

The following supplement accompanies the article

# Impacts of shifts in spawning seasonality and size at maturation on the population growth of mantis shrimp in Tokyo Bay

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## SUPPLEMENT. Details of calculation and additional data

### A. DETAILS OF THE MODEL AND ESTIMATION OF PARAMETER VALUES

#### A1. Matrix model

The population dynamics, Eqs. (1) to (10) in the main paper, can be described in matrix formula as

$$\mathbf{n}(t+1) = \mathbf{A}\mathbf{n}(t) \quad (\text{S1})$$

where  $\mathbf{n} = (N_{spr0}, N_{sum0}, N_{sprS1}, N_{sprL1}, N_{sumS1}, N_{sumL1}, N_{sprS2+}, N_{sprL2+}, N_{sumS2+}, N_{sumL2+})^T$ ,  $T$  denotes a vertical vector, and

$$\mathbf{A} = \begin{pmatrix} a_{1,1} & \cdots & a_{1,j} \\ \vdots & \ddots & \vdots \\ a_{i,1} & \cdots & a_{i,j} \end{pmatrix} \quad (i, j = 1, 2, \dots, 10)$$

$$\text{with } a_{1,1} = a_{1,3} = a_{1,5} = a_{1,7} = a_{1,9} = E_D^{\frac{4}{12}} S_A^{\frac{4}{12}} R_{Spr} S_{Spr} S_A^{\frac{6}{12}} E_D^{\frac{4}{12}},$$

$$a_{1,4} = a_{1,6} = a_{1,8} = a_{1,10} = E_L^{\frac{4}{12}} S_A^{\frac{4}{12}} R_{Lspr} S_{Spr} S_A^{\frac{6}{12}} E_D^{\frac{4}{12}},$$

$$a_{2,1} = \left[ g_0 E_D^{\frac{5}{12}} E_L^{\frac{2}{12}} R_{Lsum} + (1 - g_0) E_D^{\frac{7}{12}} R_{Ssum} \right] S_A^{\frac{7}{12}} S_{sum} S_A^{\frac{3}{12}} E_D^{\frac{1}{12}},$$

$$a_{2,2} = E_D^{\frac{7}{12}} S_A^{\frac{7}{12}} R_{Ssum} S_{sum} S_A^{\frac{3}{12}} E_D^{\frac{1}{12}},$$

$$a_{2,3} = \left[ G_{spr1} E_D^{\frac{5}{12}} E_L^{\frac{2}{12}} R_{Lsum} + (1 - G_{spr1}) E_D^{\frac{7}{12}} R_{Ssum} \right] S_A^{\frac{7}{12}} S_{sum} S_A^{\frac{3}{12}} E_D^{\frac{1}{12}},$$

$$\begin{aligned}
a_{2,4} &= a_{2,6} = a_{2,8} = a_{2,10} = E_L^{\frac{7}{12}} S_A^{\frac{7}{12}} R_{Lsum} S_{sum} S_A^{\frac{3}{12}} E_D^{\frac{1}{12}}, \\
a_{2,5} &= \left[ G_{sum1} E_D^{\frac{5}{12}} E_L^{\frac{2}{12}} R_{Lsum} + (1 - G_{sum1}) E_D^{\frac{7}{12}} R_{Ssum} \right] S_A^{\frac{7}{12}} S_{sum} S_A^{\frac{3}{12}} E_D^{\frac{1}{12}}, \\
a_{2,7} &= \left[ G_{spr2} E_D^{\frac{5}{12}} E_L^{\frac{2}{12}} R_{Lsum} + (1 - G_{spr2}) E_D^{\frac{7}{12}} R_{Ssum} \right] S_A^{\frac{7}{12}} S_{sum} S_A^{\frac{3}{12}} E_D^{\frac{1}{12}}, \\
a_{2,9} &= \left[ G_{sum2} E_D^{\frac{5}{12}} E_L^{\frac{2}{12}} R_{Lsum} + (1 - G_{sum2}) E_D^{\frac{7}{12}} R_{Ssum} \right] S_A^{\frac{7}{12}} S_{sum} S_A^{\frac{3}{12}} E_D^{\frac{1}{12}}, \\
a_{3,1} &= (1 - G_{spr0}) E_D S_A, \\
a_{4,1} &= G_{spr0} E_D^{\frac{5}{12}} E_L^{\frac{7}{12}} S_A, \\
a_{5,2} &= (1 - G_{sum0}) E_D S_A, \\
a_{6,2} &= G_{sum0} E_D^{\frac{8}{12}} E_L^{\frac{4}{12}} S_A, \\
a_{7,3} &= (1 - G_{spr1}) E_D S_A, \\
a_{7,7} &= (1 - G_{spr2}) E_D S_A, \\
a_{8,3} &= G_{spr1} E_D^{\frac{5}{12}} E_L^{\frac{7}{12}} S_A, \\
a_{8,4} &= a_{8,8} = a_{10,6} = a_{10,10} = E_L S_A, \\
a_{8,7} &= G_{spr2} E_D^{\frac{5}{12}} E_L^{\frac{7}{12}} S_A, \\
a_{9,5} &= (1 - G_{sum1}) E_D S_A, \\
a_{9,9} &= (1 - G_{sum2}) E_D S_A, \\
a_{10,5} &= G_{sum1} E_D^{\frac{5}{12}} E_L^{\frac{7}{12}} S_A, \\
a_{10,9} &= G_{sum2} E_D^{\frac{5}{12}} E_L^{\frac{7}{12}} S_A, \\
&\text{and other } a_{i,j} = 0.
\end{aligned}$$

## A2. Parameter estimation

For  $S_A$  and the sex ratio, we used the same values applied in the stock size assessment for the high-stock-level period in Nakata (1990). We assumed that survivability is constant throughout a year and a lifetime, because no data have suggested seasonality or age dependence of survival. Maturation rates and body length-dependent clutch sizes in  $R_{Lspr}$ ,  $R_{Lsum}$ ,  $R_{Sspr}$ , and  $R_{Ssum}$  were estimated from the data in Kodama et al. (2006c) and (2004), respectively. For clutch sizes of small and large females, we used the mean number of eggs calculated from the fecundity function  $58.4x^{2.79}$ , with  $x$  cm of body length (Kodama et al. 2004) when  $7 \leq x < 10$  and  $10 \leq x < 14$  at 0.01 cm intervals, respectively. The minimum body length of a mature female was considered to be 7 cm (Kodama et al. 2006c), and the maximum size for a mature individual was 13 to 14 cm (Kodama et al. 2006d).

