (d), the  
187 exponents are even closer to each other,  $d_G$  being 0.96 and  $b$  being 0.97, which results in a 99%  
188 reduction in  $W_\infty$  with just 1°C increase in temperature. Clearly an unrealistic outcome of the  
189 model, even more so since experimental evidence suggest that real world  $d_G$  and  $b$  are indeed  
190 very close to each other (Lefevre et al., 2017). In (e) the exponents are equal, 0.96, in which  
191 case anabolism and catabolism decrease at the same rate, and hence never becomes equal and  
192 growth never zero, as the two lines never cross. In this case  $W_\infty$  cannot be determined from  
193 von Bertalanffy's equation [as  $W_\infty = (H/k)^{1/(0.96-0.96)} = (H/k)^{1/0}$ , which is not defined  
194 mathematically]. Lastly, in (e) the exponent  $b$  has been set to 0.951 while  $d_G$  is kept at 0.961.  
195 In this case anabolism decrease slightly slower than catabolism, and  $W_\infty$  likewise cannot be

196 determined, because the two curves would never cross each other, unless catabolism is larger  
197 than anabolism initially, which is not possible in a biological sense [even if it is  
198 mathematically, as  $W_{\infty} = (H/k)^{1/(0.95-0.96)} = (H/k)^{1/-0.01}$ ]. Calculations are based on the equations  
199 and values used in an explanatory note written by Cheung and Pauly  
200 ([http://www.nereusprogram.org/wp-content/uploads/2017/08/Short-notes-on-body-size-](http://www.nereusprogram.org/wp-content/uploads/2017/08/Short-notes-on-body-size-calculation.pdf)  
201 [calculation.pdf](http://www.nereusprogram.org/wp-content/uploads/2017/08/Short-notes-on-body-size-calculation.pdf)), except that rather than calculating  $k$  as  $K/(b-d_G)$  we have calculated  $k$  from  
202 the predicted  $H/k$  ratio, to maintain  $H$  and  $k$  at comparable levels between the scenarios,  
203 though it does not affect the predicted  $W_{\infty}$  (see Supplementary Information Table S2 and S3  
204 for details and additional examples).

205

**Table S1:** Scaling of gill morphology parameters under assumptions of isometry, ‘hyper-allometry’, or the actual values for common carp, used in Fig. 1.

	isometric scaling	hyper-allometric scaling	common carp ( <i>Cyprinus carpio</i> )
$M_b$	$M_b$	$M_b$	$M_b$
$L_{arch}$	$M_b^{0.33}$	$M_b^{0.33}$	$M_b^{0.33}$
$W_{arch}$	$M_b^{0.33}$	$M_b^{0.33}$	$M_b^{0.152}$
$V_{arch} = L_{arch} \cdot W_{arch}^2$	$M_b^{(0.33+0.33+0.33)} = M_b^1$	$M_b^{(0.33+0.33+0.33)} = M_b^1$	$M_b^{(0.33+0.152+0.152)} = M_b^{0.634}$
$L_{fil}$	$M_b^{0.33}$	$M_b^{0.33}$	$M_b^{0.508*}$
$T_{fil}$	$M_b^{0.33}$	$M_b^{0.33}$	$M_b^{0.183}$
$W_{fil}$	$M_b^{0.33}$	$M_b^{0.33}$	$M_b^{0.183}$
$n_{fil}$	$M_b^{-0.33}$	$M_b^{-0.33}$	$M_b^{-0.33}$
$V_{fil} = n_{fil} \cdot L_{arch} \cdot L_{fil} \cdot W_{fil} \cdot T_{fil}$	$M_b^{(-0.33+0.33+0.33+0.33+0.33)} = M_b^1$	$M_b^{(-0.33+0.33+0.33+0.33+0.33)} = M_b^1$	$M_b^{(-0.33+0.33+0.508+0.183+0.183)} = M_b^{0.874}$
$L_{lam}$	$M_b^{0.33}$	$M_b^{0.33}$	$M_b^{0.183**}$
$H_{lam}$	$M_b^{0.33}$	$M_b^{0.33}$	$M_b^{0.183}$
$T_{lam}$	$M_b^{0.33}$	$M_b^0$	$M_b^{0.08}$
$n_{lam}$	$M_b^{-0.33}$	$M_b^0$	$M_b^{-0.08*}$
$V_{lam} = n_{fil} \cdot L_{arch} \cdot n_{lam} \cdot L_{fil} \cdot L_{lam} \cdot H_{lam} \cdot T_{lam}$	$M_b^{(-0.33+0.33-0.33+0.33+0.33+0.33)} = M_b^1$	$M_b^{(-0.33+0.33-0.0+0.33+0.33+0.0)} = M_b^1$	$M_b^{(-0.33+0.33-0.08+0.508+0.183+0.183+0.08)} = M_b^{0.874}$
$S_{gill} = n_{fil} \cdot L_{arch} \cdot n_{lam} \cdot L_{fil} \cdot L_{lam} \cdot H_{lam}$	$M_b^{(-0.33+0.33-0.33+0.33+0.33+0.33)} = M_b^{0.66}$	$M_b^{(-0.33+0.33-0.0+0.33+0.33+0.33)} = M_b^1$	$M_b^{(-0.33+0.33-0.08+0.508+0.183+0.183)} = M_b^{0.794*}$
$V_{gill} = V_{arch} + V_{fil} + V_{lam}$	$M_b^1 + M_b^1 + M_b^1 = 3M_b^1$	$M_b^1 + M_b^1 + M_b^1 = 3M_b^1$	$M_b^{0.844***}$

