APPENDIX: Model calibration

Complete optimization across all parameters is not possible in a 3D global context, thus we focus on using seven of the parameters (denoted with asterisks) drawn from the clusters in Figure A1, but acknowledge that there may be other pathways to similar skill. We used the results of the parameter sensitivity to parameterize the model with two goals in mind: (1) coexistence between forage and large pelagic fishes in upwelling areas and (2) high correlations with observation-based catch estimates across functional types. As discussed in the main text, the primary misfit present in the baseline simulations was very low forage fish biomass. We thus first selected the parameter having the largest single effect (θ_A) and set this to its lower limit (0.5), giving adult forage fish a marked advantage over their juvenile adult counterparts. While this was essential for buoying forage fish biomass, it was not enough on its own. We thus added the possibility of decreasing the weight sensitivity of metabolism (b_M). From the parameter sensitivity results, we selected parameters that had moderate or large effects on forage fish biomass: a_E, b_M, and θ_A. The maximum consumption rate intercept a_C was jointly varied with a_E because of their integrated effect on consumption. We initially focused our calibration on three sites spanning large ecosystem contrasts (the Eastern Bering Sea, the Peruvian Upwelling, and the Hawaii Ocean Time series), before moving to full global calibration (see appendix A1 for details). Catch calibrations, particularly of large pelagic fish, demersal fish, and their fractions, were achieved through b_M, k_M, and β, and are presented at the LME scale. We allowed each parameter to vary by as much as a factor of 2 from the mid-point values.

Symbol	Description	Value	Units
a_C	maximum consumption intercept	50	g^{bc-1} y^{-1}
a_E	encounter intercept	50	m^2 g^{be-1} y^{-1}
a_M	metabolism intercept	4	g^{bm-1} y^{-1}
α	assimilation efficiency	0.7	--
b_C	maximum consumption slope	–0.21	--
b_E	encounter slope	–0.21	--
b_M	metabolism slope	–0.21	--
β	transfer efficiency from detritus to benthic invertebrates	0.075	--
ε	reproductive efficiency	0.01	--
f	fishing mortality rate	0.3	y^{-1}
k_C	maximum consumption rate temperature sensitivity	0.063	$^oC^{-1}$
k_E	encounter rate temperature sensitivity	0.063	$^oC^{-1}$
k_M	metabolism temperature sensitivity	0.063	$^oC^{-1}$
κ	fraction of energy allocated to growth	0.5	--
μ_{nat}	natural mortality rate constant	0.1	y^{-1}
θ_A	large fishes preference on medium forage fish	0.75	--
θ_D	preference of large demersals on pelagic prey	0.75	--
θ_J	medium large pelagic fish preference on large zooplankton	0.75	--
θ_S	medium fish preference on medium zooplankton	0.25	--

Table A1. Parameter base values used in the parameter sensitivity test and varied in the model calibration by a factor of 2. Most are mid-point values from the literature or those most often employed in size-based models. Note that the rate variables have units of per year, whereas Table 1 uses per day.

Intercepts of encounter rate and maximum consumption rate

Using the mid-point literature parameters, the intercepts of encounter rate and maximum consumption rate were first examined. To calibrate the feeding responses, the encounter rate intercept (a_E) and the maximum consumption rate intercept (a_C) were adjusted so that mean feeding levels were 0.5-0.8 of maximum consumption (C) (c.f. Hartvig et al. 2011, i.e. fish stomachs are rarely completely full or empty; Figure A3) and that mean gross growth efficiency (GGE; energy available for growth as a fraction of total energy consumed) was 0.1-0.6 and decreased with size (Blaxter & Hunter 1982; Figure A4). For visual ease, a_E and a_C are presented as their values for annual rather than daily rates, i.e. $a_E = 70$ (m^2 g^{be-1} y^{-1}) = $a_E = 70/365$ (m^2 g^{be-1} d^{-1}) = 0.1918 (m^2 g^{be-1} d^{-1}; Table 1). A lower intercept of maximum consumption rate was necessary to simulate forage fish coexistence in upwelling areas (Figures A1, A2). This lower intercept of $a_C = 10$ (y^{-1}) was also required for GGE to decrease with size (Figure A5). However, this maximum consumption rate led to feeding levels higher than the desired 0.8 (Figure A4). Lower feeding levels and increased forage fish biomass were next sought by varying the weight exponents of metabolism and maximum consumption rate using a slightly higher $a_C = 20$ (y^{-1}).