For the estimates of survival from fishing,  $E_L$  and  $E_D$ , we first describe the change in the population size  $N$  as

$$N_{t+1} = N_t e^{-Z} \quad (S2)$$

where  $Z$  denotes the total rate of instantaneous mortality, consisting of both fishing mortality ( $F$ ) and natural mortality ( $M$ ), i.e.  $Z = F + M$ , where  $S_A = \exp[-M]$  (Haddon 2001). This value of  $F$  is the average mortality due to both landing and discarding (denoted by  $F_L$  and  $F_D$ , respectively). The values of  $F_D$  and  $F_L$  should satisfy [ $F =$  proportion of non-fishery target individuals  $\times F_D +$  proportion of fishery-target individuals  $\times F_L$ ], of which the ratio between the first term and the second in the bracket is equal to the proportions of death due to discarding and landing. Monthly ratios of discarding to total catch (= discarding + landing) and mortality after discarding were reported by Kitahara & Maki (1997) to be 0.55 and 0.36 in annual averages, respectively. The ratio of death due to discarding to death due to landing is calculated as [ratio of discarding to total catch  $\times$  mortality after discarding] / [1 – ratio of discarding to total catch], which was 0.44 (note that mortality after landing = 1). For the proportions of small and large individuals, size (small or large) and age (0, 1, 2, 3, and 4 yr old) distributions in September and December 2004 and March 2005 provided by Kodama et al. (2006d) were used (small:large = 0.95:1 on average). Next, we estimated  $Z$ . As an index for the time series of fishery-targeted population sizes ( $N_{L1,t}$  and  $N_{L2+,t}$ ), landings per unit effort (LPUE, number of inds. ship<sup>-1</sup> h<sup>-1</sup>) data for each of the 4 body-length categories in September, December, and March (of the next year) 1991 to 2003 (Shimizu 2004, Kodama et al. 2006c) were available. To estimate changes in the non-fishery targeted population ( $N_{Spr,t}$ ,  $N_{Sum,t}$ ,  $N_{S1,t}$ , and  $N_{S2+,t}$ ), we multiplied the population ratios of small to large individuals at each age by the LPUE data (both described above); this provided the age-specific time series for the index of the non-fishery target population sizes on the same scale as LPUE for the fishery-target population. The sum of the indices of fishery target and non-fishery target population sizes at each age were fitted to Eq. (S2), and the average value of  $Z$  (= 2.4) was obtained. Because  $M$  was estimated as 0.751 by Nakata (1990),  $F = 1.649$ . Then  $E_D = \exp[-F_D] = 0.369$ , and  $E_L = \exp[-F_L] = 0.104$ .

We assumed all young of the year (YOY) have the potential to be captured by fishing for several reasons. First, in the laboratory, juveniles attained 5 cm, which is the minimum body length that the fishing net can capture (in the late 1990s; Kitahara & Maki 1997), within 64 d after settlement and continued to grow until the final observation on Day 400 (Hamano & Matsuura 1987). Therefore, considering the time after settlement in year  $t$  until the start of year  $t + 1$ , which is approximately 6 mo for the spring cohort and 3 mo for the summer cohort (see Fig. 2b in the main paper), we assumed that YOY are large enough to be captured during year  $t + 1$ . Second, the proportion of individuals  $\geq 7.5$  cm that escaped from the fishing nets used from 1992 until around 2001 was  $< 5\%$  (Ishii et al. 2001). Most of the fishery data used to estimate fishing mortality were collected during this period. Although the escape probability data of individuals 5 to 7 cm are not available, the probability of escape from a similar net for individuals of 5, 6, and 7 cm classes was  $< 8\%$ ,  $< 5\%$ , and  $< 3\%$ , respectively (Shimizu 1990). Therefore, for simplicity, we assumed here that no individuals escape from the fishing net regardless of body size.

The number of landings was calculated as follows (Haddon 2001):

