Supplementary Information

Integration of bioenergetics in an Individual Based Model to hindcast anchovy dynamics in the Bay of Biscay

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Table S1. List of parameters used in the anchovy DEB-IBM model. For DEB parameters, the values are given for a reference temperature T_{ref} = 20ºC. For literature sources see Gatti et al. (2017).

Parameter	**Symbol**	**Unit**	**Value**
Maximum assimilation rate	$\{\dot{p}_{Am}\}$	J cm^{-2} d^{-1}	820
Volume specific maintenance cost	$[\dot{p}_M]$	J cm^{-3} d^{-1}	158
Volume specific cost for structure	$[E_G]$	J cm^{-3}	3725
Energy conductance	$\dot{v}$	cm^{-2} d^{-1}	0.49
Fraction of energy allocated to growth	κ	_	0.71
Fraction of energy fixed into eggs	$K_R = \rho_R / \rho_E$	_	0.79
Maturity threshold at birth (first feeding)	H_b	J	0.09
Maturity threshold at metamorphosis	H_j	J	30.00
Maturity threshold at puberty	H_p	J	12026
Arrhenius temperature	T_A	K	7722
Reference temperature	T_{ref}	K	293
Shape parameter (adult)	δ_a	_	0.2
Density of structure	d_v	g cm^{-3}	0.106
Energy density of structure	ρ_V	J g^{-1}	20100
Energy density of reserve	ρ_E	J g^{-1}	31332
Energy density of reproductive buffer	ρ_R	J g^{-1}	24937
Half saturation constant for food	K_f	mgC m^{-3}	0.8
Shape coefficient (early larva)	δ_b	_	0.077
Size at first feeding	l_b	mm	4.0
Size at metamorphosis	lj	cm	4.0
Energy of one egg	E_0	J	0.66
Relative batch fecundity	R_{bf}	eggs g^{-1}	478.9
Spawning frequency	S_f	d^{-1}	0.33

Table S2. Processes considered in the bioenergetic model with their respective equations, considering the parameters described in Table S1. T is temperature in K. Bibliographic references and parameters for these equations are compiled in Gatti et al. (2017) (Appendix A).

Process and fluxes	**Equation**
Development of early stages	
Egg development rate (d^{-1})	$df_t + dt * 2.33 * 10^{-5} * \theta^{2.30}$
Yolk-sac larva development rate (d^{-1})	$df_t + dt * 3.12 * 10^{-5} * \theta^{2.17}$
Fluxes	
Assimilation	$\dot{p}_A = \dot{p}_{Am} - fL^2 cor_L$
Catabolic utilisation	$\dot{p}_C = \left(\frac{E}{L^3}\right)\frac{v^{\cdot}[EG]L^2 + \dot{p}_M}{[EG] + \kappa\frac{E}{L^3}}$
Somatic maintenance	$\dot{p}_M = [\dot{p}_M]\ L^3$
Growth	$\dot{p}_G = \max(\kappa\dot{p}_C - \dot{p}_M, 0)$
Maturity maintenance	$\dot{p}_j = \dot{k}_j H$
Reproduction/development	$\dot{p}_R = (1-\kappa)\ \dot{p}_C - \dot{p}_j$
Reproduction buffer mobilisation	$\dot{p}_{R2} = \min(E_{batch}, R)$
Gamete allocation	$\dot{p}_{Gam} = \max(0, K_R\ (\dot{p}_{R2} - \dot{p}_{M2})$
Emergency maintenance	$\dot{p}_{M2} = \min(-\dot{p}_G - R)$
Atresia	$\dot{p}_{M3} = \min(K_R G - \dot{p}_{Gam} - \dot{p}_{M2})$
State variables	
Reserve (J)	$\frac{dE}{dt} = \dot{p}_A - \dot{p}_C$
Structural length (cm)	$\frac{dL_V}{dt} = \frac{\dot{p}_G}{3L_V^2[E_G]}$
Maturity level (J)	$\frac{dE_H}{dt} = \dot{p}_R$ if $E_H < E^p_H$
Reproduction (J)	$\frac{dE_R}{dt} = \dot{p}_{R} - \max(\dot{p}_{R2}, \dot{p}_{M2})$ if $E_H < E^p_H$
Gametes (J)	If $G \geq 2E_{batch}$, $\frac{dG}{dt} = \dot{p}_{Gam} - \dot{p}_R - E_{batch}$ If $G \geq 2E_{batch}$, $\frac{dG}{dt} = \dot{p}_{Gam} - \dot{p}_R$

Figure S1. Interannual variability of temperature (ºC) between 0 and 30 m depth. The gray shadow shows the average climatology for the period 2000-2015 and the blue line the values for each year.