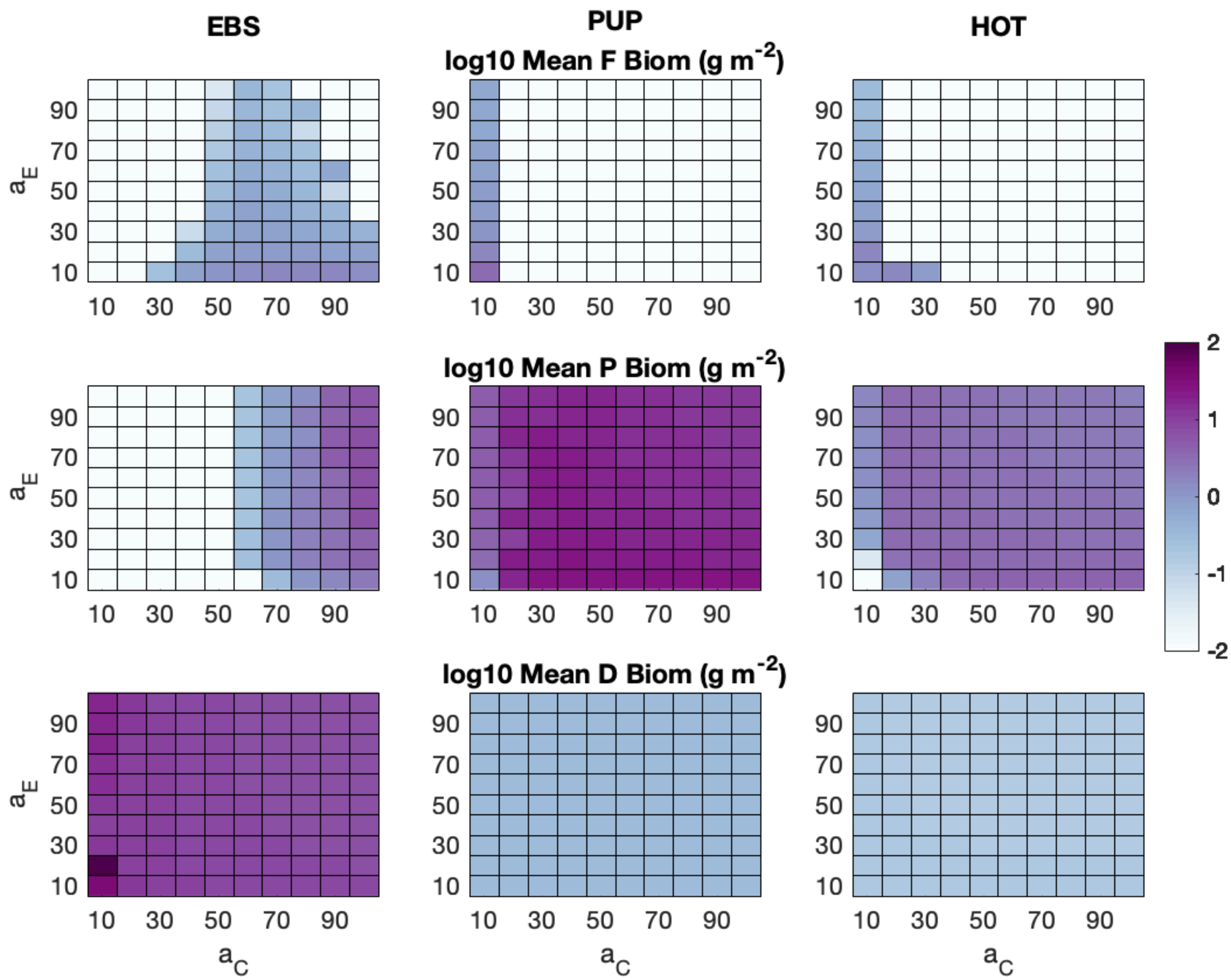

Figure A1. Mean log10 biomass of (Top) forage fish (F), (Middle) large pelagic fish (P), and (Bottom) demersal fish (D) at the 3 domain example locations: Eastern Bering Sea (EBS), Peruvian Upwelling (PUP), and Hawaii Ocean Time series (HOT). θ_A=0.5, $b_C = b_E = b_M = -0.21$.

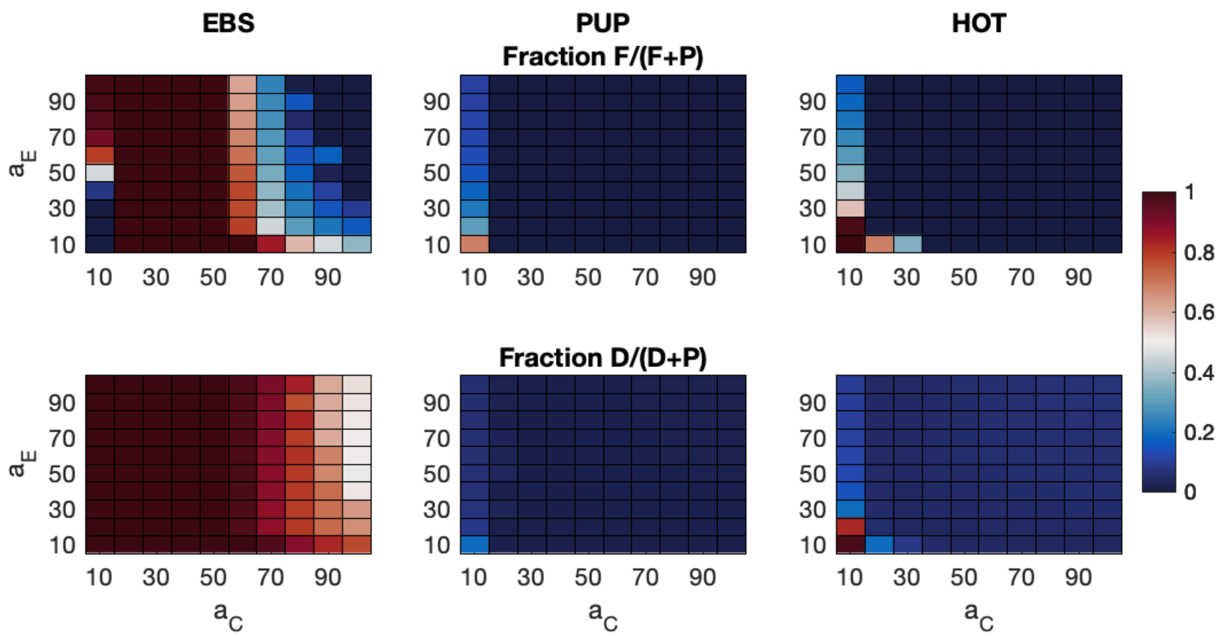

Figure A2. Fractions of (Top) forage fish (F) and (Bottom) demersal fish (D) in reference to large pelagic fish (P) at the 3 domain example locations: Eastern Bering Sea (EBS), Peruvian Upwelling (PUP), and Hawaii Ocean Time series (HOT). θ_A=0.5, $b_C = b_E = b_M = –0.21$.

