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

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11 Running head: GOLT projects unrealistic fish shrinkage

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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_∞) 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_∞ dictates the ratio

67 between the constants, H for anabolism and k for catabolism, in the von Bertalanffy equation

68 ($dW/dt = H \cdot W^{dG} - k \cdot W^b \leftrightarrow H/k = W_\infty^b / W_\infty^{dG}$; see Supplementary Information p. 3 for

69 derivation). Thus in the original paper (Cheung et al., 2013), with W_∞ 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_∞ 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_∞ of fishes now or in any future. The most parsimonious explanation for these unrealistic

80 predictions is that the current observed W_∞ is in fact not determined by limitations in oxygen

81 supply; hence it cannot reliably be used to predict the future W_∞ 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_∞ 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.

116 **Conflicts of Interest**

117 The authors declare that no conflict of interests exists.

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

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

201   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_∞ (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 (*Cyprinus carpio*)
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	$M_b^{-0.08}*$
$V_{lam} = n_{fil} \cdot L_{arch} \cdot n_{lam} \cdot L_{fil} \cdot L_{lam} \cdot H_{lam} \cdot T_{lam}$	$M_b^{(-0.33+0.33-0.33+0.33+0.33+0.33+0.33)} = M_b^1$	$M_b^{(-0.33+0.33-0.0+0.33+0.33+0.33+0.0)} = M_b^1$	$M_b^{(-0.33 + 0.33 - 0.08 + 0.508 + 0.183 + 0.183 + 0.08)} = M_b^{0.874}$
$S_{gill} = n_{fil} \cdot L_{arch} \cdot n_{lam} \cdot L_{fil} \cdot L_{lam} \cdot H_{lam}$	$M_b^{(-0.33+0.33-0.33+0.33+0.33+0.33)} = M_b^{0.66}$	$M_b^{(-0.33+0.33- 0.0+0.33+0.33+0.33)} = M_b^1$	$M_b^{(-0.33 + 0.33 - 0.08 + 0.508 + 0.183 + 0.183)} = M_b^{0.794}*$
$V_{gill} = V_{arch} + V_{fil} + V_{lam}$	$M_b^1 + M_b^1 + M_b^1 = 3M_b^1$	$M_b^1 + M_b^1 + M_b^1 = 3M_b^1$	$M_b^{0.844}***$

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_∞) of a few different fish when k is set to 1.

Species	L_∞ (cm)[a]	a[a]	b'[a]	W_∞ (kg)	T_{now} (K)	b	d_G	ΔT	H/k	H	h	g	H_1	k_1	H_2	k_2	$W_{\infty 1}$	$W_{\infty 2}$	ΔW_∞
yellowfin tuna	192	0.0216	2.98	139.2	299.15[b]	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
(*Thunnus albacares*)							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	100	0.0016	3.2	4.019	287.15[c]	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
(*Scyliorhinus canicula*)							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[d]	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	266	0.0058	3.3	582.8	296.15[c]	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
(*Carcharhinus plumbeus*)							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[d]	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
							0.74	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	120	0.0058	3.1	16.2	281.15[c]	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
(*Anoplopoma fimbria*)							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[e]	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
							0.83	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_∞, maximum observed length. a, length-weight constant. b', length-weight exponent. W_∞, asymptotic (maximum) body mass. T_{now}, current average/preferred temperature. ΔT, 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_∞. Note that $W_{\infty 1}$ and W_∞ are identical (as they should be). ΔW_∞, predicted change in W_∞ as a result of a ΔT change in temperature. [a]Cheung et al. 2013 (supplementary material). [b]Pauly and Cheung, 2017 (explanatory note). [c]Based on averages from Encyclopedia of Life. [d]Wegner, 2016 (Fish Physiology Vol 34A, Chapter 3, pp. 101-151). [e]Friedman et al., 2012 (Limnology and Oceanography, 57, 1701-1710). See below for equations.