$$n = \frac{F_L}{F_L + M} (1 - \exp[-F_L - M]) N_t \quad (\text{S3})$$

Because we assumed that spring- and summer-spawned populations have the same somatic growth rate, the difference between the probabilities of growing larger at age  $k$ ,  $G_{sprk}$  and  $G_{sumk}$ , is due to the difference in length of time since birth. To estimate the proportion of individuals that grow to a large size class ( $G_{spr0}$ ,  $G_{sum0}$ ,  $g_0$ ,  $G_{spr1}$ ,  $G_{spr2}$ ,  $G_{sum1}$ , and  $G_{sum2}$ ), we used the age and size distributions in August 2003, June, September, December 2004, and March 2005 reported by Kodama et al. (2005, 2006d) and estimated survivability,  $E_D$  and  $E_L$ . For age estimation, Kodama et al. (2005, 2006d) assumed that most of the observed individuals were spawned in August (i.e. summer-spawned). Because these observed proportions of large ( $\geq 10$  cm) individuals are biased by individual loss due to size-dependent fishing mortality, which may be higher for large individuals, we recalculated the proportions of large individuals (hereafter ‘%L’) at each sampling as [(observed number of large individuals /  $E_L$ ) / (observed number of large individuals /  $E_L$  + observed number of small individuals /  $E_D$ )]. We fitted 3 non-linear equations to the arcsine-transformed %L on age (yr): (1) asymptotic model ( $1.516 - 2.451 \times 0.355^{age}$ ), (2) logistic model ( $1.434 / [1 + 17.628 \times 11.874^{-age}]$ ) and (3) logarithmic model ( $0.649 \ln[age] + 0.649$ ). All models produced a significant relationship between age and %L ( $F$  test,  $p < 10^{-15}$  for all models). The asymptotic model had the smallest value of Akaike’s information criterion (AIC,  $-11.3$ ; logistic model:  $-5.6$ , logarithmic model:  $-7.9$ ); therefore, we used this model to calculate %L of each age at the time of the population count (for %L and fitted curve, see Fig. S2). %L of spring-spawned individuals at the age of 1.25 yr (= 15 mo, from birth in May until the beginning of summer spawning in August of the following year) represents  $g_0$ , and values at age 1.667 yr (= 20 mo, from May to December of the next year), i.e. the proportion of spring-spawned YOY at the end of the calendar year in which they became 1 yr old, represent  $G_{spr0}$  (note that  $G_{spr0}$  is the proportion of  $N_{spr0}$  [i.e. individuals spawned in year  $t$ ] that grow to a large size class by the end of the calendar year  $t + 1$ , when they are counted as age-1 individuals; see Fig. 2b in the main paper for the life cycle).  $G_{sum0}$  was obtained using the relationship  $age = 1.417$  yr (= 17 mo, from August to December of the next year). For  $G_{spr1}$ , we first calculated %L at the age of 2.667 yr. Here, we assumed %L of age-2 at the end of year  $t = [(1 - \%L)$  of age-1 individuals at the end of year  $t \times G_{spr1} + \%L$  of age-1 individuals at the end of year  $t]$  (for the assumption of size and age transition, see Eq. 2 and Fig. 2a in the main paper). Substituting  $(1 - G_{spr0})$  and  $G_{spr0}$  into this equation as the proportions of small and large individuals, respectively, we obtained  $G_{spr1}$ . Likewise, we estimated  $G_{spr2}$ ,  $G_{sum1}$ , and  $G_{sum2}$ , from the equation  $age = 2.667$  (32 mo), 2.417 (29 mo), 3.667 (44 mo), and 3.417 (41 mo), respectively.

### A3. Population size estimation

The fishery-targeted population size (i.e.  $N_{L1,t}$  and  $N_{L2+,t}$ ) for age  $a$  in year  $t$  provides the population size in the next year, according to the following equation:

$$N_{a+1,t+1} = N_{a,t} E_L S_A \quad (\text{S4})$$

We assumed that the fishery was conducted intensively in the middle of year  $t$ . Therefore, the population size in year  $t + 1$  was described with individuals landed in year  $t$ ,  $n_{a,t}$ , with Pope's approximation (Haddon 2001) as

$$N_{a+1,t+1} = N_{a,t} S_A - n_{a,t} S_A^{1/2} \quad (\text{S5})$$

From Eqs. (S4) and (S5), we have

$$N_{a,t} = S_A^{-1/2} n_{a,t} / (1 - E_L) \quad (\text{S6})$$

Size-classed landing data in 2003 (Shimizu 2004, Kodama et al. 2006c) were divided into ages with size- and age-distribution data, as described above, and substituted into Eq. (S6). Thus, the fishery-targeted population sizes in 2003 were estimated (= 10 547 716) and used with size- and age-distribution data to calculate the population sizes (see 'Model: Equations' in the main paper for details).

## **B. SIMULATIONS AND CALCULATIONS WITH DIFFERENT MODEL ASSUMPTIONS**

The details of different model scenarios are provided below. The number of eggs and recruitments and the population growth rate  $\lambda$  of the scenarios are presented in Fig. S3 in Section C. Note that we re-calculated the stable population size distribution for each of the scenarios to estimate the number of eggs.

### **B1. Simulation with somatic growth dependent on the parents' body length**

For this simulation, we calculated the population sizes of each stage for individuals spawned by large and small females separately with different  $G_{ik}$ . Values of  $G_{ik}$  for offspring of large and small females were estimated from the asymptotic regression curve with estimated parameters + SE and estimated parameters - SE (regression curves are shown in Fig. S2 in Section C). For these calculations, we used the same *age* as described above for the original estimation. The stable population size distribution obtained in this scenario, using the same method as the original model described in 'Model: Equations' in the main paper, was  $N_{sum0} = 6$ ,  $N_{sumS1} = 1$ , and others = 0.

### **B2. Size-dependent escape probability**

Ishii et al. (2001) devised a fishing net with larger and differently shaped mesh than nets used by the local fishery in ca. 1992 to 2000. Their new design resulted in higher escape probabilities for smaller individuals (Ishii et al. 2001). Here, we estimated that  $E_D$  and  $E_L$  increased when using this redesigned net and then recalculated  $\lambda$ , the expected number of eggs, and recruitment.

The escape probability with the new fishing net closely matched the escape probability curve of body sizes estimated for another population of *Oratosquilla oratoria* by Tokai et al. (1990) (Ishii et al. 2001). Because the escape probability data of Ishii et al. (2001) lack individuals <7.5 cm, we used the probability curve of Tokai et al. (1990) for estimation. The escape probability was defined by Tokai et al. (1990) for body lengths of 3.8 to 14.3 cm (corresponding to escape probabilities of 98 to 0%). We assumed escape probabilities of individuals <3.8 cm and >14.3 cm as 100 and 0%, respectively.