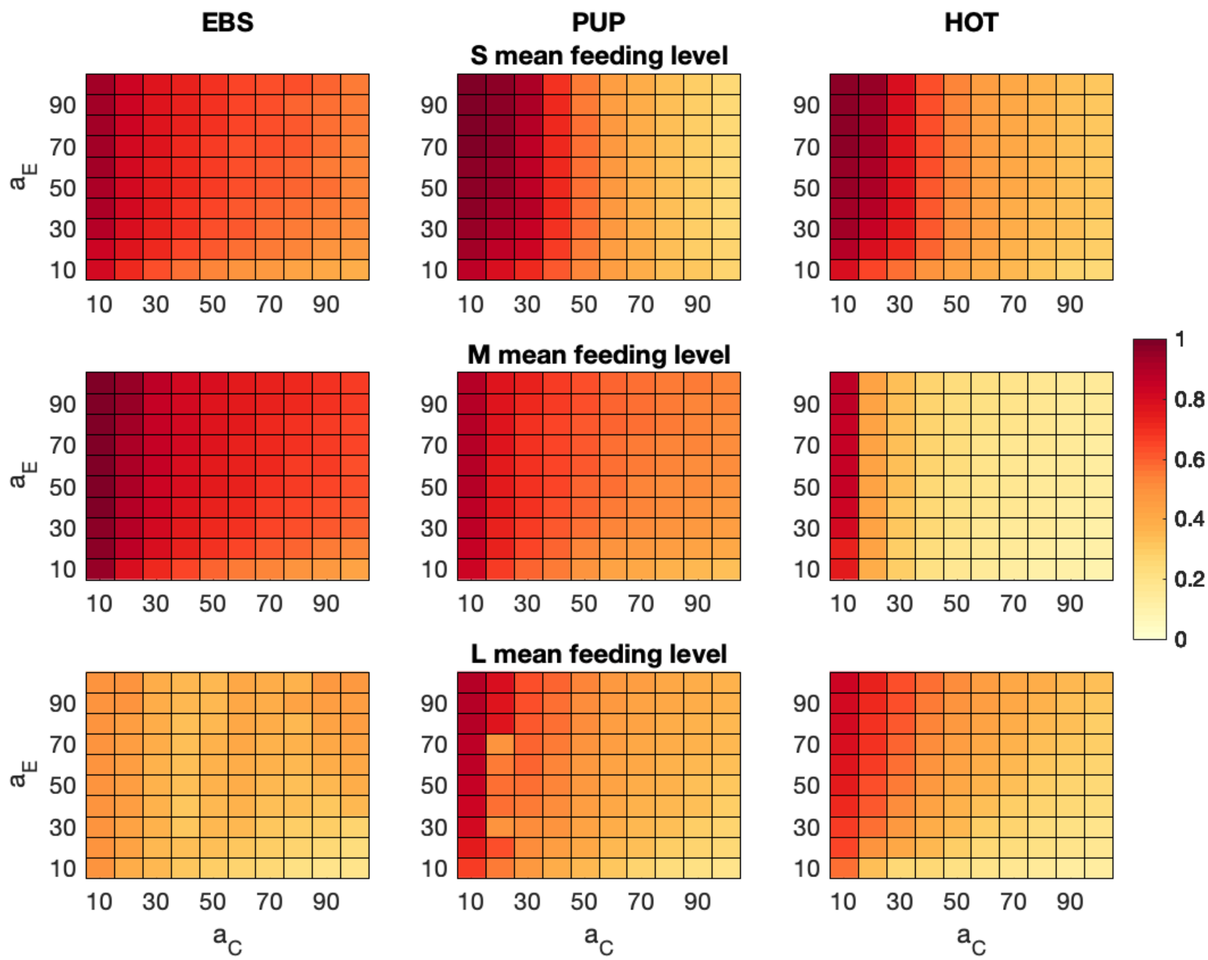

Figure A3. Feeding level (fraction of maximum consumption rate) of (Top) small (S), (Middle) medium (M), and (Bottom) large (L) fishes at the 3 domain example locations: Eastern Bering Sea (EBS), Peruvian Upwelling (PUP), and Hawaii Ocean Time series (HOT). θ_A=0.5, b_C = b_E = b_M = –0.21.

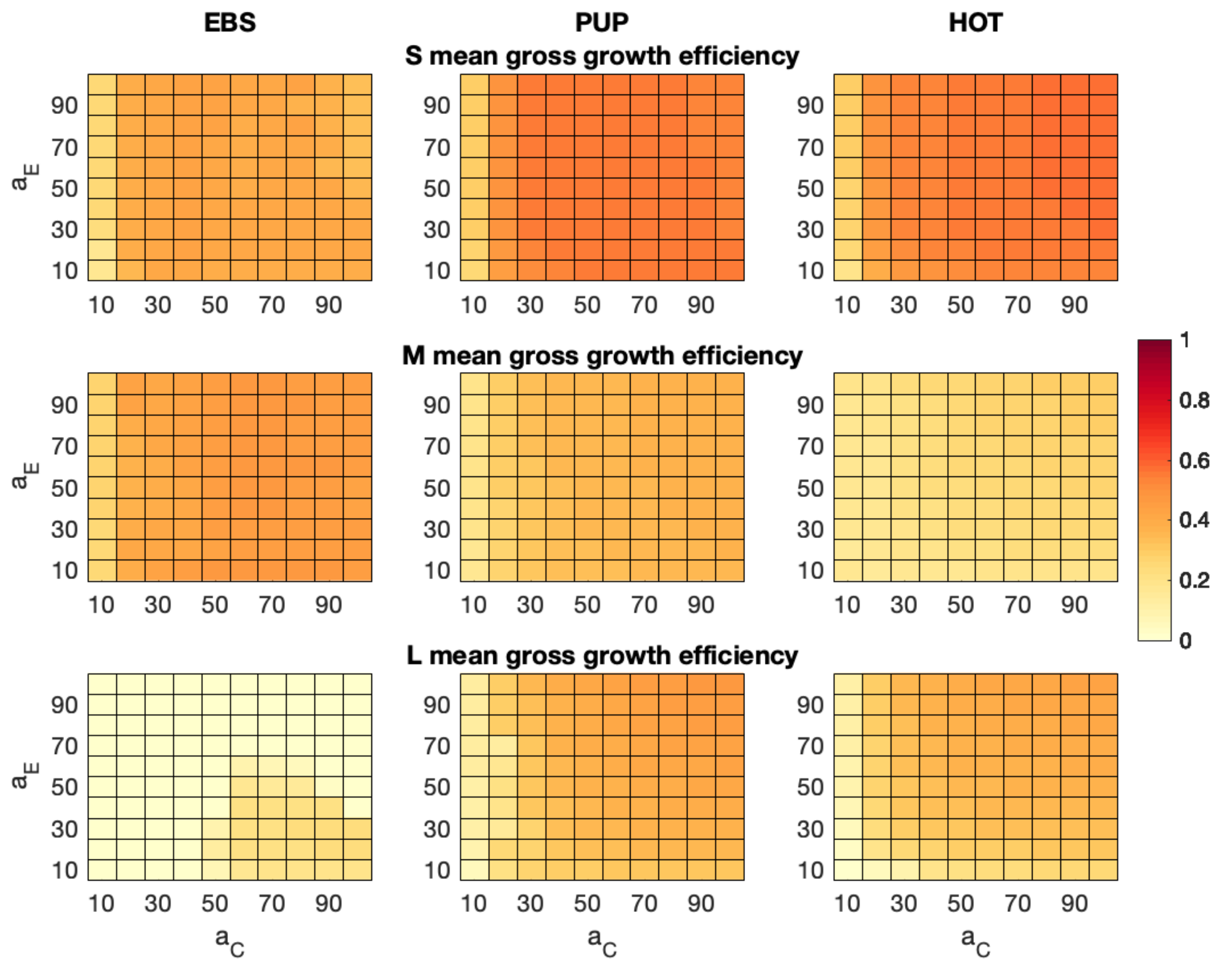

Figure A4. Gross growth efficiency of (Top) small (S), (Middle) medium (M), and (Bottom) large (L) fishes at the 3 domain example locations: Eastern Bering Sea (EBS), Peruvian Upwelling (PUP), and Hawaii Ocean Time series (HOT). θ_A=0.5, $b_C = b_E = b_M = -0.21$.

Weight exponents of metabolism and maximum consumption rate

The intercepts were changed to $a_C = 20$ (y^{-1}) and $a_E = 70$ (y^{-1}) to next examine the effects of the weight sensitivity of metabolism (b_M) and maximum consumption rate (b_C). For these simulations and all following, $b_E = –0.20$ following Hartvig et al. (2011) and Hartvig and Andersen (2013; Table 1). Coexistence could be achieved by lowering the metabolic rate size-sensitivity (less negative exponent) with respect to the maximum consumption rate size-sensitivity, particularly near a difference of 0.075 in the exponents (Figures A5, A6).