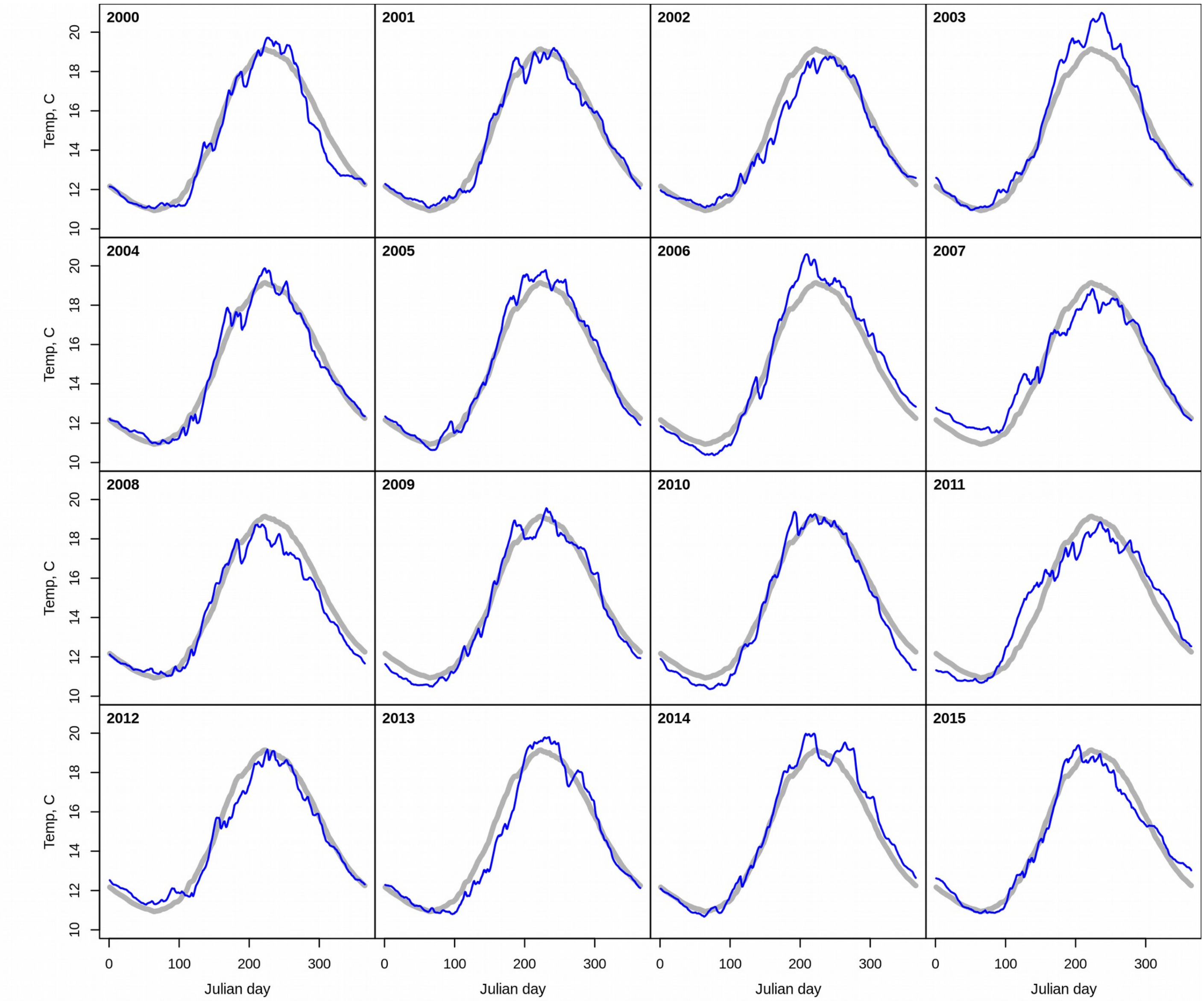


Figure S2. Interannual variability of temperature (ºC) between 0 and 150 m depth. The gray shadow shows the average climatology for the period 2000-2015 and the blue line the values for each year.

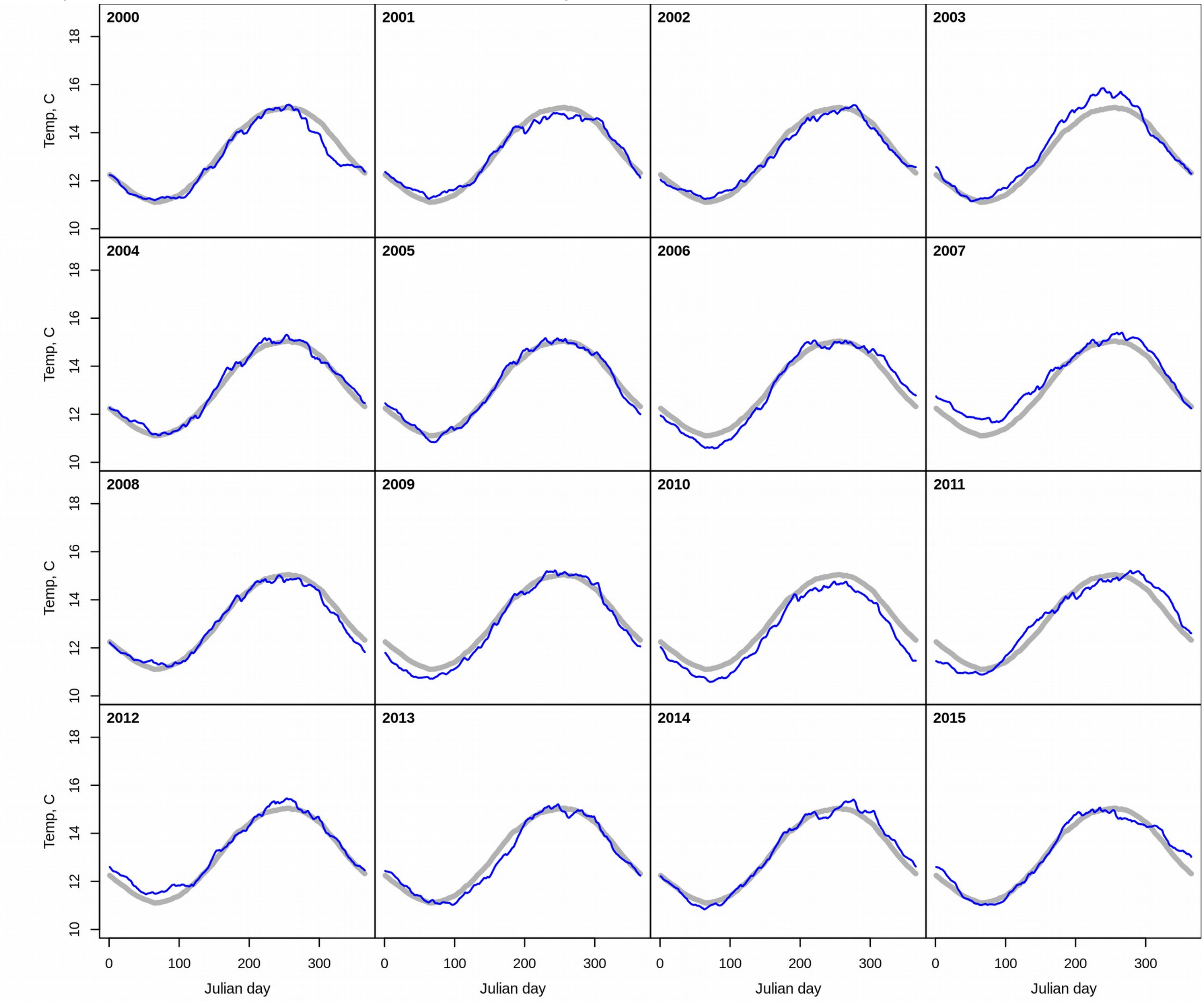


Figure S3. Interannual variability of the zooplankton concentration (mg C m^{-3}) between 0 and 50 m depth. The gray shadow shows the average climatology for the period 2000-2015 and the blue line the values for each year.