$M_b$ , body mass. L, lengths. W, widths. V, total volumes. n, numbers per length. H, heights. T, thicknesses. S, surface areas. Note that the only difference (shaded areas) between isometric scaling and hyper-allometric scaling is that the thickness of the lamella and hence the number of lamellae per length of filament is kept constant under the latter. \*Scaling exponents actually measured by Oikawa & Itazawa (1985). \*\*Scaling exponent for the surface area was measured to be 0.366, and given that the surface area is calculated as  $L_{lam} \cdot H_{lam}$  the scaling exponents for each measure would have to be 0.183, assuming symmetrical growth. The scaling exponent of  $L_{lam}$  is also reflected in the scaling exponent for  $W_{fil}$  and  $T_{fil}$ , as there is no reason to think that the filament would get wider or thicker than the lamellae as the fish grows bigger. Lastly, the fact that  $L_{fil}$  grows with an exponent of 0.508 ( $0.508-0.33=0.178$  more than expected) affects the scaling exponent for  $W_{arch}$ , which has to be reduced accordingly ( $0.33-0.178=0.152$ ) to make room for the filaments. \*\*\*This is the scaling exponent measured by Oikawa & Itazawa (1984).

**Table S2:** Effect of varying scaling exponents ( $d_G$  and  $b$ ) on predicted maximum weight ( $W_\infty$ ) of a few different fish when  $k$  is set to 1.