The average escape probability from time  $T_1$  until time  $T_2$  is  $\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} E(G) dt$ , where

$E(G)$  denotes the escape probability of Tokai et al. (1990) determined by the somatic growth curve  $G(\tau)$ , which describes body length as a function of time since settlement,  $\tau$  (see Fig. S4 in Section C for details of the functions).

The somatic growth curve for juveniles (for 400 d after settlement) was provided by Hamano & Matsuura (1987) based on laboratory breeding. The escape probability of individuals at 5 cm calculated from the curve of Tokai et al. (1990) was 94.3%. Therefore, we used the simplified assumption, as in the original model (Eqs. 9 & 10 in the main paper), that individuals would not be caught until they reach 5 cm, which is approximately 2 mo after settlement. From 2 mo after settlement until the end of year  $t$ , the average escape probability of individuals spawned in the spring of that year (i.e. from their third to sixth months after settlement; Fig. 2b & Eq. 9 in the main paper) would be 84.1%, whereas that of the summer cohort would be 88.2%. Thus, Eqs. (9) & (10) in the main paper would change to:

$$N_{spr0,t+1} = (Egg_{Lspr,t+1} + Egg_{Sspr,t+1}) S_{spr} S_A^{\frac{6}{12}} (1 + 0.841) E_D^{\frac{4}{12}} \quad (S7)$$

and

$$N_{sum0,t+1} = (Egg_{Lsum,t+1} + Egg_{Ssum,t+1}) S_{sum} S_A^{\frac{3}{12}} (1 + 0.882) E_D^{\frac{1}{12}} \quad (S8)$$

The average escape probabilities after year  $t + 1$  are calculated separately for individuals that grow to a large size class and those that do not. For the former group, we substituted the growth curve of Hamano & Matsuura (1987) and extrapolated it until it reached 14.3 cm (achieved at 23.8 mo), at which point the escape probability = 0. We assumed that the escape probability = 0 for individuals >4.3 cm. In this modified model, the escape probability caused  $E_D$  to increase until 10 mo after settlement, which was the length of time until individuals grew to a large size class in our model (see Eq. 4 in the main paper). After 11 mo from settlement, the escape probability caused  $E_L$  to increase.  $E_D$  in year  $t + 1$  increased for the spring and summer cohort spawned in year  $t$  by the average probabilities of 66.9 and 72.9%, respectively;  $E_L$  also increased by 28.4 and 38.9%, respectively. Thus, the population dynamics of Eq. 4 in the main paper were modified respectively as:

$$N_{sprL1,t+1} = N_{spr0,t} G_{spr0} (1 + 0.669) E_D^{\frac{5}{12}} (1 + 0.284) E_L^{\frac{7}{12}} S_A \quad (S9a)$$

and

$$N_{sumL1,t+1} = N_{sum0,t} G_{sum0} (1 + 0.729) E_D^{\frac{8}{12}} (1 + 0.389) E_L^{\frac{4}{12}} S_A \quad (S9b)$$

For the group that does not grow to a large size class, we estimated the body length–age curve from field data reported by Kodama et al. (2005, 2006d; the same data sets used to estimate  $G_{ik}$  as shown in Section A2) instead of the somatic growth curve used above (Hamano & Matsuura 1987), which was obtained from well-fed individuals in the laboratory. In fact, the 75<sup>th</sup> percentile of the size-class distribution at each age for the data of Kodama et al. (2005, 2006d) was similar to the curve for body length <10 cm of Hamano & Matsuura (1987). We used the 25<sup>th</sup> percentile from Kodama et al. (2005, 2006d) to estimate the somatic growth curve of individuals that do not grow to a large size (*body length* [cm] = 11.05 – 8.60 × 0.93 <sup>$\tau$</sup> ,  $\tau$  = time [mo] since settlement). However, we should note that this curve could underestimate growth in the field,

especially for body lengths >10 cm, due to higher fishing mortality for larger individuals. Therefore, our results in this section are based on the highest expectation of escape from the redesigned net, which provides a good contrast with our original model that included no escape. The estimated escape probabilities in year  $t + 1$  for small individuals spawned in spring and summer in year  $t$  were 77.4 and 83.8%, respectively. Thus, the population dynamics of Eq. (3) in the main paper were separated for the spring and summer cohort as:

$$N_{sprS1,t+1} = N_{spr0,t} (1 - G_{spr0}) (1 + 0.774) E_D S_A \quad (S10a)$$

and

$$N_{sumS1,t+1} = N_{sum0,t} (1 - G_{sum0}) (1 + 0.838) E_D S_A \quad (S10b)$$

Escape probabilities for age class 2+ were likewise estimated. For individuals that grow from a small to large size class in the middle of the year, the 25<sup>th</sup> percentile curve of Kodama et al. (2005, 2006d) was used as the somatic growth curve. The dynamic equations of age >2+ (Eqs. 1 & 2 in the main paper) were separated for spring and summer cohorts and modified respectively as described above (Eqs. S7 to S9) as:

$$N_{sprL2+,t+1} = (N_{sprL1,t} \times 1.011 + N_{sprL2+,t}) E_L S_A + N_{sprS1,t} G_{spr1} \times 1.592 \times E_D^{\frac{5}{12}} \times 1.492 \times E_L^{\frac{7}{12}} S_A + N_{sprS2+,t} G_{spr2+} \times 1.418 \times E_D^{\frac{5}{12}} \times 1.367 \times E_L^{\frac{7}{12}} S_A \quad (S11a)$$