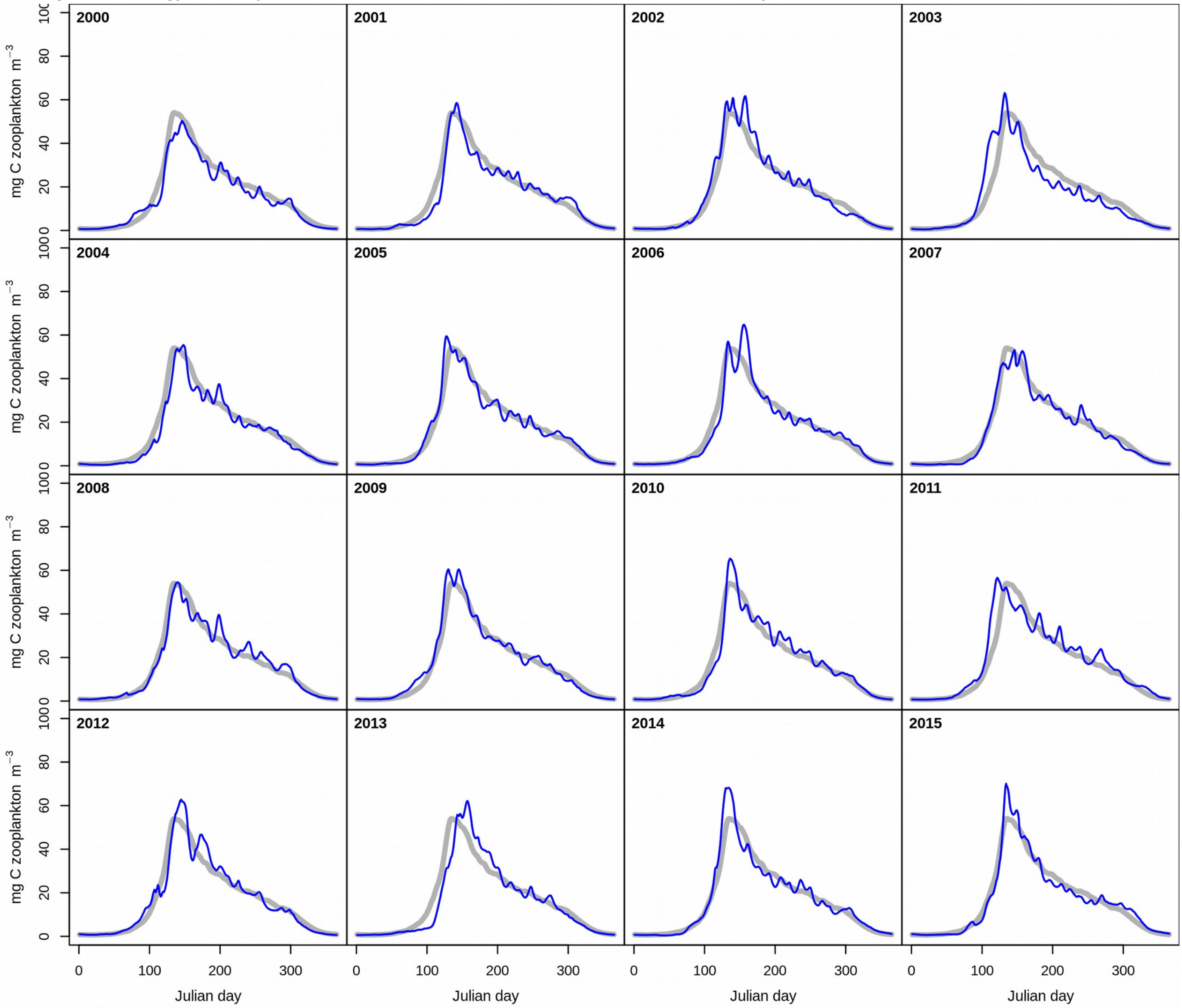


Figure S4. Summary of the forcing environmental variables considering four descriptors: annual mean temperature between 0 and 30 m (panel A); annual mean temperature between 0 and 150 m (panel B); annual mean zooplankton concentration (panel C); and julian day of the annual zooplankton maximum (panel D). Horizontal dashed lines in each panel show the respective value of the descriptors for the daily climatology obtained for the period 2000-2015.

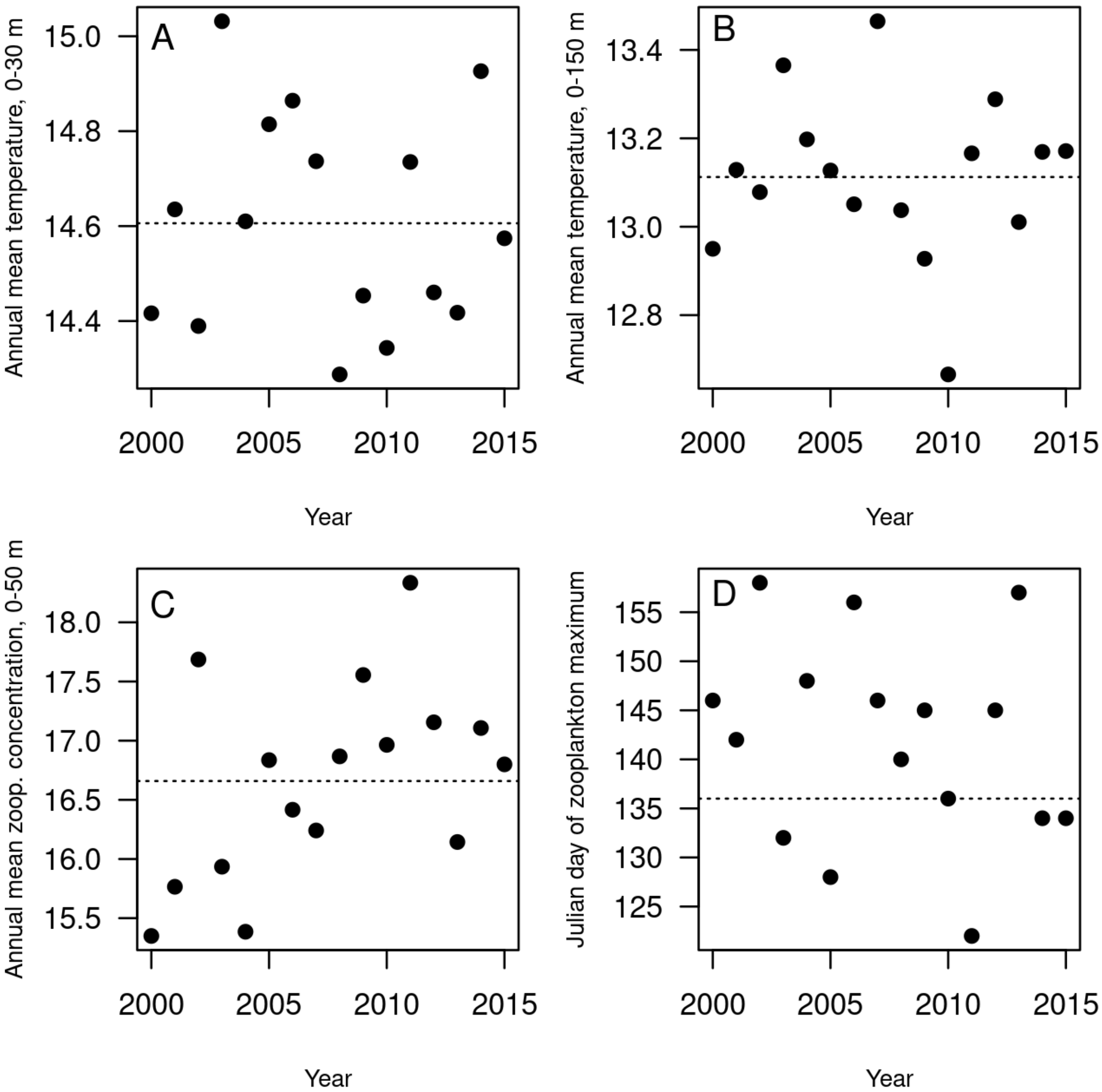


Figure S5. Traits at the individual level from the individual run. This run consisted on exposing individual anchovies to daily climatologies of the period 1996-2015. The dots show the observations from spring and autumn fisheries surveys (see Gatti et al., 2017 for more details). Traits analyzed: A) Individual length (cm), B) individual weight (g), C) energy density of individuals (kJ/g).