Asymptotic weight, W_∞: $\quad\quad\quad\quad\quad$ $W_\infty = a \cdot L_\infty^{b'}$ (Cheung and Pauly, 2017)

H/k derived from von Bertalanffy: $\quad$ $dW/dt = H \cdot W^{dG} - k \cdot W^b \leftrightarrow 0 = H \cdot W_\infty^{dG} - k \cdot W_\infty^b \leftrightarrow H \cdot W_\infty^{dG} = k \cdot W_\infty^b \leftrightarrow H/k = W_\infty^b / W_\infty^{dG} = W_\infty^{b-dG}$

Constant for anabolism, H: $\quad\quad\quad$ $k = 1^* \rightarrow H = H/k$ and $H = W_\infty^{b-dG}$

Constant h: $\quad\quad\quad\quad\quad\quad\quad$ $H = h \cdot e^{j1/T}$, where j_1 is 4500** (Pauly and Cheung, 2017, explanatory note) and $T = T_{now}$

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ $H = h \cdot e^{j1/T} \leftrightarrow h = H/e^{j1/T} \leftrightarrow h = W_\infty^{b-dG}/e^{j1/T}$

Constant g: $\quad\quad\quad\quad\quad\quad\quad$ $g = k/e^{j2/T}$ where j_2 is 8000** (Pauly and Cheung, 2017, explanatory note).

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ $k = 1 \rightarrow g = 1/e^{j2/T}$

Using T_{now} and $T_{now}+\Delta T$: $\quad\quad$ $H_1 = h \cdot e^{j1/T}$

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ $H_2 = h \cdot e^{j1/T+\Delta T}$

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ $k_1 = g \cdot e^{j2/T}$ (in this case k_1 is just $k=1^*$)

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ $k_2 = g \cdot e^{j2/T+\Delta T}$

Current and predicted W_∞: $\quad\quad$ $H/k = W_\infty^{b-dG} \leftrightarrow (H/k)^{1/(b-dG)} = (W_\infty^{b-dG})^{1/b-dG} \leftrightarrow W_\infty = (H/k)^{1/(b-d_G)}$, $W_{\infty 1} = (H_1/k_1)^{1/(b-d_G)}$, $W_{\infty 2} = (H_2/k_2)^{1/(b-d_G)}$

Predicted change in W_∞, ΔW_∞: $\quad\quad$ $\Delta W_\infty = ((W_{\infty 2} - W_{\infty 1})/W_{\infty 1}) \cdot 100$

*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, $W_t = W_\infty[1 - e^{-k(1-dG)(t-t0)}]^{1/(1-d_G)} = W_\infty[1 - e^{-K(t-t0)}]^{1/(1-d_G)}$ (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_∞ 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_∞, 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 (ΔT) and growth parameter (K) on predicted maximum weight (W_∞) of yellowfin tuna (*Thunnus albacares*) when k is calculated as k = K/(b-d_G).

L_∞ (cm)	a_{L-W}	b_{L-W}	W_∞ (kg)	T_{now} (K)	K	b	d_G	ΔT	k	h	g	H_1	k_1	H_2	k_2	$W_{\infty 1}$	$W_{\infty 2}$	$ΔW_\infty$
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
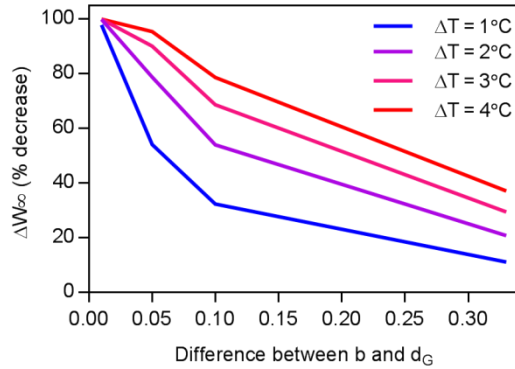
Parameters are defined as above in Table S2, but here, the constant for catabolism k, rather than being set at 1, is calculated as K/(b-d_G). Consequently, k and H varies more, but this does not affect the predicted weights, and it is also evident that the growth parameter ultimately has no effect on the result (we have just set it arbitrarily to 1/10 of the original value). The predicted changes in W_∞ 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.