

Supplement: *Model parameter values and equations*

Following Ellner & Rees (2006), the population density (ind./m²) at time $t+1$ for a given length l is described by the following equation:

$$n_{t+1}(l) = G(l|L_0)R_t + \int (S(l', l)G(l|l'))n_t(l')dl' \quad (\text{S.1})$$

where: $n_t(l)$ is number of individuals of size l at time t ; R_t are the annual recruits at time t ; L_0 is the initial length of recruits; $G(l|l')$ is the growth function, i.e. the probability to growth from size l' to size l in one year; and $S(l', l)$ is the survival function, accounting for both size-dependent natural mortality and fishing mortality. Note that initial survival for new recruits is already incorporated into the R_t value. Growth, survival, fecundity, and catch functions are defined below.

Growth

We used a probabilistic non-negative Gompertz growth function to model annual green abalone growth (Figure 2a) (Gompertz 1825, Bardos 2005), parameterized by Rossetto *et al.* (2015). This model allows for variable growth dynamics by creating a distribution of possible growth increments Δl for any specific starting length l and allowing maximum length L_∞ to vary dynamically with l (further discussion in Aalto *et al.* 2019). The mean and variance of L_∞ are determined by L_n and σ_L , respectively, with associated scaling parameters β and γ . Thus, the probability of an abalone of length l growing by the length increment Δl is:

$$G(\Delta l|l) = \frac{\lambda^\rho}{\Gamma(\rho)} (L_\infty - l)^{\rho-1} e^{-\lambda(L_\infty-l)} \frac{1}{1-e^{-G}} \left(\frac{\Delta l+l}{l}\right)^{\frac{1}{e^G-1}} \quad (\text{S.2})$$

where G is the Gompertz growth parameter, $\Gamma()$ is the gamma function, and:

$$L_\infty = \left\{ (l + \Delta l) l^{-e^{-G}} \right\}^{\frac{1}{1-e^{-G}}} \quad (\text{S.3})$$

$$\lambda = \frac{L_n}{1+(\beta \frac{l}{L_n})^3} / \left(\frac{\sigma_L}{1+(\gamma \frac{l}{L_n})^3} \right)^2 \quad (\text{S.4})$$

$$\rho = \left(\frac{L_n}{1+(\beta \frac{l}{L_n})^3} / \frac{\sigma_L}{1+(\gamma \frac{l}{L_n})^3} \right)^2 \quad (\text{S.5})$$

Survival

The instantaneous mortality rate $\mu(l)$ for abalone in natural environments is related linearly to body mass $w(l)$ (Figure 2b; Rossetto et al. 2013), which can be estimated from length (Shepherd 1998):

$$\ln \mu(l) = \theta + \alpha_x \ln w(l) \quad (\text{S.6})$$

$$w(l) = a_w * l^{b_w} \quad (\text{S.7})$$

where θ , a_w , and b_w are scaling parameters. The scaling parameter α_x is, by default, the same for all lengths, but when testing sensitivity to changes in survival we split it into three sub-parameters: juvenile survival α_J , for $l < 50\text{mm}$; immature adult survival α_Y , for $l \geq 50\text{mm}$ and $< L_{mat}$; and mature adult survival α_M for $l \geq L_{mat}$.

To estimate annual survival for an individual, we integrated instantaneous survival from starting length l_0 to ending length l_1 and assumed that all harvest occurs at the end of the year:

$$S(l_0, l_1) = \begin{cases} (1 - h) \int_{l_0}^{l_1} e^{-\mu(l)} dl & \text{if } l_1 > L_{minH} \\ \int_{l_0}^{l_1} e^{-\mu(l)} dl & \text{otherwise} \end{cases} \quad (\text{S.8})$$

where h is the constant annual harvest proportion based on the assumption of constant effort and L_{minH} is the minimum harvest size (see Catch below).

Fecundity

The number of eggs produced at time t is calculated as follows from eggs per unit mass e_w , and the total mature biomass (Tutschulte 1976, Rossetto et al. 2013), multiplied by $\frac{1}{2}$ to track only females and modified by the Allee effect $Allee_t$:

$$E_t = 0.5 * Allee_t * e_w \int p_{mature}(l)w(l)n_t(l)dl \quad (\text{S.9})$$

with egg production increasing exponentially with length (Figure 2c). The proportion of reproductive individuals for a specific length l is:

$$p_{mature}(l) = 0.5 * \frac{1}{1 + e^{-\frac{l-L_{mat}}{a_{mat}}}} \quad (\text{S.10})$$

where a_{mat} is a scaling parameter and L_{mat} is the length at which half of individuals are mature (Rossetto et al. 2013).