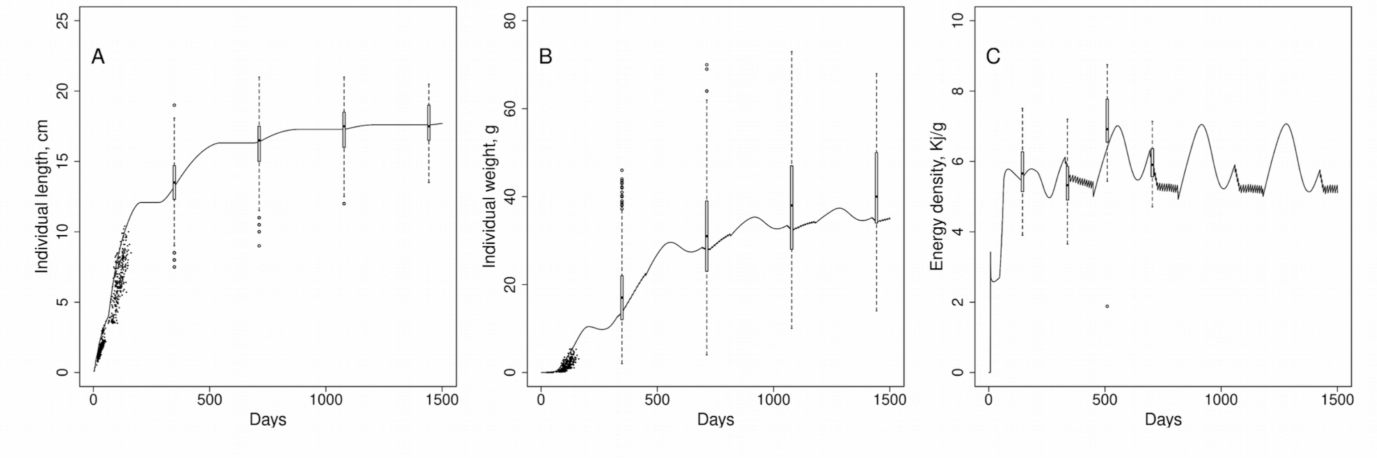


Figure S6. Relationship between instantaneous natural mortality rate and individual size (cm) as described in Eq. 1 of the main text. During the larval phase, the density-dependent larval mortality Z_{DD} is added to the natural mortality. Z_{DD} values corresponding to egg concentrations of 0, 1, 10 and 100 eggs m^{-3} are shown. During the adult stage, fishing mortality rate values are summed to the natural mortality rate. Z_F values of 0 and 0.015 day^{-1} are shown.

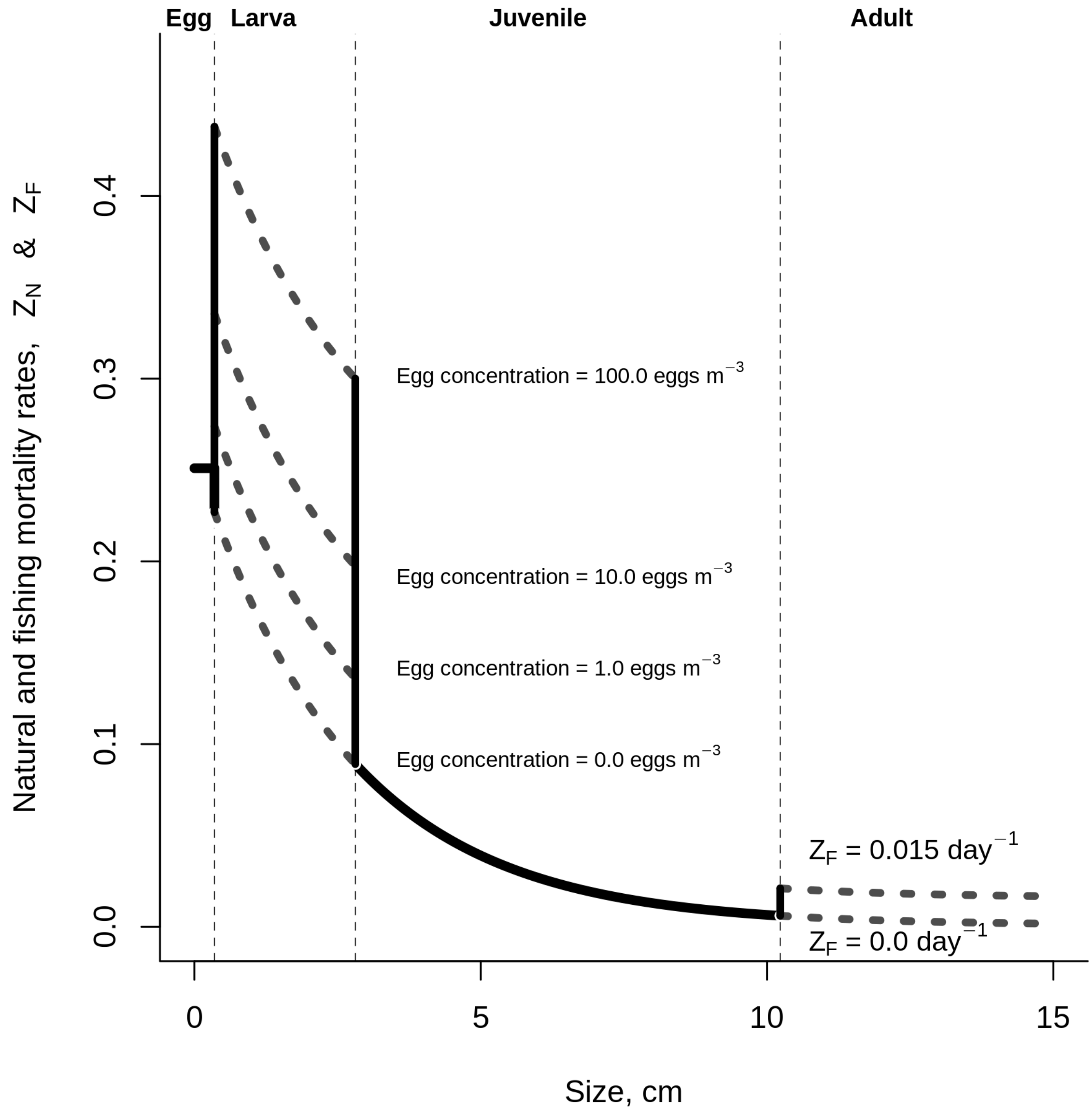


Figure S7. Ecological indicators obtained from the DEB-IBM model (III) (I and II are shown in the main text). Panels represent: A) Recruitment, in number of individuals, on January 1st. B) Recruitment, in number of individuals, on May 15th. C) Weight gain (g) of age 1 individuals between January 1st and May 15th. D) Yearly average Fulton's condition factor (Fcf) calculated as Fcf = (W*100)/L^3 (being W and L the average weight and length of the adult population respectively). E) Average energy density (kJ g^{-1}) of age 1 individuals on 1st January. F) Survival defined as the number of age 1 individuals on January 1st next year over the total number of eggs spawned during the current year. G) Fecundity defined as the total number of eggs spawned during a given year over the number of adult individuals alive on May 15th of the same year. H) Yearly average size at age. I Daily weight average of adults (g). J) Population average of the distribution of individual energy (J) according to the compartments of energy described by DEB-theory (Struct: structure; Repr: reproduction).