Species	$L_\infty$ (cm) <sup>a</sup>	$a^a$	$b^a$	$W_\infty$ (kg)	$T_{now}$ (K)	$b$	$d_G$	$\Delta T$	H/k	H	h	g	$H_1$	$k_1$	$H_2$	$k_2$	$W_{\infty 1}$	$W_{\infty 2}$	$\Delta W_\infty$								
yellowfin tuna ( <i>Thunnus albacares</i> )	192	0.0216	2.98	139.2	299.15 <sup>b</sup>	1	0.67	1	5.18	5.18	1.8E+07	4.1E+11	5.18	1.00	5.45	1.09	139.2	123.8	-11.0								
								0.90	1	1.64	1.64	5.6E+06	4.1E+11	1.64	1.00	1.72	1.09	139.2	94.3	-32.3							
									2	1.64	1.64	5.6E+06	4.1E+11	1.64	1.00	1.81	1.19	139.2	64.0	-54.0							
								0.95	1	1.28	1.28	4.4E+06	4.1E+11	1.28	1.00	1.35	1.09	139.2	63.8	-54.1							
									2	1.28	1.28	4.4E+06	4.1E+11	1.28	1.00	1.41	1.19	139.2	29.4	-78.9							
								0.99	1	1.05	1.05	3.6E+06	4.1E+11	1.05	1.00	1.10	1.09	139.2	2.8	-98.0							
								0.91	0.90	1	1.05	1.05	3.6E+06	4.1E+11	1.05	1.00	1.10	1.09	139.2	2.8	-98.0						
									2	1.05	1.05	3.6E+06	4.1E+11	1.05	1.00	1.16	1.19	139.2	0.059	-99.96							
								small-spotted catshark ( <i>Scyliorhinus canicula</i> )	100	0.0016	3.2	4.019	287.15 <sup>c</sup>	1	0.67	1	1.59	1.59	1.0E+07	1.3E+12	1.59	1.00	1.68	1.10	4.019	3.540	-11.9
								0.90								1	1.15	1.15	7.4E+06	1.3E+12	1.15	1.00	1.21	1.10	4.019	2.633	-34.5
	2	1.15	1.15	7.4E+06	1.3E+12	1.15	1.00	1.28								1.21	4.019	1.730	-57.0								
0.96 <sup>d</sup>	1	1.06	1.06	6.8E+06	1.3E+12	1.06	1.00	1.12								1.10	4.019	1.396	-65.3								
	2	1.06	1.06	6.8E+06	1.3E+12	1.06	1.00	1.18								1.21	4.019	0.488	-87.8								
0.99	1	1.01	1.01	6.5E+06	1.3E+12	1.01	1.00	1.07								1.10	4.019	0.058	-98.5								
0.97	0.96	1	1.01	1.01	6.5E+06	1.3E+12	1.01	1.00								1.07	1.10	4.019	0.058	-98.5							
	2	1.01	1.01	6.5E+06	1.3E+12	1.01	1.00	1.13								1.21	4.019	0.00088	-99.98								
sandbar shark ( <i>Carcharhinus plumbeus</i> )	266	0.0058	3.3	582.8	296.15 <sup>c</sup>	1	0.67	1								8.35	8.35	3.3E+07	5.4E+11	8.35	1.00	8.79	1.10	582.8	517.3	-11.2	
0.90								1								1.89	1.89	7.5E+06	5.4E+11	1.89	1.00	1.99	1.10	582.8	391.6	-32.8	
0.90								2	1.89	1.89	7.5E+06	5.4E+11	1.89	1.00	2.09	1.20	582.8	263.8	-54.7								
0.74 <sup>d</sup>								1	5.24	5.24	2.1E+07	5.4E+11	5.24	1.00	5.51	1.10	582.8	500.2	-14.2								
0.74								2	5.24	5.24	2.1E+07	5.4E+11	5.24	1.00	5.80	1.20	582.8	429.6	-26.3								
0.99								1	1.07	1.07	4.2E+06	5.4E+11	1.07	1.00	1.12	1.10	582.8	10.9	-98.1								
0.75								0.74	1	1.07	1.07	4.2E+06	5.4E+11	1.07	1.00	1.12	1.10	582.8	10.9	-98.1							
								2	1.07	1.07	4.2E+06	5.4E+11	1.07	1.00	1.18	1.20	582.8	0.210	-99.96								
sablefish ( <i>Anoplopoma fimbria</i> )								120	0.0058	3.1	16.2	281.15 <sup>c</sup>	1	0.67	1	2.53	2.53	2.3E+07	2.3E+12	2.53	1.00	2.68	1.11	16.2	14.2	-12.4	
0.90															1	1.32	1.32	1.2E+07	2.3E+12	1.32	1.00	1.40	1.11	16.2	10.4	-35.7	
0.90	2	1.32	1.32	1.2E+07	2.3E+12	1.32	1.00								1.48	1.22	16.2	6.7	-58.5								
0.83 <sup>e</sup>	1	1.61	1.61	1.4E+07	2.3E+12	1.61	1.00								1.70	1.11	16.2	12.5	-22.9								
0.83	2	1.61	1.61	1.4E+07	2.3E+12	1.61	1.00								1.80	1.22	16.2	9.6	-40.4								
0.99	1	1.03	1.03	9.2E+06	2.3E+12	1.03	1.00								1.09	1.11	16.2	0.2	-98.8								
0.84	0.83	1	1.03	1.03	9.2E+06	2.3E+12	1.03								1.00	1.09	1.11	16.2	0.1962	-98.8							
	2	1.03	1.03	9.2E+06	2.3E+12	1.03	1.00								1.15	1.22	16.2	0.0025	-99.98								