$$N_{sumL2+,t+1} = (N_{sumL1,t} \times 1.047 + N_{sumL2+,t}) E_L S_A + N_{sumS1,t} G_{sum1} \times 1.653 \times E_D^{\frac{5}{12}} \times 1.539 \times E_L^{\frac{7}{12}} S_A + N_{sumS2+,t} G_{sum2+} \times 1.452 \times E_D^{\frac{5}{12}} \times 1.390 \times E_L^{\frac{7}{12}} S_A \quad (S11b)$$

$$N_{sprS2+,t+1} = N_{sprS1,t} (1 - G_{spr1}) \times 1.534 \times E_D S_A + N_{sprS2+,t} (1 - G_{spr2+}) \times 1.388 \times E_D S_A \quad (S12a)$$

$$N_{sumS2+,t+1} = N_{sumS1,t} (1 - G_{sum1}) \times 1.587 \times E_D S_A + N_{sumS2+,t} (1 - G_{sum2+}) \times 1.416 \times E_D S_A \quad (S12b)$$

$$Egg_{Lspr,t+1} = (N_{sprL1,t} \times 1.032 + N_{sumL1,t} \times 1.122 + N_{sprL2+,t} + N_{sumL2+,t}) E_L^{\frac{4}{12}} S_A^{\frac{4}{12}} R_{Lspr} \quad (S13)$$

$$Egg_{Sspr,t+1} = (N_{spr0,t} \times 1.695 + N_{sprS1,t} \times 1.602 + N_{sumS1,t} \times 1.663 + N_{sprS2+,t} \times 1.423 + N_{sumS2+,t} \times 1.458) E_D^{\frac{4}{12}} S_A^{\frac{4}{12}} R_{Sspr} \quad (S14)$$

$$\begin{aligned}
Egg_{Lsum,t+1} = & \\
& (N_{spr0,t} g_0 \times 1.669 E_D^{\frac{5}{12}} \times 1.465 E_L^{\frac{2}{12}} + N_{sprS1,t} G_{spr1} \times 1.592 E_D^{\frac{5}{12}} \times 1.530 E_L^{\frac{2}{12}} + \\
& N_{sumS1,t} G_{sum1} \times 1.653 E_D^{\frac{5}{12}} \times 1.582 E_L^{\frac{2}{12}} + N_{sprS2+,t} G_{spr2} \times 1.418 E_D^{\frac{5}{12}} \times 1.385 E_L^{\frac{2}{12}} + \\
& N_{sumS2+,t} G_{sum2} \times 1.452 E_D^{\frac{5}{12}} \times 1.412 E_L^{\frac{2}{12}} ) S_A^{\frac{7}{12}} R_{Lsum} + (N_{sprL1,t} \times 1.018 + N_{sumL1,t} \times \\
& 1.080 + N_{sprL2+,t} + N_{sumL2+,t}) E_L^{\frac{7}{12}} S_A^{\frac{7}{12}} R_{Lsum} \tag{S15}
\end{aligned}$$

and

$$\begin{aligned}
Egg_{Ssum,t+1} = & \\
& [N_{spr0,t} (1 - g_0) \times 1.611 + N_{sum0,t} \times 1.752 + N_{sprS1,t} (1 - G_{spr1}) \times 1.574 + N_{sumS1,t} (1 - \\
& G_{sum1}) \times 1.633 + N_{sprS2+,t} (1 - G_{spr2}) \times 1.409 + N_{sumS2+,t} (1 - G_{sum2}) \times 1.440] \\
& E_D^{\frac{7}{12}} S_A^{\frac{7}{12}} R_{Ssum}. \tag{S16}
\end{aligned}$$

Note that escape probabilities of  $N_{iL2+} = 0$ .

### B3. Seasonal mortality of discarded individuals

The mortality data of discarded individuals (Kitahara & Maki 1997) suggested lower survival in July and August (i.e. summer) compared to other months. The average monthly survival in July to August and other months was 0.18 and 0.73, respectively.

Thus, the annual survivability,  $E_D$ , would be a product of lower survival for 2 mo,  $E_{Dl}^{\frac{2}{12}}$ , and higher survival for 10 mo,  $E_{Dh}^{\frac{10}{12}}$ . Therefore, from  $E_{Dl}^{\frac{2}{12}} \times E_{Dh}^{\frac{10}{12}} = E_D$  and  $E_{Dl} / E_{Dh} = 0.18 / 0.73$ , we obtained  $(E_{Dl}, E_{Dh}) = (0.115, 0.466)$ . The model Eqs. (1–10) in the main paper would be modified to:

$$(1) N_{iS2+,t+1} = [N_{iS1,t} (1 - G_{i1}) + N_{iS2+,t} (1 - G_{i2+})] E_{Dl}^{\frac{2}{12}} E_{Dh}^{\frac{10}{12}} S_A \tag{S17}$$

$$(2) N_{iL2+,t+1} = (N_{iL1,t} + N_{iL2+,t}) E_L S_A + (N_{iS1,t} G_{i1} + N_{iS2+,t} G_{i2+}) E_{Dh}^{\frac{5}{12}} E_L^{\frac{7}{12}} S_A \tag{S18}$$

$$(3) N_{iS1,t+1} = N_{i0,t} (1 - G_{i0}) E_{Dl}^{\frac{2}{12}} E_{Dh}^{\frac{10}{12}} S_A \tag{S19}$$

$$(4a) N_{sprL1,t+1} = N_{spr0,t} G_{spr0} E_{Dh}^{\frac{5}{12}} E_L^{\frac{7}{12}} S_A \tag{S20a}$$

$$(4b) N_{sumL1,t+1} = N_{sum0,t} G_{sum0} E_{Dl}^{\frac{2}{12}} E_{Dh}^{\frac{6}{12}} E_L^{\frac{4}{12}} S_A \tag{S20b}$$