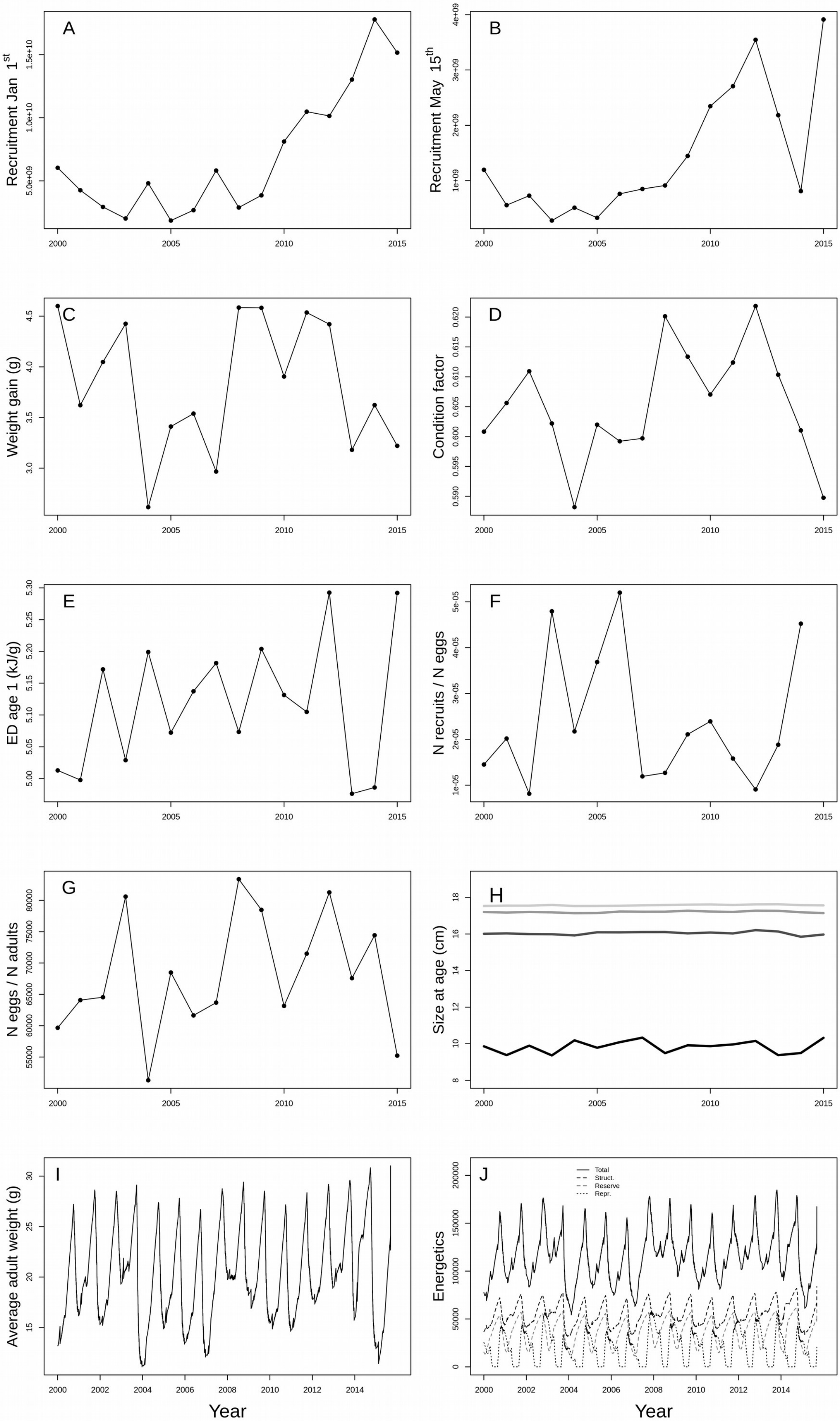

A
Recruitment Jan 1st
B
Recruitment May 15th
C
Weight gain (g)
D
Condition factor
E
ED age 1 (kJ/g)
F
N recruits / N eggs
G
N eggs / N adults
H
Size at age (cm)
I
Average adult weight (g)
J
Energetics
Total
Struct.
Reserve
Repr.
Year
Year

Figure S8 - S13. These figures show the most relevant indicators obtained from the DEB-IBM model to understand the mechanisms driving the population dynamics under the scenarios presented in Table 1 and Figs. 3B and 7 of the main text. Panels represent: A) Proportion, in number of individuals, of each age class on January 1st. The colors of the bars represent the different age classes: orange age 1, red age 2, dark red age 3, and violet age 4. B) Proportion, in number of individuals, of each age class on May 15th. Colors as in panel A. C) Biomass distribution (tonnes) by age class on January 1st. Colors as in panel A. D) Recruitment, in number of individuals, on January 1st. E) Recruitment, in number of individuals, on May 15th. F) Weight gain (g) of age 1 individuals between January 1st and May 15th. G) Yearly average Fulton's condition factor (Fcf) calculated as Fcf = $(W*100)/L^3$ (being W and L the average weight and length of the adult population respectively). H) Average energy density (kJ g^{-1}) of age 1 individuals on 1st January. I) Survival defined as the number of age 1 individuals on January 1st next year over the total number of eggs spawned during the current year. J) Fecundity defined as the total number of eggs spawned during a given year over the number of adult individuals alive on May 15th of the same year. K) Yearly average size at age. Colors as in panel A. Panel L to AA) Sources of mortality as proportion of the total number of individuals obtained during the simulation. Green: natural mortality; red: DEB mortality; blue: fishing mortality. Panel AB) Daily weight average of adults (g). Panel AC) Daily average energy density (kJ g^{-1}) of adults. Panel AD) Daily total number of eggs spawned by the population. Panel AE) Population average of the distribution of individual energy (J) according to the compartments of energy described by DEB-theory (structure in blue, reserve in green, 1-reproductive buffer in red, and total energy in black).

Figure S8. Ecological indicators from simulation with no Z_{DEB}.