$L_\infty$ , maximum observed length.  $a$ , length-weight constant.  $b'$ , length-weight exponent.  $W_\infty$ , asymptotic (maximum) body mass.  $T_{now}$ , current average/preferred temperature.  $\Delta T$ , temperature rise.  $d_G$ , oxygen supply/gill surface area scaling exponent.  $b$ , oxygen demand/maintenance metabolism scaling exponent.  $H/k$ , ratio between the constant for anabolism ( $H$ ) and catabolism ( $k$ ).  $h$ , constant in Arrhenius equation for anabolic.  $g$ , constant in Arrhenius equation for catabolic reaction.  $H_1$  and  $H_2$ , coefficients for anabolism.  $k_1$  and  $k_2$ , coefficients for catabolism.  $W_{\infty 1}$  and  $W_{\infty 2}$ , current and predicted  $W_\infty$ . Note that  $W_{\infty 1}$  and  $W_{\infty 2}$  are identical (as they should be).  $\Delta W_\infty$ , predicted change in  $W_\infty$  as a result of a  $\Delta T$  change in temperature. <sup>a</sup>Cheung et al. 2013 (supplementary material). <sup>b</sup>Pauly and Cheung, 2017 (explanatory note). <sup>c</sup>Based on averages from Encyclopedia of Life. <sup>d</sup>Wegner, 2016 (Fish Physiology Vol 34A, Chapter 3, pp. 101-151). <sup>e</sup>Friedman et al., 2012 (Limnology and Oceanography, 57, 1701-1710). See below for equations.

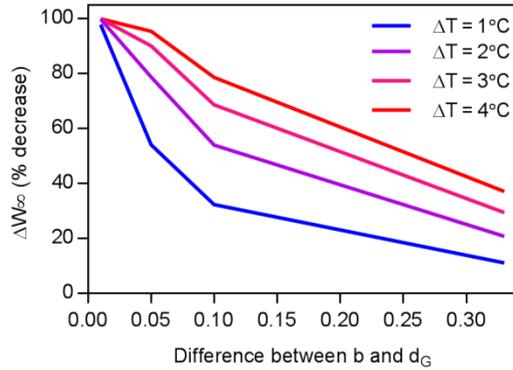
Asymptotic weight, $W_\infty$ :	$W_\infty = a \cdot L_\infty^{b'}$ (Cheung and Pauly, 2017)
H/k derived from von Bertalanffy:	$dW/dt = H \cdot W^{dG} - k \cdot W^b \leftrightarrow 0 = H \cdot W_\infty^{dG} - k \cdot W_\infty^b \leftrightarrow H \cdot W_\infty^{dG} = k \cdot W_\infty^b \leftrightarrow H/k = W_\infty^b / W_\infty^{dG} = W_\infty^{b-dG}$
Constant for anabolism, H:	$k = 1^* \rightarrow H = H/k$ and $H = W_\infty^{b-dG}$
Constant h:	$H = h \cdot e^{-j_1/T}$ , where $j_1$ is 4500** (Pauly and Cheung, 2017, explanatory note) and $T = T_{\text{now}}$ $H = h \cdot e^{-j_1/T} \leftrightarrow h = H/e^{-j_1/T} \leftrightarrow h = W_\infty^{b-dG}/e^{-j_1/T}$
Constant g:	$g = k/e^{-j_2/T}$ where $j_2$ is 8000** (Pauly and Cheung, 2017, explanatory note). $k = 1 \rightarrow g = 1/e^{-j_2/T}$
Using $T_{\text{now}}$ and $T_{\text{now}+\Delta T}$ :	$H_1 = h \cdot e^{-j_1/T}$ $H_2 = h \cdot e^{-j_1/(T+\Delta T)}$ $k_1 = g \cdot e^{-j_2/T}$ (in this case $k_1$ is just $k=1^*$ ) $k_2 = g \cdot e^{-j_2/(T+\Delta T)}$
Current and predicted $W_\infty$ :	$H/k = W_\infty^{b-dG} \leftrightarrow (H/k)^{1/(b-dG)} = (W_\infty^{b-dG})^{1/(b-dG)} \leftrightarrow W_\infty = (H/k)^{1/(b-dG)}$ , $W_{\infty 1} = (H_1/k_1)^{1/(b-dG)}$ , $W_{\infty 2} = (H_2/k_2)^{1/(b-dG)}$
Predicted change in $W_\infty$ , $\Delta W_\infty$ :	$\Delta W_\infty = ((W_{\infty 2} - W_{\infty 1})/W_{\infty 1}) \cdot 100$