$$(5) \text{Egg}_{Lspr,t+1} = (N_{sprL1,t} + N_{sumL1,t} + N_{sprL2+,t} + N_{sumL2+,t}) E_L^{\frac{4}{12}} S_A^{\frac{4}{12}} R_{Lspr} \quad (\text{S21})$$

$$(6) \text{Egg}_{Sspr,t+1} = (N_{spr,t} + N_{sprS1,t} + N_{sumS1,t} + N_{sprS2+,t} + N_{sumS2+,t}) E_{Dh}^{\frac{4}{12}} S_A^{\frac{4}{12}} R_{Sspr} \quad (\text{S22})$$

$$(7) \text{Egg}_{Lsum,t+1} = (N_{spr,t} g_0 + N_{sprS1,t} G_{spr1} + N_{sumS1,t} G_{sum1} + N_{sprS2+,t} G_{spr2} + N_{sumS2+,t} G_{sum2}) E_{Dh}^{\frac{5}{12}} E_L^{\frac{2}{12}} S_A^{\frac{7}{12}} R_{Lsum} + (N_{sprL1,t} + N_{sumL1,t} + N_{sprL2+,t} + N_{sumL2+,t}) E_L^{\frac{7}{12}} S_A^{\frac{7}{12}} R_{Lsum} \quad (\text{S23})$$

$$(8) \text{Egg}_{Ssum,t+1} = [N_{spr,t} (1 - g_0) + N_{sprS1,t} (1 - G_{spr1}) + N_{sumS1,t} (1 - G_{sum1}) + N_{sprS2+,t} (1 - G_{spr2}) + N_{sumS2+,t} (1 - G_{sum2})] E_{Dl}^{\frac{1}{12}} E_{Dh}^{\frac{6}{12}} S_A^{\frac{7}{12}} R_{Ssum} \quad (\text{S24})$$

$$(9) N_{spr0,t+1} = (\text{Egg}_{Lspr,t+1} + \text{Egg}_{Sspr,t+1}) S_{spr} S_A^{\frac{6}{12}} E_{Dh}^{\frac{4}{12}} \quad (\text{S25})$$

$$(10) N_{sum0,t+1} = (\text{Egg}_{Lsum,t+1} + \text{Egg}_{Ssum,t+1}) S_{sum} S_A^{\frac{3}{12}} E_{Dh}^{\frac{1}{12}} \quad (\text{S26})$$

The population growth rate  $\lambda$  increased with  $E_{Dh}$  more quickly than with  $E_{Dl}$  (Fig. S5 in Section C; see Fig. 4 in the main paper for a corresponding result of the original model). Therefore, elasticity of  $\lambda$  in response to  $E_{Dh}$  is larger than that to  $E_{Dl}$ .

#### B4. Age-dependent survivability

Here, we used different intrinsic survivability for ages 0, 1, and 2+ as  $S_{A0}$ ,  $S_{A1}$ , and  $S_{A2+}$ , respectively, instead of  $S_A$  in Eqs. (1) to (10) in the main paper (converted equations not shown). The elasticity of  $\lambda$  was larger in response to survival at younger ages (Fig. S6 in Section C). When we assumed that intrinsic survivability decreases with age, such as  $S_{A0} = 0.708$ ,  $S_{A1} = 0.472$ , and  $S_{A2+} = 0.236$  (note that the average survivability of a lifetime is the same as the original estimate  $S_A$ ),  $\lambda$  increased to exceed 1 ( $\lambda = 1.24$ ). Next, we alternated the values of  $S_{A2+}$  and  $S_{A0}$  to describe increasing survivability with age. This ascending order of survival corresponds to lower survival in early life stages, which is often observed in many organisms. We then obtained  $\lambda = 0.53$  (see also Fig. S3 in Section C for other results obtained from this model).

#### B5. Fluctuating survivability

No study has estimated the annual (or any other time period) variation of  $S_A$  for the population of *Oratosquilla oratoria* in Tokyo Bay. To present an example of how our model is affected by variation in  $S_A$ , we used the annual total of LPUE data from 1991 to 2003 (Shimizu 2004, Kodama et al. 2006c) as a reference for the range of variation. We should note, however, that LPUE shows only the number of individuals at the body size of fishery targets, and the dataset also contains fluctuations due to observation error. The coefficient of variance (CV) of LPUE data was 0.27. The same CV value was obtained for  $S_A$  when we assumed that the mean was equal to the originally estimated value of  $S_A$ ,  $SD = 0.13$ . We calculated the number of eggs, recruitments, and  $\lambda$  using  $S_A = [\text{mean} + SD]$  and  $[\text{mean} - SD]$ , using the results as the upper and lower limits of the range, respectively. In both scenarios with  $S_A = \text{mean} \pm SD$ , spawning in the summer and by small individuals largely contributed to the numbers of eggs and recruitments, as in the original model (Fig. S3 in Section C). The population growth rate  $\lambda$  exhibited a large difference between the scenarios with  $S_A = \text{mean} \pm SD$ , indicating that a large fluctuation in intrinsic survival would also cause the population dynamics to strongly fluctuate. Therefore, in addition to increasing the accuracy of the  $S_A$  estimate as mentioned in the ‘Discussion’ of the main paper, monitoring its natural variation should improve our understanding of *O. oratoria* population dynamics.