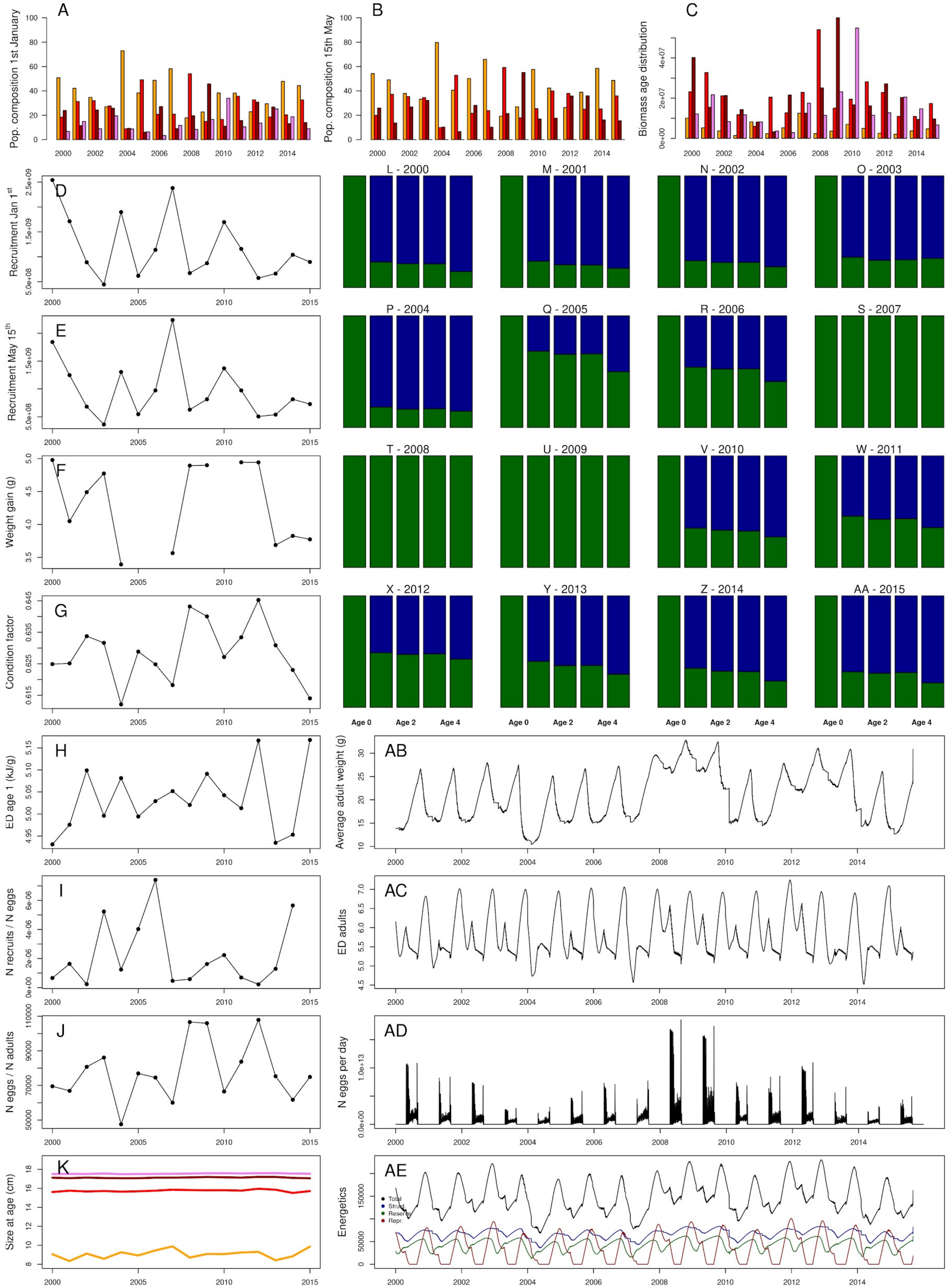


Figure S9. Ecological indicators from scenario 1 (constant fishing mortality).

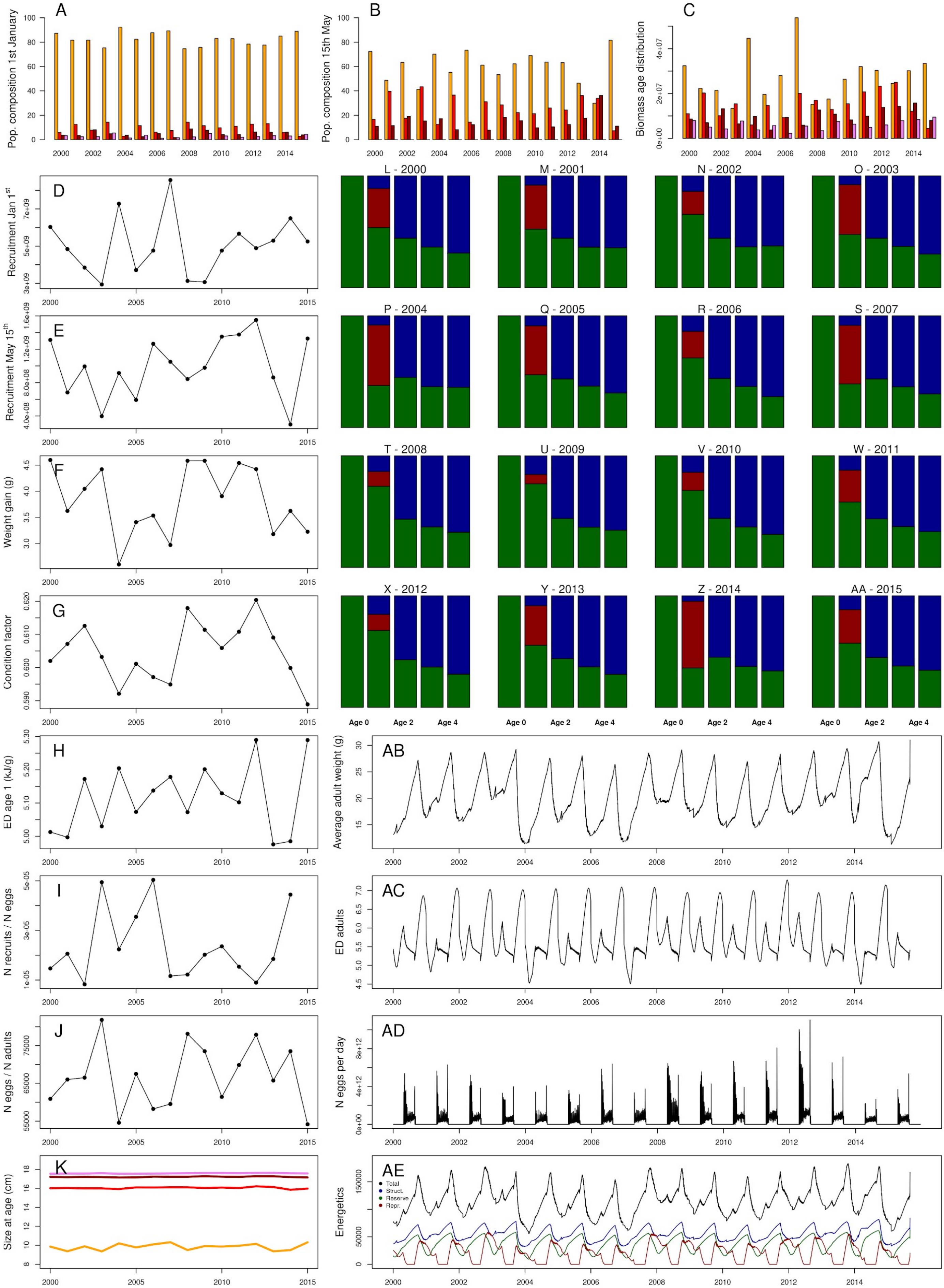


Figure S10. Ecological indicators from scenario 2 (constant environment)