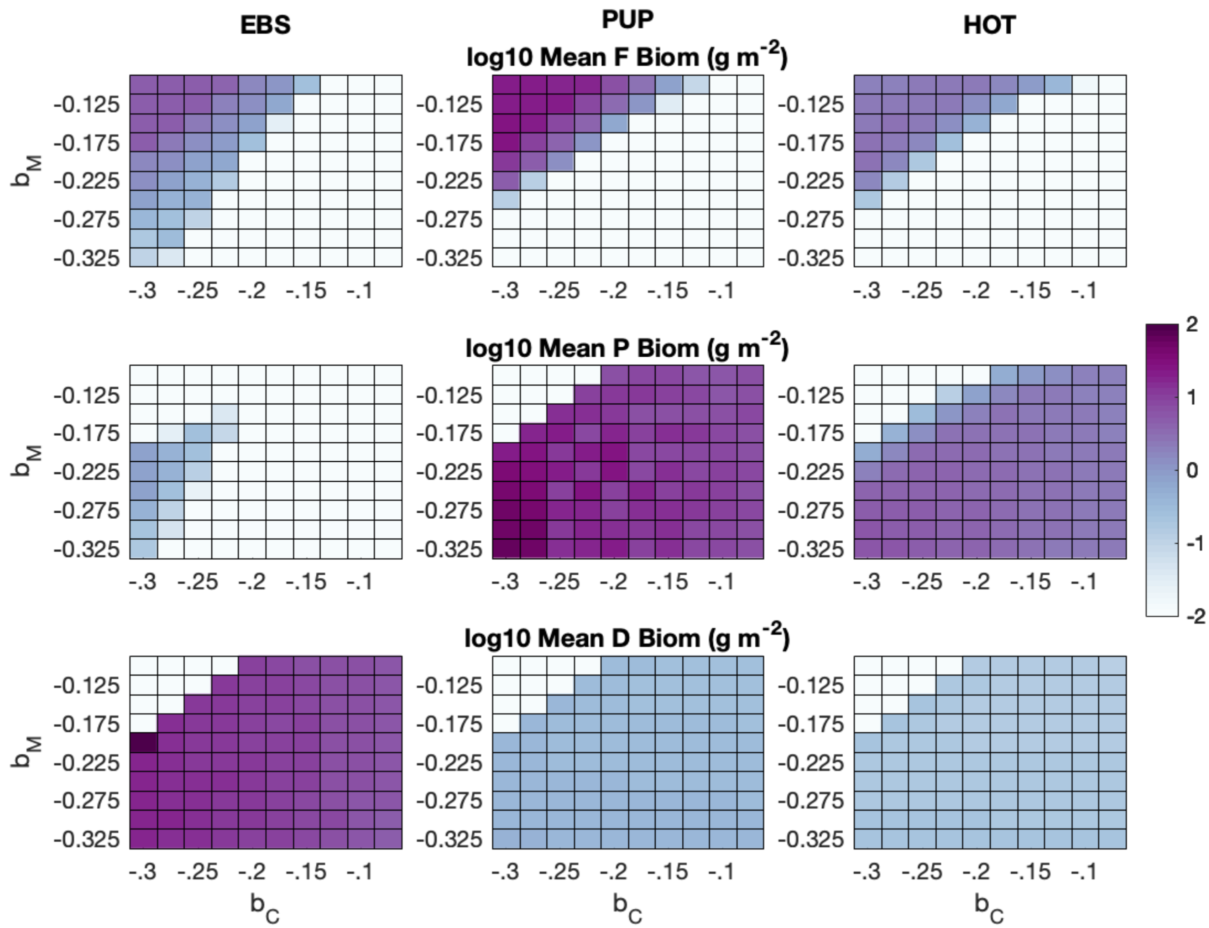

Figure A5. Mean log10 biomass of (Top) forage fish (F), (Middle) large pelagic fish (P), and (Bottom) demersal fish (D) at the 3 domain example locations: Eastern Bering Sea (EBS), Peruvian Upwelling (PUP), and Hawaii Ocean Time series (HOT). θ_A=0.5, a_C = 20, a_E = 70, b_E = –0.20.

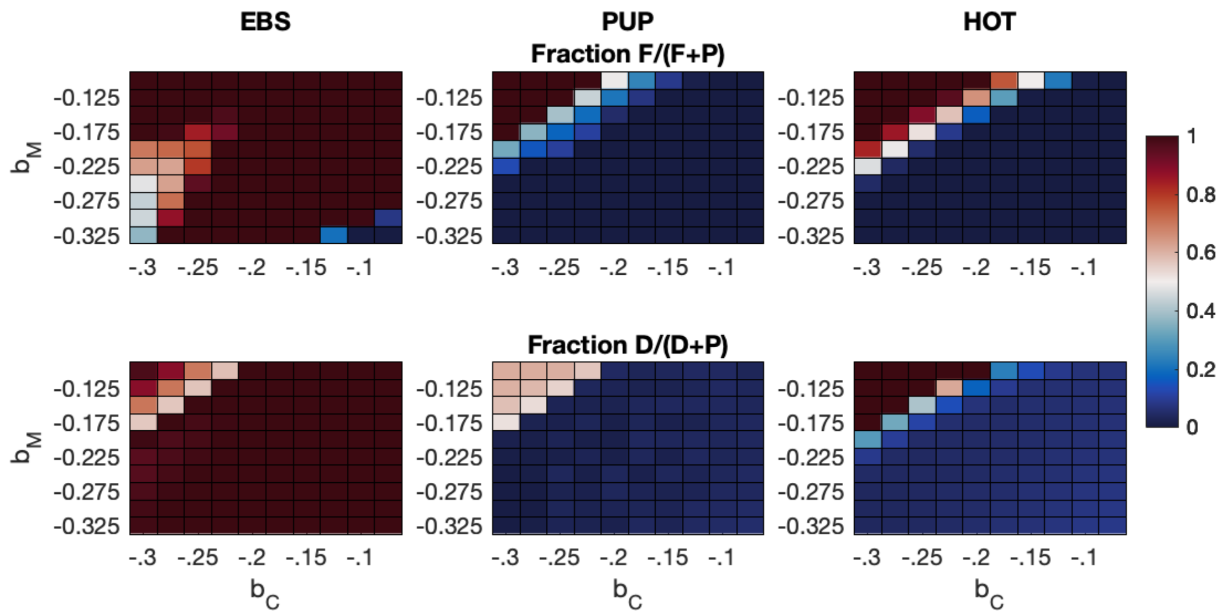

Figure A6. Fractions of (Top) forage fish (F) and (Bottom) demersal fish (D) in reference to large pelagic fish (P) at the 3 domain example locations: Eastern Bering Sea (EBS), Peruvian Upwelling (PUP), and Hawaii Ocean Time series (HOT). θ_A=0.5, a_C = 20, a_E = 70, b_E = –0.20.

Weight exponent and temperature sensitivity of metabolism

The maximum consumption rate exponent was set at b_C = –0.25 (Hartvig et al. 2011, Hartvig & Andersen 2013; Table 1) to next examine the catch correlations using various weight (b_M) and temperature sensitivities (k_M) of metabolism. Catch correlations of forage fish, demersals, and all fish were rather insensitive, but large pelagic catch and the fraction of the catch that was large pelagics benefitted from stronger metabolic weight sensitivity (more negative exponents) and temperature-dependence that ranged from 0.07-0.09 (Figure A7). When the weight exponent and the temperature dependence of metabolism were at the higher values, large pelagic catch and the fraction of the catch that was large pelagics were underestimated in warm LMEs (Figures A8-11). To achieve both coexistence and high catch correlations, a metabolic rate exponent of b_M = –0.175 was selected.