In order to assess possible OA effects on the ability of a population to recover from a mass-mortality event, we included an Allee effect in the fecundity function. Following Button (2008), the Allee effect at time t $Allee_t$ (Figure 2d) is modeled as a relative breeding success multiplier bounded between 0 and 1 and determined by mean aggregation size Agg_t :

$$Allee_t = P_{mixed}(Agg_t). \quad (S.11)$$

Agg_t is calculated using the total density of mature individuals M_t :

$$M_t = \int p_{mature}(l)n_t(l)dl \quad (S.12)$$

to estimate mean aggregation size (Button 2008):

$$Agg_t = a_{agg} * M_t + b_{agg} \quad (S.13)$$

and used to determine the probability of mixed gender aggregations:

$$P_{mixed}(Agg_t) = 1 - 0.5^{Agg_t-1}. \quad (S.14)$$

The aggregation regression parameters a_{agg} and b_{agg} were derived from Button (2008) by setting the 80% breeding success threshold for the Allee effect to 0.2 mature adults/m². This value is similar to that seen in prior work (0.15-0.2, Shepherd & Brown 1993, Shepherd & Partington

1995; 0.3, Babcock & Keesing 1999) and consistent with recruitment failure seen in the field (failure at 0.003 vs. success at 0.85, Rogers-Bennett *et al.* 2004).

Recruitment

The number of larvae settling at time t was calculated as follows:

$$S_{z,t} = r(t)\sigma_E E_{j,t} \quad (\text{S.16})$$

where σ_E represents the survival from eggs to settlers, and $r(t)$ is a random variable with mean =1 and log-normal distribution that represents relative annual fluctuations in settler survival rate due to year-to-year environmental variability (Szuwalski *et al.* 2015).

Following Micheli *et al.* (2008) and Rossetto *et al.* (2013), we modeled successful recruitment R_t as a Ricker function (Ricker 1954) of the form:

$$R_t = \sigma_S S_t \exp\left(-\frac{S_t}{K}\right) \quad (\text{S.17})$$

with density-dependence occurring only at the settlement stage and $r(t)$ in Eq.16 accounting for year-to-year environmental variability. We set carrying capacity K to produce an unfished density of ~ 0.2 ind./m², the assumed Allee threshold, based on the work of McShane (1991) and Daume *et al.* (2004) and consistent with field observations (Rogers-Bennett *et al.* 2004, Micheli *et al.* 2008).

Catch

Catch is calculated in metric tons as:

$$C_t = 10^{-6} A \int_{L_{minH}}^{L_{max}} hw(l)n_{z,t}(l)dl \quad (S.18)$$

where A is the area of the fishery and h is the proportion of commercial size abalone that is harvested in year t , representing a constant level of harvest. We set harvest proportion h to 2/3 of F_{MSY} as a precautionary compromise.

Table S1: Model parameter values

<i>Parameter</i>	<i>Symbol</i>	<i>Value</i>	<i>Units</i>	<i>Source</i>
<i>Population dynamics</i>				
Length at recruitment	L_0	1	mm	
Length for 50% maturity	L_{mat}	135.99	mm	a
Minimum harvest length	L_{minH}	155	mm	a
Annual harvest proportion	h	0.06		b
Weight scaling value	a_w	$2.24 \cdot 10^{-5}$	$g \text{ mm}^{-b_w}$	c
Weight exponent	b_w	3.36		c
No-shell wt. proportion		0.4		a
Gompertz growth param.	G	0.5635		d
Gomp. max length mean	L_n	150.39	mm	d
Gomp. max length var.	σ_L^2	55.95		d
Gomp. mean scaling	β	1.478		d
Gomp. var. scaling	γ	1.719		d
Mortality scaling	α_x	-0.317		e
Mortality intercept	θ	0.635		e
Maturity scaling value	a_{mat}	30.2	mm	a
Fecundity	e_w	3772	eggs g^{-1}	f
Slope for aggregation est.	a_{agg}	11.6		g
Intercept for agg. est.	b_{agg}	1		g
Survival of eggs	σ_E	0.005704		h
Survival of recruits	σ_S	0.01		a
Carrying capacity for recruits	K	$2.59 \cdot 10^7$	indiv.	i
Recruit. log-normal mean	r_m	0		j
Recruit. log-normal sd	r_{sd}	0.7		j

- a. From Rossetto et al. 2015.
- b. Harvest proportion was set to 2/3 of F_{MSY} .
- c. From Shepherd et al. 1998
- d. Parameters from Bardos 2005 model estimated by fitting observed growth data as described in Rossetto et al. 2015.
- e. The mortality parameters are for *Haliotis fulgens* from Rossetto et al. 2012. Similar to non-size-dependent values seen in other abalone literature ($M=0.38$, Shepherd 1990; $M=0.77$, Button & Rogers-Bennett 2011). The default value for each age class (juvenile, young adult, mature adult) is the same.
- f. From Tutschulte 1976.
- g. The aggregation regression is from Button 2008 with slight alterations. We changed a_{agg} from 11.3 to 11.6, a value within the given 95% uncertainty range, to set 80% breeding success to 0.2 ind./m². We set the intercept $b_{agg}=1$ instead of 1.959 so that aggregation size =1 when density approaches 0.
- h. The original egg survival value from Rossetto et al. 2013 = 3.09×10^{-3} . We adjusted this survival value by 1.846 to remove the implicit Allee effect estimated from the observed densities of 0.015 ind./m².
- i. The original estimated value of K from McShane 1991 and Duame et al. 2004 was 10^7 . We adjusted this slightly to produce a mean unfished density of ~ 0.2 ind./m².
- j. Following the observations of Shepherd 1990, we set these values to produce an $\sim 15x$ ratio between highest and lowest recruitment years after trimming outliers.

Literature cited

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