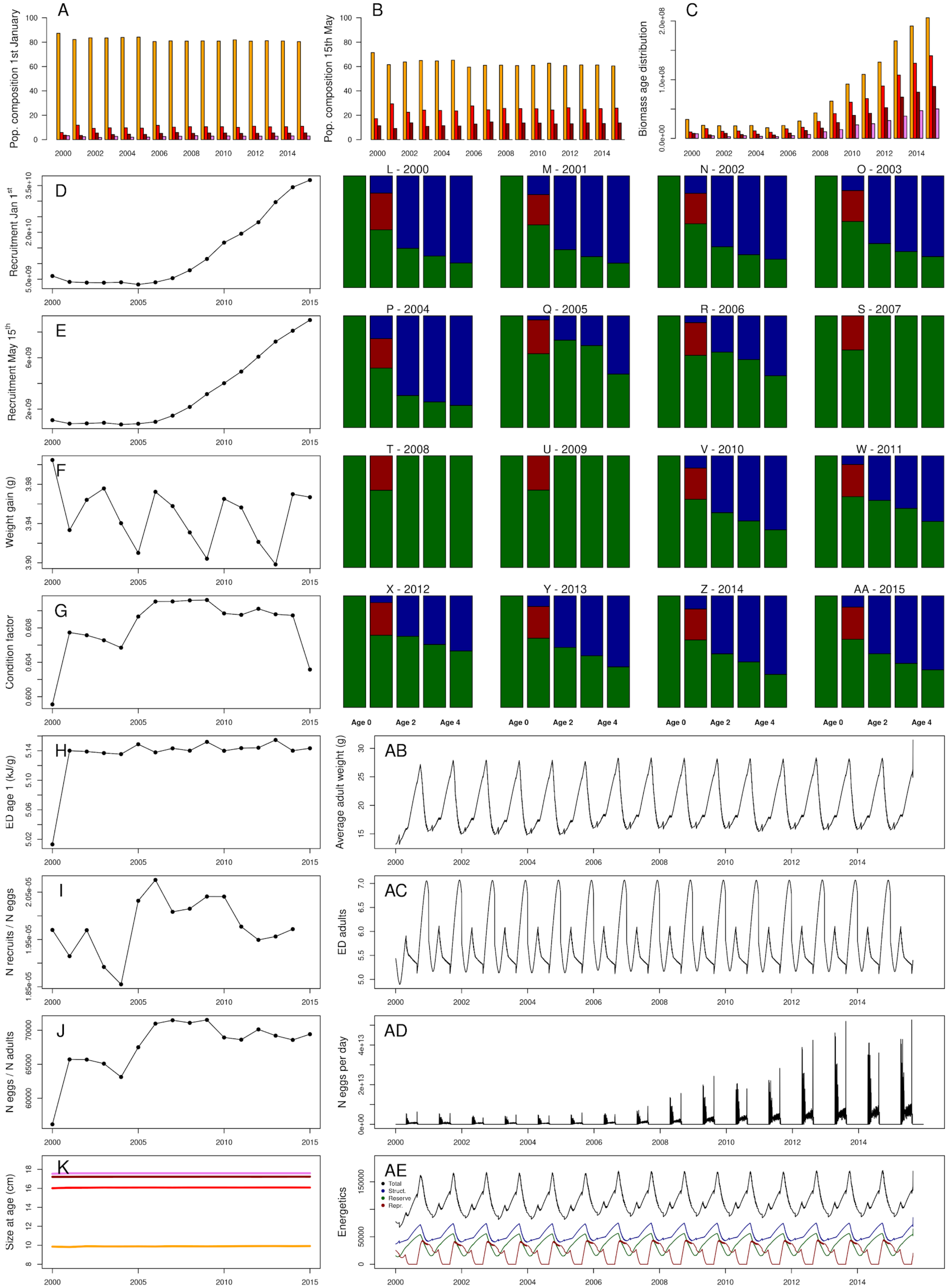


Figure S11. Ecological indicators from the scenario 3 (no closure of the fishery)

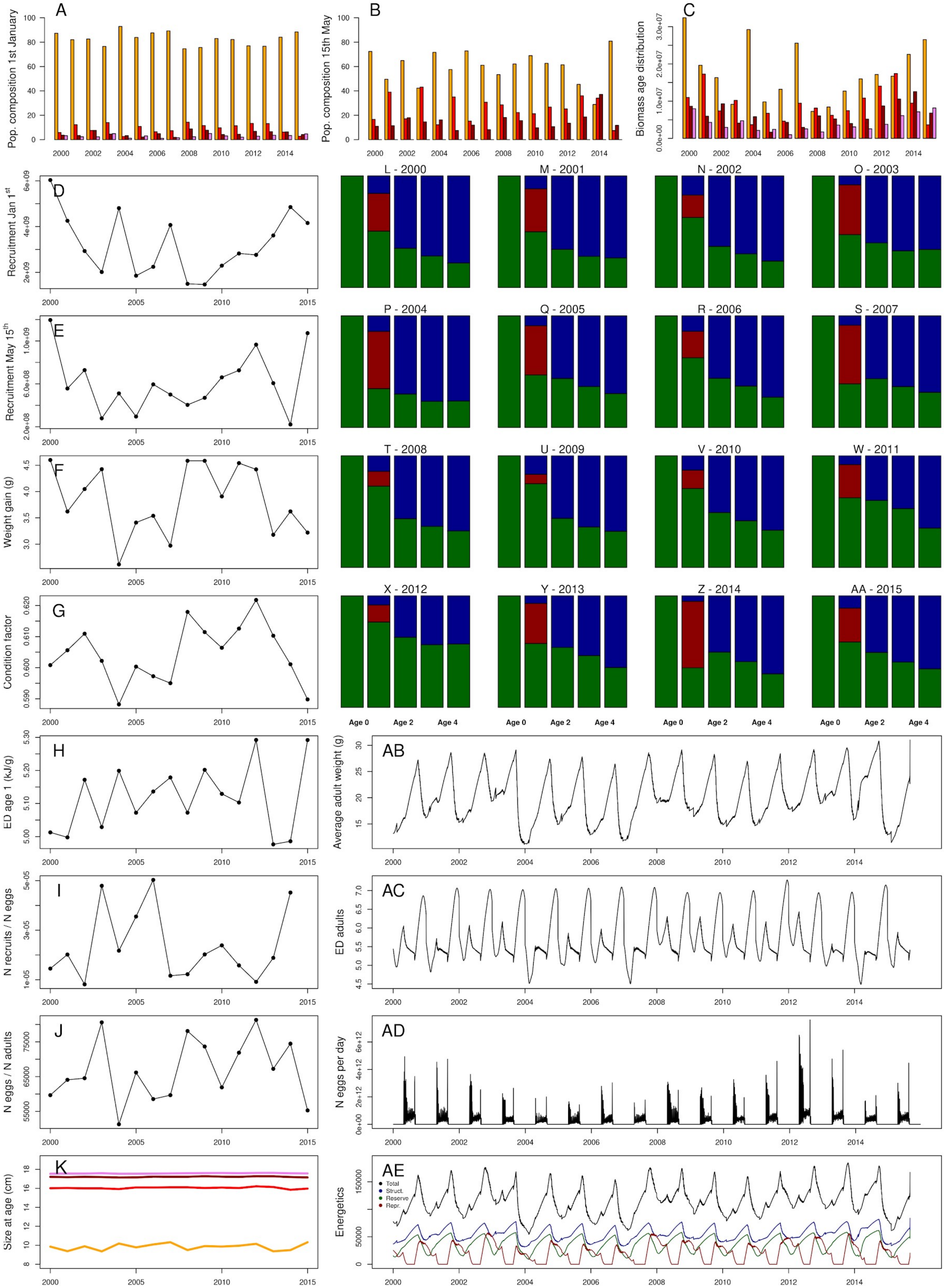


Figure S12. Ecological indicators from the scenario 4 (HCR applied in 2000).