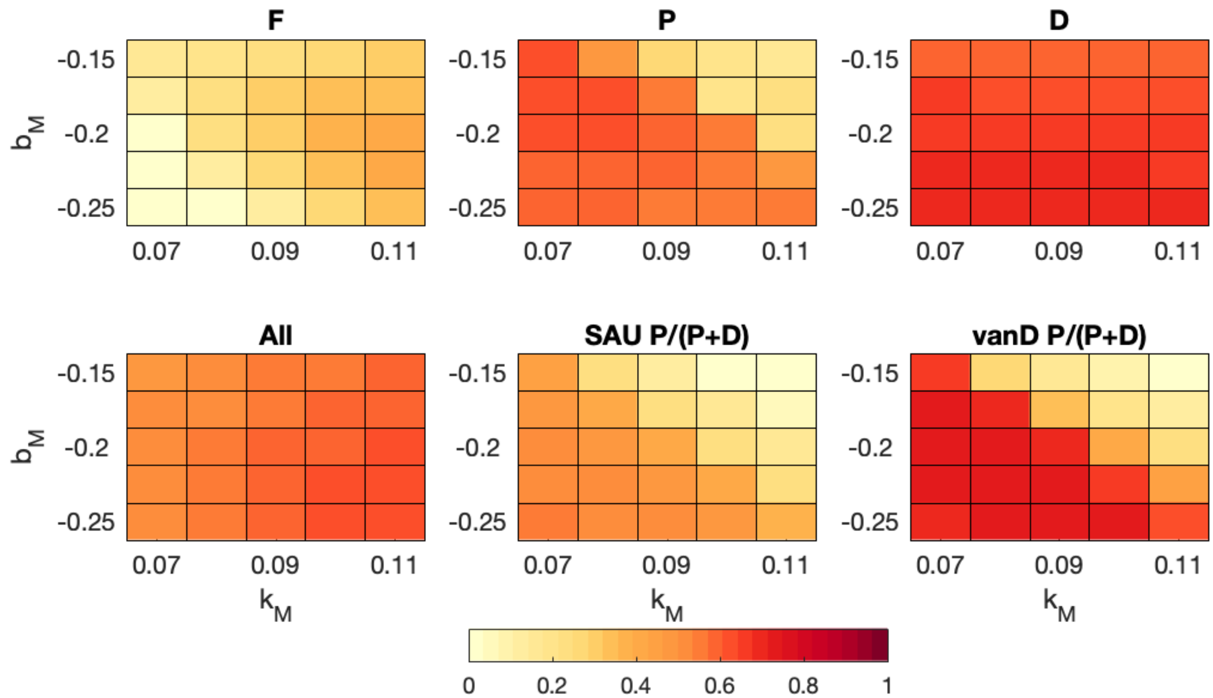

Figure A7. Correlation (r) with SAU catches and Van Denderen (vanD) fraction pelagics by LME. θ_A=0.5, a_C = 20, a_E = 70, b_E = –0.20, b_C = –0.25.

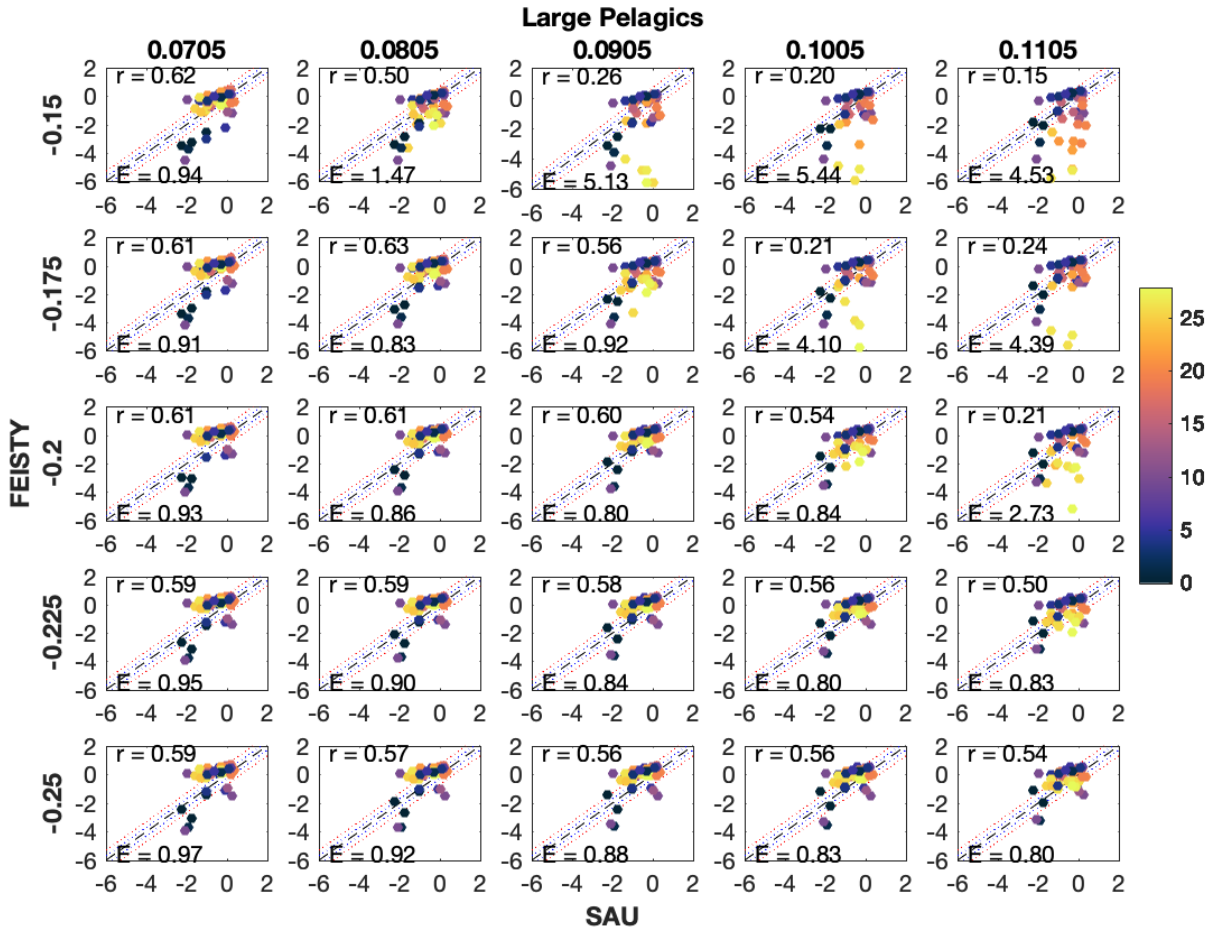

Figure A8. Comparison of FEISTY large pelagic fish catch with SAU catch by LME. The rows are different values of metabolic weight sensitivity (b_M) and the columns are different values of metabolic temperature sensitivity (k_M). Correlations (r) and root mean square error (E) are given. Dot color indicates mean pelagic (top 100 m) temperature (ºC) of the LME. Dashed lines represent 1:1 (black), 2x difference (blue), 5x difference (red). θ_A=0.5, a_C = 20, a_E = 70, b_E = –0.20, b_C = –0.25.