### C. ESTIMATION OF MATURATION FREQUENCIES IN 1987

This paper seeks to estimate the effect of the reduction in size at maturation in *Oratosquilla oratoria* in Tokyo Bay. To demonstrate the reduction, we compared the sizes at which 50% of the population became reproductively mature in 1987 and 2002. The data in 2002 were obtained from Kodama et al. (2004). Here, we calculated the size at 50% maturity in 1987 from published data (Ohtomi et al. 1988). The published time series of mature female frequencies at each body length (BL) class of (1)  $8 \leq BL < 10$ , (2)  $10 \leq BL < 12$ , and (3)  $BL \geq 12$  cm in 1987 (Ohtomi et al. 1988) were reanalyzed to obtain the size class at which 50% of the population matured (Fig. S1). The published

data were summarized in a figure with sampling dates on the horizontal axis and the frequency of mature females on the vertical axis. The frequencies were plotted for each size class. We scanned the figure and obtained the maturation rates. The size at 50% maturation was  $10 \leq BL < 12$  cm. For the maturation rates in 2002, we scanned monthly histograms of the occurrence of ovaries at 6 developmental stages for the size classes: (1)  $7 \leq BL < 8$ , (2)  $8 \leq BL < 9$ , (3)  $9 \leq BL < 10$ , (4)  $10 \leq BL < 11$ , (5)  $11 \leq BL < 12$ , and (6)  $BL \leq 12$  cm, with each sample size as in Kodama et al. (2004). We assumed that ovaries were mature at developmental stages 3 to 6 (primary vitellogenesis, secondary vitellogenesis, maturation, and spent, respectively). Kodama et al. (2004) stated that the size class at 50% maturation was  $7 \leq BL < 8$  cm. Our reorganized results are shown in Fig. S1b,c.

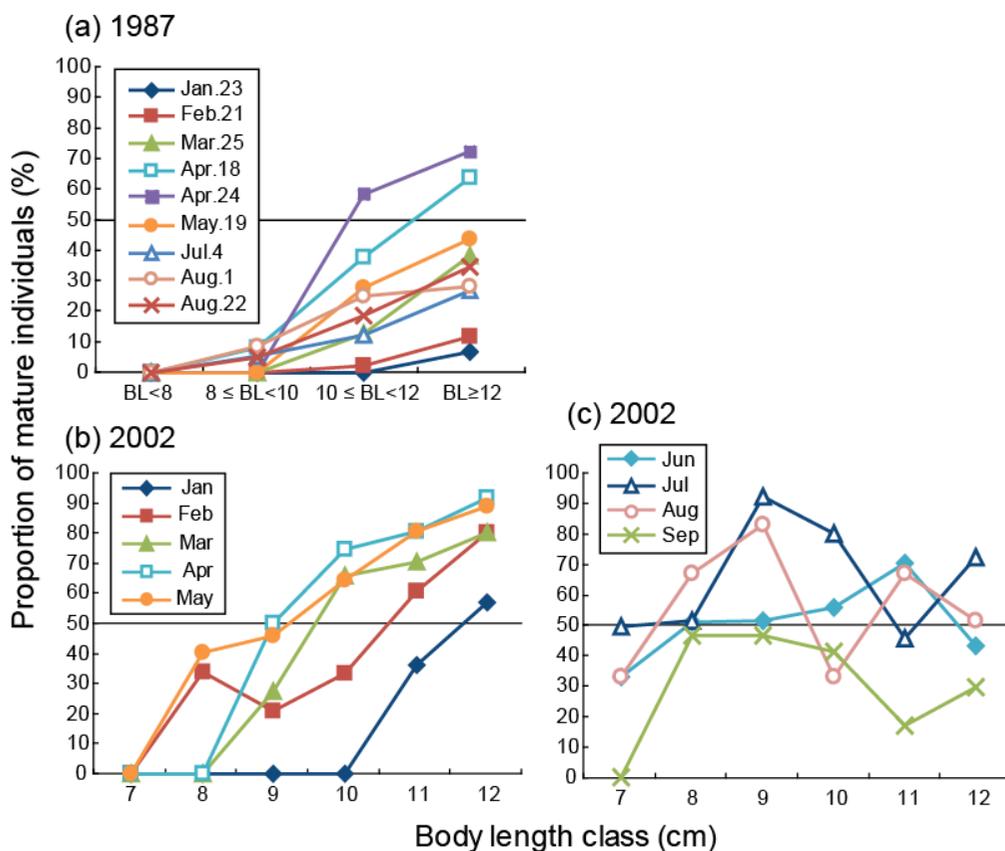


Fig. S1. *Oratosquilla oratoria*. Proportion of mature individuals in the female population at each body length class (a) on each sampling date in 1987 (data from Ohtomi et al. 1988) and during each monthly sampling period in (b) early and (c) late 2002. BL: body length. See text in Section C for detailed calculations

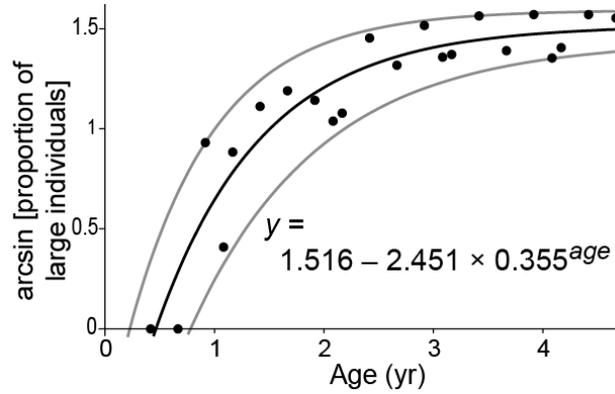


Fig. S2. *Oratosquilla oratoria*. Arc-sine-transformed proportion of large ( $\geq 10$  cm) individuals, calculated from age-size distribution data of Kodama et al. (2005, 2006b), and estimated fishing mortality (details of calculations are described in Section A2). Asymptotic regression curves with estimated parameter values (black line; equation is shown in the figure) and  $\pm$  SE of parameter estimates (gray lines)