\*We are aware that  $k$  is calculated as  $K/(1-d_G)$  by Pauly and Cheung, but it is unclear if it is the same as  $K/(b-d_G)$ , given that the expression is a substitution in the integrated form of the von Bertalanffy equation,  $W_t = W_\infty [1 - e^{-k(1-d_G)(t-t_0)}]^{1/(1-d_G)} = W_\infty [1 - e^{-K(t-t_0)}]^{1/(1-d_G)}$  (Cheung et al., 2011). Given that  $k$  is the constant for catabolism and hence maintenance metabolism, it would be strange if it was only affected by the scaling exponent for the gill area ( $d_G$ ) and not by the scaling factor for maintenance metabolism ( $b$ ). Given that we have derived  $W_\infty = (H/k)^{1/(b-d_G)}$  from Bertalanffy, while Cheung has derived  $W_\infty = (H/k)^{1/(1-d_G)}$  (see Cheung et al., 2011), it does seem that  $1-d_G$  is simply  $b-d_G$ , at least in some of the equations. Calculating  $k$  using  $K/(b-d_G)$ , nonetheless, gives the exact same results for predicted  $W_\infty$  in the end (see Table S3 below), though  $k$  obviously varies much more as a result. In the end, the only thing that seems to affect the projections is the difference between  $b$  and  $d_G$  and the initial observed  $W_\infty$ , so the conclusions remain the same: using evidence-based, physiologically relevant exponents leads to absurd shrinkage of fish with very small changes in temperature.

\*\*Together,  $j_1$  and  $j_2$  reflects a  $Q_{10}$  of 2.4, according to Cheung et al. (2011).

**Table S3:** Effect of varying scaling exponents ( $d_G$  and  $b$ ), temperature change ( $\Delta T$ ) and growth parameter ( $K$ ) on predicted maximum weight ( $W_\infty$ ) of yellowfin tuna (*Thunnus albacares*) when  $k$  is calculated as  $k = K/(b-d_G)$ .