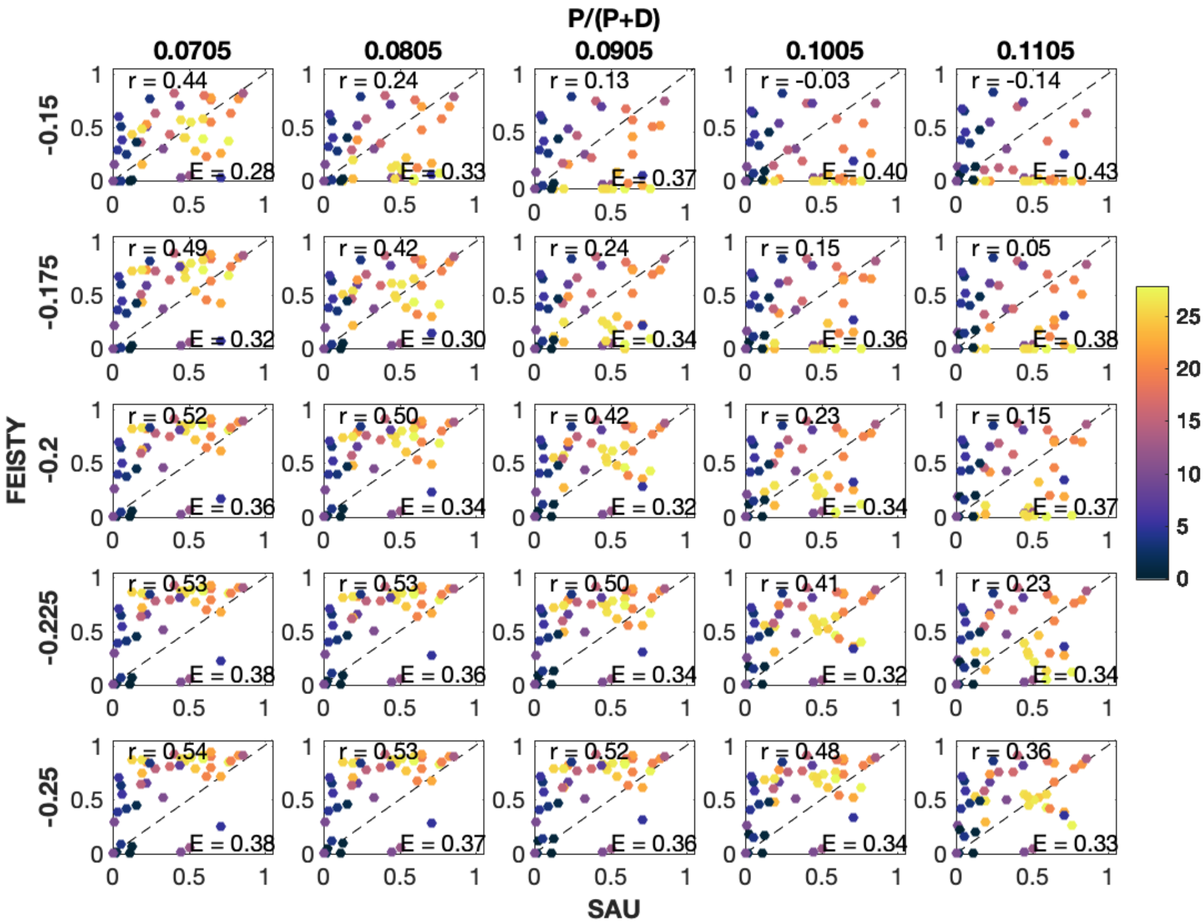

Figure A9. Comparison of FEISTY fraction of catch that is large pelagic fish with SAU catch by LME. The rows are different values of metabolic weight sensitivity (b_M) and the columns are different values of metabolic temperature sensitivity (k_M). Correlations (r) and root mean square error (E) are given. Dot color indicates mean pelagic (top 100 m) temperature (ºC) of the LME. Dashed lines represent 1:1 (black), 2x difference (blue), 5x difference (red). θ_A=0.5, a_C = 20, a_E = 70, b_E = –0.20, b_C = –0.25.