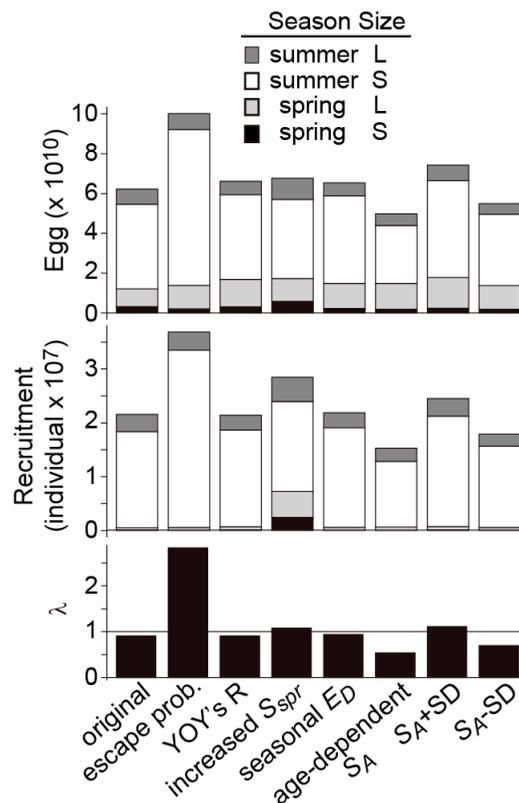


Fig. S3. *Oratosquilla oratoria*. Number of eggs and recruitments and population growth rate  $\lambda$  expected from each of the following simulation scenarios: (1) original model shown in the text (Eqs. 1–10 in the main paper), (2) size-dependent escape probability, (3) the same reproductive parameter for the spring spawning by spring-spawned young of the year (YOY) as the summer spawning by summer-spawned YOY (i.e. using  $R_{Ssum}$  instead of  $R_{Sspr}$  for only  $N_{spr}$  in Eq. 6 in the main paper), (4)  $S_{spr}$  increased to the same level as  $S_{sum}$ , (5) seasonal mortality of discarded individuals, (6) intrinsic survivability increasing with age, (7) intrinsic survivability increased by its SD, and (8) intrinsic survivability reduced by its SD. Note that assumptions and/or parameter values are hypothetical and are not supported by data for models (2) to (8), except for (5). See ‘Discussion’ in the main paper and Section B for details of the model scenarios



Fig. S4. Escape probability  $E(G)$  shown in Tokai et al. (1990) as a function of body length  $G(\tau)$  calculated from the somatic growth curve of Hamano & Matsuura (1987) (solid line) and the 25<sup>th</sup> percentile of data from Kodama et al. (2005, 2006b) (dashed line), where:

$$E(G) = \begin{cases} 1 - (-0.09189 + 0.1677r - 0.09515r^2 + 0.03514r^3) & \text{for } 1.05 \leq r < 3.34 \\ 1 - (-13.90 + 9.768r - 2.132r^2 + 0.1548r^3) & \text{for } 3.34 \leq r < 4.39 \end{cases}$$

where  $r = (\text{body length [mm]} - 5.07)(\text{mesh size [mm]} - 3.65)$ , and  $\text{mesh size} = 35$  mm. The curve of Hamano & Matsuura (1987) was described as:

$\text{carapace length [mm]} =$

$$\begin{cases} \left( (\sqrt{f})^{-1} \ln \left[ 2f(\tau' - c) + 2\sqrt{f^2(\tau' - c)^2 + fa} \right] + d \right) & \text{for } \tau' < 95.4 \\ 11.9473 + 0.0319893\tau' & \text{for } \tau' \geq 95.4 \end{cases}$$

where  $\tau'$  denotes days after settlement,  $a = 32.7066$ ,  $c = 47.0217$ ,  $d = 5.10445$ , and  $f = 0.0767384$ . We should note that in our calculation, we converted the original curve described as carapace length at each day since settlement into body length (mm) at each month after settlement assuming that 1 mo = 30 d and  $\text{body length} = 4.3401 \text{ carapace length}^{0.9842}$  (Hamano 2006)

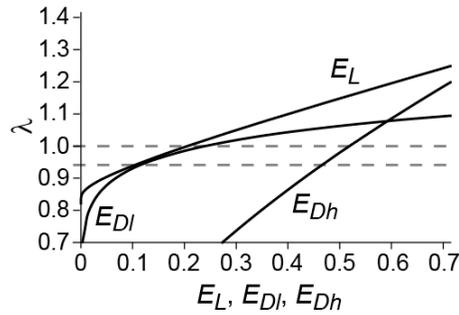


Fig. S5. *Oratosquilla oratoria*. Population growth rate  $\lambda$  as a function of survivability against discarding in July to August ( $E_{Dl}$ ) and in other months ( $E_{Dh}$ ), and against landing ( $E_L$ ) (solid lines). Dashed lines describe  $\lambda = 0.94$  (the value estimated from the converted model) and  $\lambda = 1$

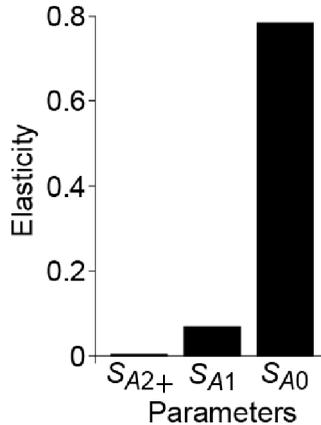


Fig. S6. *Oratosquilla oratoria*. Elasticity of the population growth rate  $\lambda$  in response to intrinsic survival at age 0 ( $S_{A0}$ ), age 1 ( $S_{A1}$ ), and age 2+ ( $S_{A2+}$ )

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