$L_\infty$ (cm)	$a_{L-W}$	$b_{L-W}$	$W_\infty$ (kg)	$T_{now}$ (K)	$K$	$b$	$d_G$	$\Delta T$	$k$	$h$	$g$	$H_1$	$k_1$	$H_2$	$k_2$	$W_{\infty 1}$	$W_{\infty 2}$	$\Delta W_\infty$				
192.4	0.02	2.98	139.2	299.2	0.37	1	0.67	1	1.11	2.0E+07	4.6E+11	5.75	1.11	6.05	1.21	139.2	123.8	-11.0				
								2	1.11	2.0E+07	4.6E+11	5.75	1.11	6.36	1.33	139.2	110.3	-20.8				
								0.90	1	3.7	2.1E+07	1.5E+12	6.06	3.70	6.37	4.04	139.2	94.3	-32.3			
									2	3.7	2.1E+07	1.5E+12	6.06	3.70	6.70	4.42	139.2	64.0	-54.0			
								0.95	1	7.4	3.2E+07	3.0E+12	9.47	7.40	9.96	8.09	139.2	63.8	-54.1			
									2	7.4	3.2E+07	3.0E+12	9.47	7.40	10.47	8.84	139.2	29.4	-78.9			
								0.99	1	37	1.3E+08	1.5E+13	38.87	37.00	40.87	40.45	139.2	2.824	-98.0			
									2	37	1.3E+08	1.5E+13	38.87	37.00	42.96	44.19	139.2	0.059	-99.96			
								0.9	0.57	1	1.11	2.0E+07	4.6E+11	5.75	1.11	6.05	1.21	139.2	123.8	-11.0		
										2	1.11	2.0E+07	4.6E+11	5.75	1.11	6.36	1.33	139.2	110.3	-20.8		
									0.80	1	3.7	2.1E+07	1.5E+12	6.06	3.70	6.37	4.04	139.2	94.3	-32.3		
										2	3.7	2.1E+07	1.5E+12	6.06	3.70	6.70	4.42	139.2	64.0	-54.0		
									0.85	1	7.4	3.2E+07	3.0E+12	9.47	7.40	9.96	8.09	139.2	63.8	-54.1		
										2	7.4	3.2E+07	3.0E+12	9.47	7.40	10.47	8.84	139.2	29.4	-78.9		
									0.89	1	37	1.3E+08	1.5E+13	38.87	37.00	40.87	40.45	139.2	2.8	-98.0		
										2	37	1.3E+08	1.5E+13	38.87	37.00	42.96	44.19	139.2	0.059	-99.96		
									0.037	1	0.67	1	0.11	2.0E+06	4.6E+10	0.58	0.11	0.60	0.12	139.2	123.8	-11.0
												2	0.11	2.0E+06	4.6E+10	0.58	0.11	0.64	0.13	139.2	110.3	-20.8
								0.90		1	0.37	2.1E+06	1.5E+11	0.61	0.37	0.64	0.40	139.2	94.3	-32.3		
										2	0.37	2.1E+06	1.5E+11	0.61	0.37	0.67	0.44	139.2	64.0	-54.0		
0.95	1	0.74	3.2E+06	3.0E+11	0.95	0.74	1.00	0.81		139.2	63.8	-54.1										
	2	0.74	3.2E+06	3.0E+11	0.95	0.74	1.05	0.88		139.2	29.428	-78.9										
0.99	1	3.7	1.3E+07	1.5E+12	3.89	3.70	4.09	4.04		139.2	2.824	-98.0										
	2	3.7	1.3E+07	1.5E+12	3.89	3.70	4.30	4.42		139.2	0.059	-99.96										
0.9	0.57	1	0.11	2.0E+06	4.6E+10	0.58	0.11	0.60		0.12	139.2	123.8	-11.0									
		2	0.11	2.0E+06	4.6E+10	0.58	0.11	0.64		0.13	139.2	110.3	-20.8									
	0.80	1	0.37	2.1E+06	1.5E+11	0.61	0.37	0.64	0.40	139.2	94.3	-32.3										
		2	0.37	2.1E+06	1.5E+11	0.61	0.37	0.67	0.44	139.2	64.0	-54.0										
	0.85	1	0.74	3.2E+06	3.0E+11	0.95	0.74	1.00	0.81	139.2	63.8	-54.1										
		2	0.74	3.2E+06	3.0E+11	0.95	0.74	1.05	0.88	139.2	29.4	-78.9										
0.89	1	3.7	1.3E+07	1.5E+12	3.89	3.70	4.09	4.04	139.2	2.8	-98.0											
	2	3.7	1.3E+07	1.5E+12	3.89	3.70	4.30	4.42	139.2	0.059	-99.96											



Parameters are defined as above in Table S2, but here, the constant for catabolism  $k$ , rather than being set at 1, is calculated as  $K/(b-d_G)$ . Consequently,  $k$  and  $H$  varies more, but this does not affect the predicted weights, and it is also evident that the growth parameter ultimately has no effect on the result (we have just set it arbitrarily to 1/10 of the original value). The predicted changes in  $W_\infty$  are only affected by the difference between  $b$  and  $d_G$  (as illustrated in the insert figure), and it does not seem to matter, either, whether  $b$  is 1 or 0.9. Obviously, the change in temperature also has an effect.