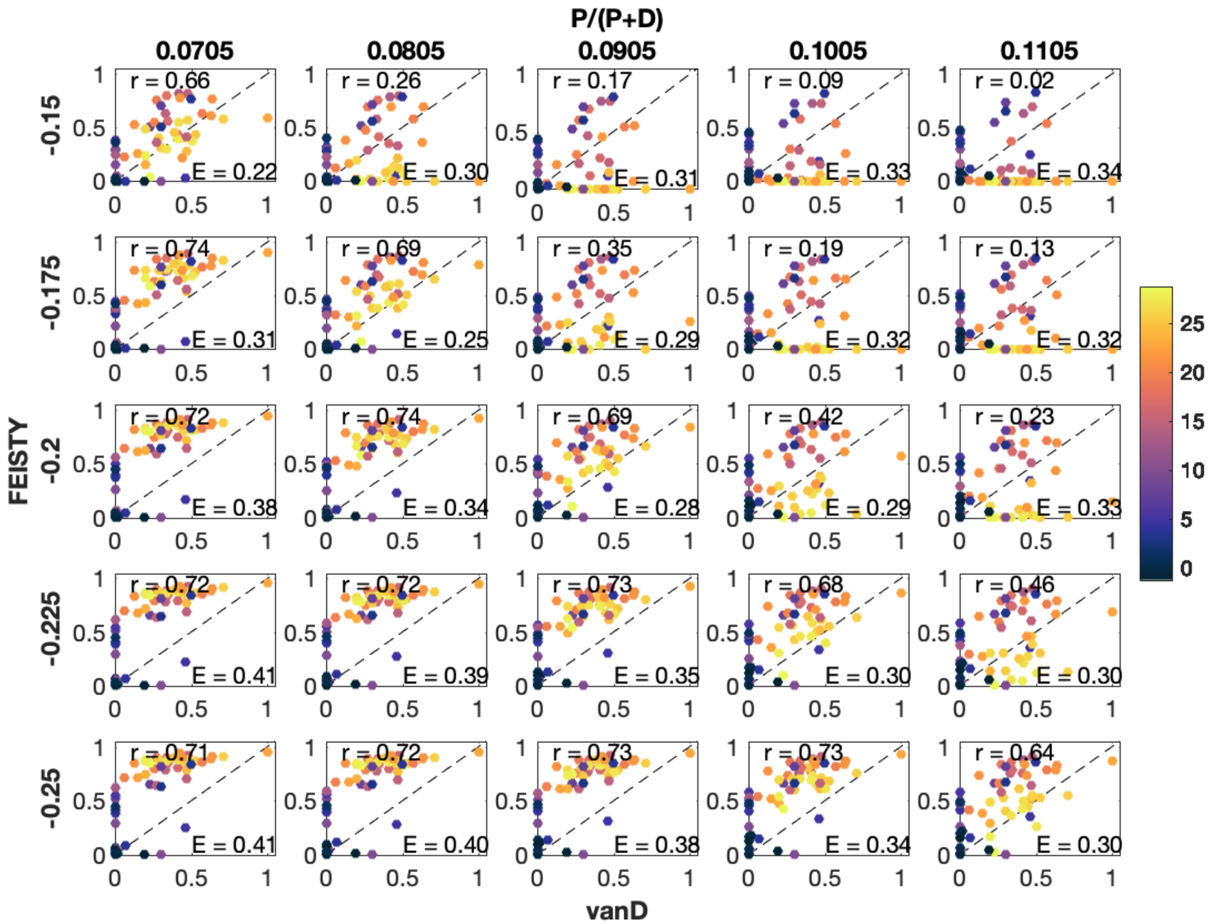

Figure A10. Comparison of FEISTY fraction of catch that is large pelagic fish with van Denderen model predictions by LME. The rows are different values of metabolic weight sensitivity (b_M) and the columns are different values of metabolic temperature sensitivity (k_M). Correlations (r) and root mean square error (E) are given. Dot color indicates mean pelagic (top 100 m) temperature (ºC) of the LME. Dashed lines represent 1:1 (black), 2x difference (blue), 5x difference (red). θ_A=0.5, a_C = 20, a_E = 70, b_E = –0.20, b_C = –0.25.

Temperature sensitivity of metabolism and benthic efficiency

The temperature sensitivity of metabolism, in combination with the benthic efficiency (β), was further tuned with the demersal catch and fraction of catch that was large pelagics rather than demersals. Lower temperature sensitivity and higher benthic efficiency was helpful in this vein, with catch being less sensitive to benthic efficiency (Figure A11). Higher values of k_M led to underestimation of large pelagic catch in warm LMEs (Figure A12), while lower values of β led to underestimation of demersal catch in cold LMEs (Figure A13). The final parameters selected were k_M = 0.0855 and β =0.075.

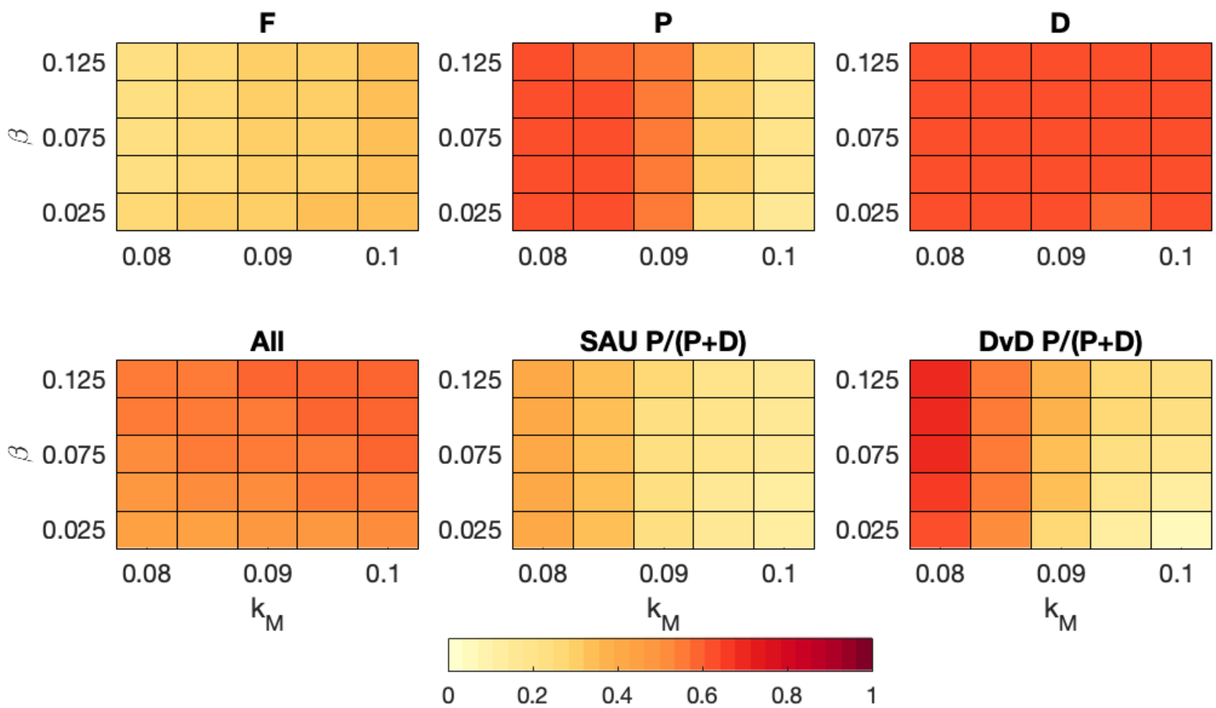

Figure A11. Correlation (r) with SAU catches and Van Denderen (vanD) fraction pelagics by LME. θ_A=0.5, a_C = 20, a_E = 70, b_E = –0.20, b_C = –0.25, b_M = –0.175.