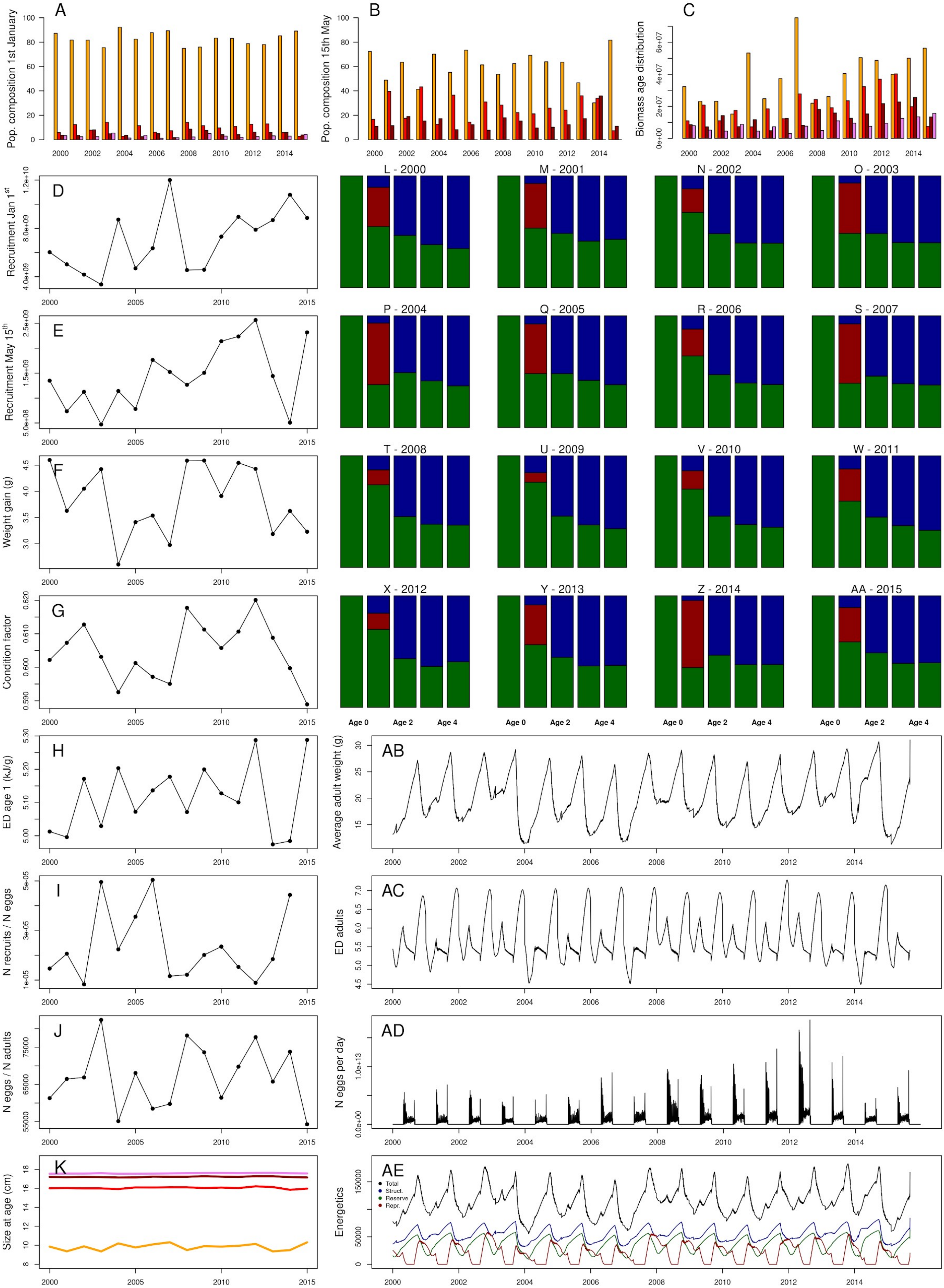
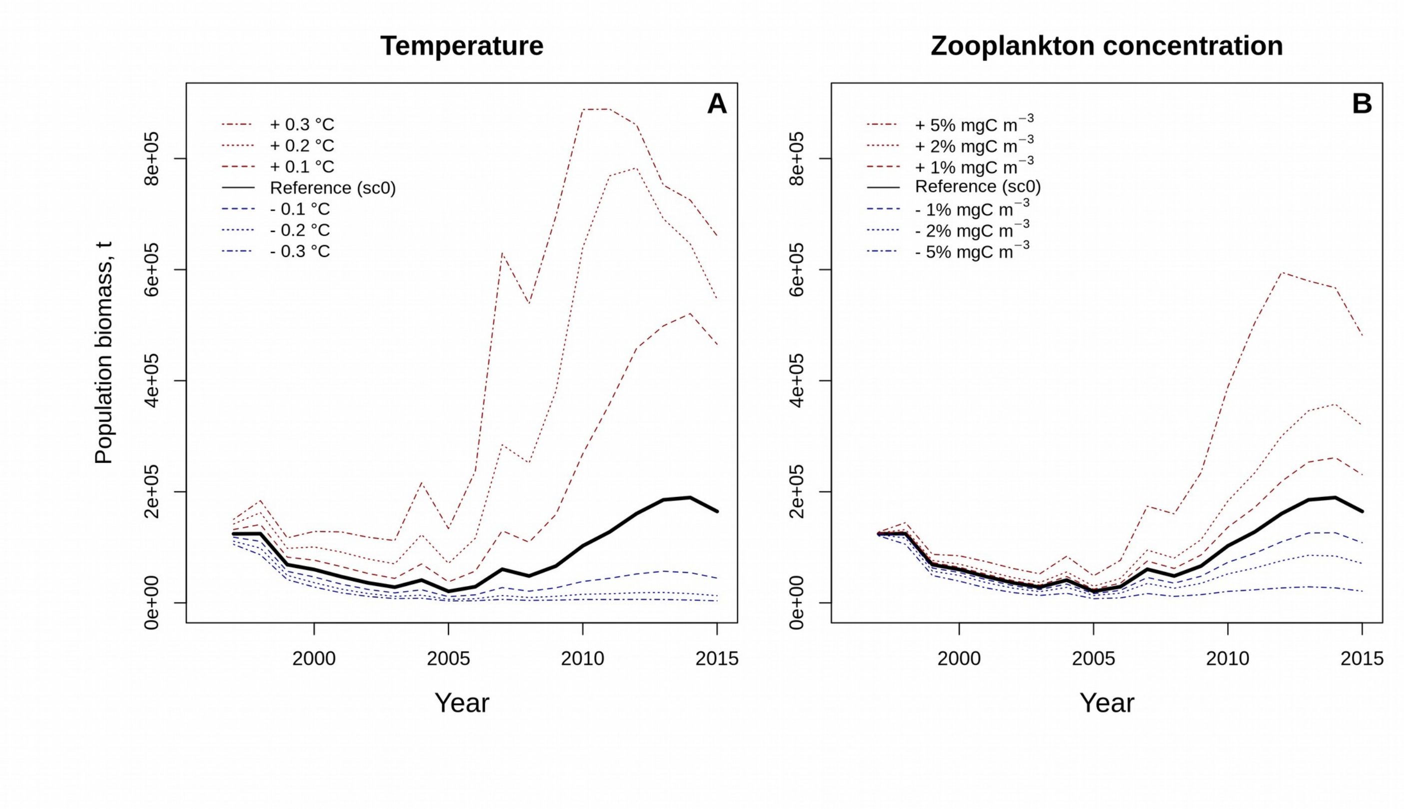


Figure S13. Sensitivity analysis to forcing variables. Sensitivity of the simulated population to changes in A) temperature, B) zooplankton concentration. Black line shows the population biomass under sceanrio sc0. Note the different y-axis in both panels.



Bibliography

- Gatti, P., Petitgas, P., Huret, M. 2017. Comparing biological traits of anchovy and sardine in the Bay of Biscay: A modelling approach with the Dynamic Energy Budget. Ecological Modelling 348: 93-109.