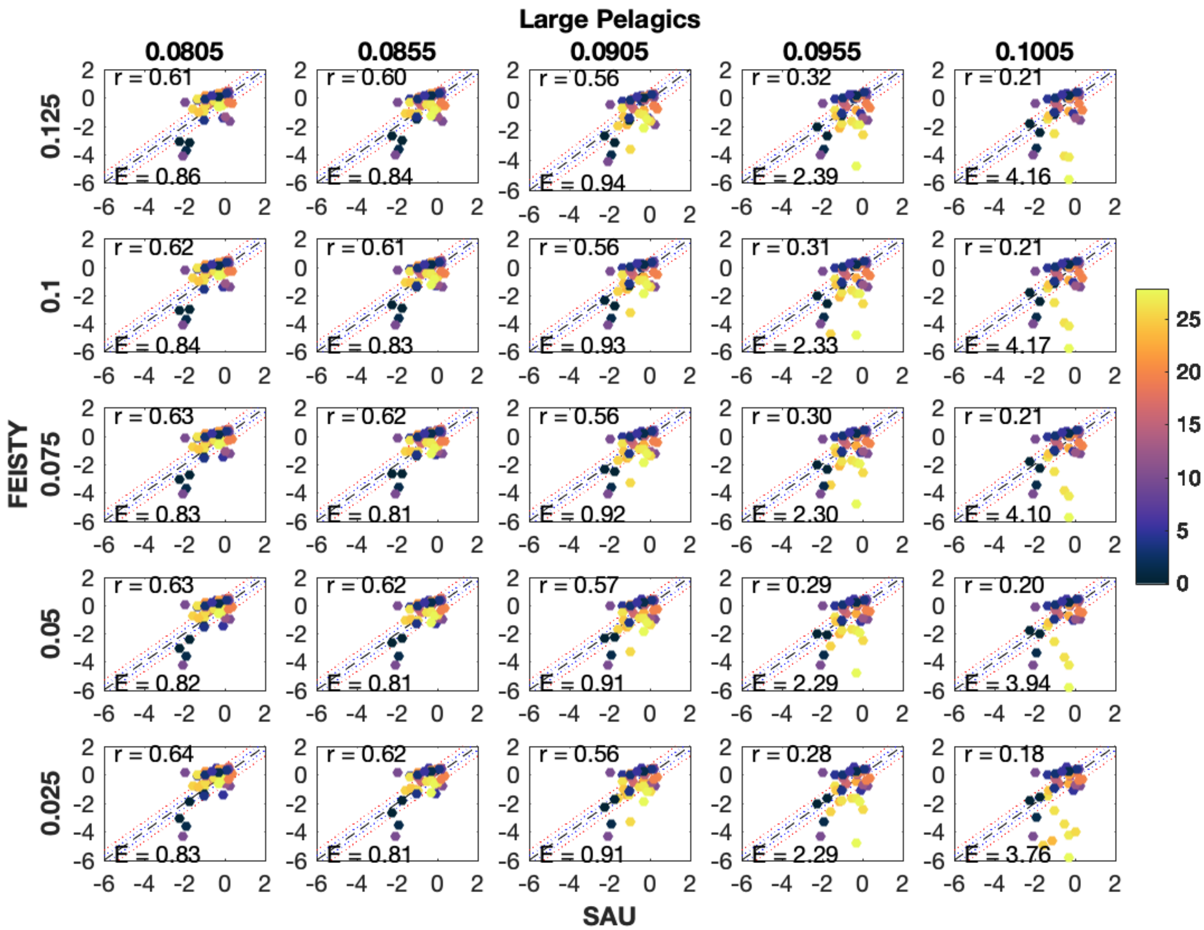

Figure A12. Comparison of FEISTY large pelagic fish catch with SAU catch by LME. The rows are different values of benthic efficiency (β) and the columns are different values of metabolic temperature sensitivity (k_M). Correlations (r) and root mean square error (E) are given. Dot color indicates mean pelagic (top 100 m) temperature (ºC) of the LME. Dashed lines represent 1:1 (black), 2x difference (blue), 5x difference (red). θ_A=0.5, a_C = 20, a_E = 70, b_E = –0.20, b_C = –0.25, b_M = –0.175.

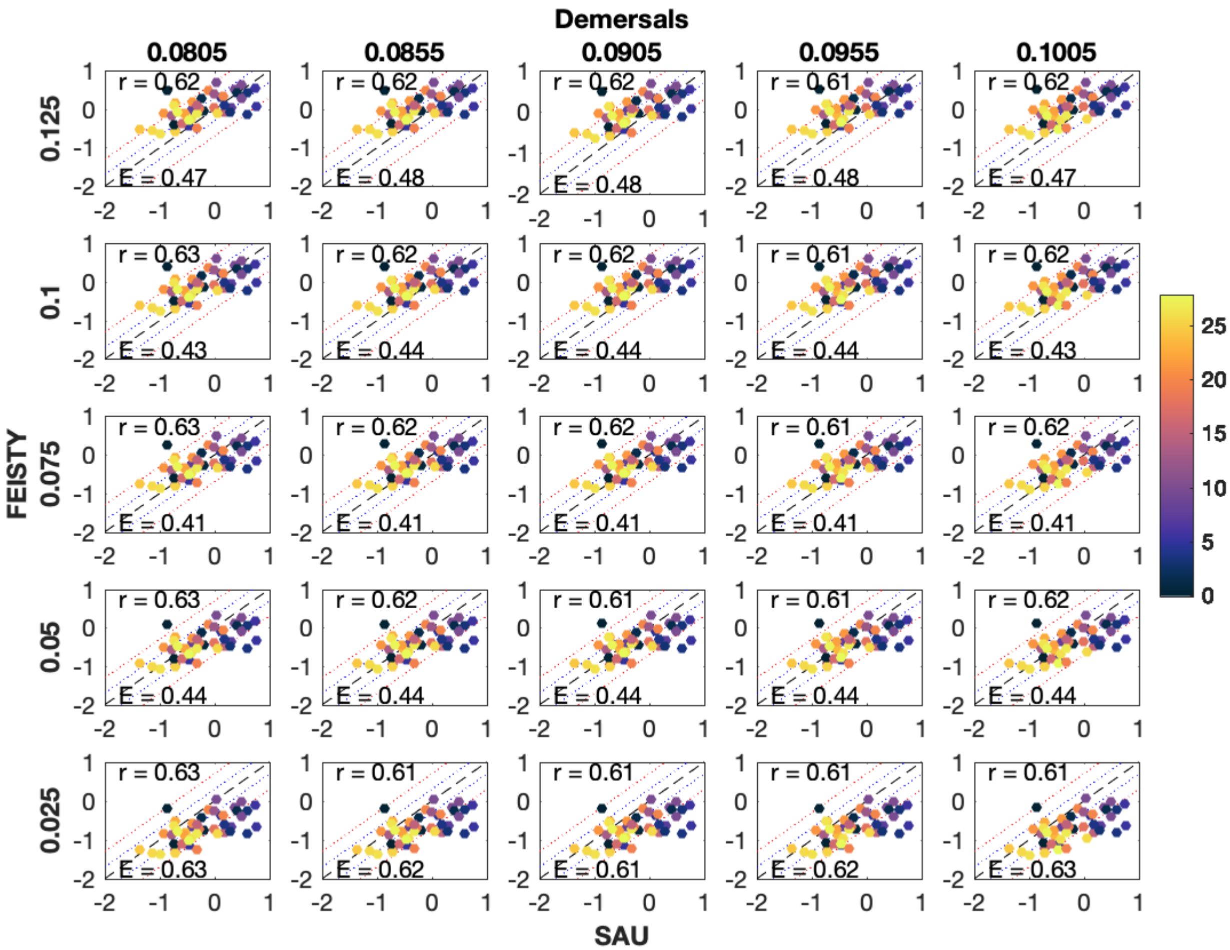

Figure A13. Comparison of FEISTY demersal fish catch with SAU catch by LME. The rows are different values of benthic efficiency (β) and the columns are different values of metabolic temperature sensitivity (k_M). Correlations (r) and root mean square error (E) are given. Dot color indicates mean pelagic (top 100 m) temperature (ºC) of the LME. Dashed lines represent 1:1 (black), 2x difference (blue), 5x difference (red). θ_A=0.5, a_C = 20, a_E = 70, b_E = –0.20, b_C = –0.25, b_M = –0.175.