

**Appendix A.** Description of the fully size-structured model and parameter domains of ontogenetic asymmetry and ontogenetic symmetry.

### A.1 Description of the fully size-structured population model

Here we briefly describe the size-structured model that was used to generate the model results in figures 1, 3 and 4. For full details of the model specification and model analysis we refer to De Roos et al. (2013). The size-structured model assumes juveniles to be born at a fixed size, allocate their entire net production into somatic growth and mature at a fixed size. Adults are assumed to allocate their entire net production into reproduction. Changes in juvenile size distribution are hence a result of individual food-dependent growth, mortality, inflow of newborn individuals through reproduction and outflow of individuals through maturation.

The mass-specific ingestion rates of resources by juveniles ( $\omega_J$ ) and adults ( $\omega_A$ ) are described by the functions:

$$\omega_J(R) = (2 - q)M_c \frac{R}{H_c + R}$$

$$\omega_A(R) = qM_c \frac{R}{H_c + R}$$

Juveniles and adults hence differ in their mass-specific intake rate via the constant  $q$ . If  $q > 1$  adult mass-specific intake is higher than that of juveniles whereas the reverse is the case for  $q < 1$ . We follow Yodzis and Innes (1992) in assuming that maintenance rates are directly proportional to body mass of individual consumers. The balance between assimilation through feeding and maintenance costs for juveniles and adults, the net production of biomass ( $v_J$ ,  $v_A$ ) respectively, will hence per unit of biomass equal:

$$v_J(R) = \sigma_c \omega_J(R) - T_c$$

$$v_A(R) = \sigma_c \omega_A(R) - T_c$$

As we have assumed that the conversion efficiency into growth (for juveniles) and reproduction (adults) is the same and that maintenance requirements are directly proportional to body mass, the only factor that energetically differentiates juveniles and adults on a per unit of body mass is  $q$ . Juveniles will thereby have a higher net-production of biomass for  $q < 1$ , whereas adults will have a net-production of biomass for  $q > 1$ . Juveniles will by definition only use their net biomass production to grow in somatic mass. For simplicity we assume that adults use their net biomass production entirely to reproduce.

Since the consumer population may exhibit cohort cycles involving temporary resource depression we have to consider the possibility that individuals starve. We handle this possibility by assuming that juvenile growth and adult reproduction equal zero when net production is negative. Individual juvenile growth rates in biomass, denoted by  $g(R, s)$ , and

adult fecundity in terms of the number of newborns produced, denoted by  $b(R, s_m)$  with  $s_m$  the size at maturation, are therefore both restricted to non-negative values and follow:

$$g(R, s) = v_j^+(R)s = \begin{cases} \left( \sigma_c(2-q)M_c \frac{R}{H_c + R} - T_c \right) s & \text{if } R > \frac{H_c}{\sigma_c(2-q)M_c/T_c - 1} \\ 0 & \text{otherwise} \end{cases}$$

$$b(R, s_m) = v_A^+(R) \frac{s_m}{s_b} = \begin{cases} \left( \sigma_c q M_c \frac{R}{H_c + R} - T_c \right) \frac{s_m}{s_b} & \text{if } R > \frac{H_c}{\sigma_c q M_c/T_c - 1} \\ 0 & \text{otherwise} \end{cases}$$

A.2. Note that the functions  $v_j^+(R)$  and  $v_A^+(R)$  are defined identical to  $v_j(R)$  and  $v_A(R)$ , respectively, but restricted to non-negative values. Also note that the multiplication with the ratio of adult size over birth size ( $s_m/s_b$ ) takes care of converting the mass-specific reproduction rate in terms of biomass,  $v_A^+(R)$ , to the number of offspring produced, each of which requires an investment of biomass equal to  $s_b$ . Juveniles and adults are assumed to be exposed to a background mortality equal to  $(2-p)\mu$  and  $p\mu$ , respectively. Furthermore, when food intake is insufficient to cover maintenance requirements, juveniles and adults suffer from additional starvation mortalities equal to  $-v_j(R)$  and  $-v_A(R)$ , respectively. The total death rate of juveniles ( $d_j(R)$ ) and adults ( $d_A(R)$ ), respectively, are hence given by:

$$d_j(R) = \begin{cases} (2-p)\mu & \text{if } R > \frac{H_c}{\sigma_c(2-q)M_c/T_c - 1} \\ (2-p)\mu - v_j(R) & \text{otherwise} \end{cases}$$

$$d_A(R) = \begin{cases} p\mu & \text{if } R > \frac{H_c}{\sigma_c q M_c/T_c - 1} \\ p\mu - v_A(R) & \text{otherwise} \end{cases}$$

Under non-starvation conditions juveniles and adults hence differ in mortality via the constant  $p$  with juveniles and adults experiencing a higher mortality if  $p < 1$  and  $p > 1$ , respectively.

To specify the model at the population level, we denote the size distribution of juveniles over the juvenile size range  $s_b \leq s \leq s_m$  as  $c(t, s)$  and the total number of adult consumer with body size  $s = s_m$  as  $C(t)$ . The dynamics of the consumer-resource system can now be described by 4 population-level equations. The first one describes the change in the size distribution of juveniles ( $c(t, s)$ ) as a result of individual growth and mortality:

$$\frac{\partial c(t, s)}{\partial t} + \frac{\partial g(R, s)c(t, s)}{\partial s} = -d_j(R)c(t, s)$$

The second equation is a boundary condition for the partial differential equation above, which accounts for the increase in juvenile numbers as a result of reproduction of offspring:

$$g(R, s_b)c(t, s_b) = b(R, s_m)C$$

The third equation describes the dynamics of adult consumer number as a balance between the maturation of juvenile individuals into adults and adult mortality:

$$\frac{dC}{dt} = g(R, s_m)c(t, s_m) - d_A(R)C$$

The final equation describes the change in resource density as a result of resource production and foraging by consumers:

$$\frac{dR}{dt} = G(R) - \omega_j(R) \int_{s_b}^{s_m} sc(t, s)ds - \omega_A(R)s_m C$$

We model the internal dynamics of the resource using semichemostat resource dynamics:

$$G(R) = \rho(R_{max} - R)$$

where  $R_{max}$  is the resource density in the absence of consumers and  $\rho$  is the resource turn over rate. This choice for the resource dynamics ensures that its productivity is constant and hence independent of resource density itself, such that any increase in consumer biomass results exclusively from a more efficient use of available resources.

For simulating the dynamics over time we used the Escalator Boxcar Train (EBT) method, which is a numerical method specifically designed to handle the numerical integration of the equations that occur in physiologically structured models (De Roos and Persson 2013). For computation of equilibrium densities, such as shown in Figure 1, however, the model can also be reformulated into a system of 3 differential equations, one describing the dynamics of the resource biomass  $R$ , one describing the dynamics of juvenile biomass  $J$  and one describing the dynamics of adult biomass  $A$ :

$$\frac{dR}{dt} = G(R) - \omega_j(R)J - \omega_A(R)A$$

$$\frac{dJ}{dt} = v_A^+(R)A + v_j(R)J - \gamma(v_j^+(R), d_j(R))J - d_j(R)J$$

$$\frac{dA}{dt} = \gamma(v_j^+(R), d_j(R))J - d_A(R)A$$

where  $\gamma(v_j^+(R), d_j(R))$  is the mass-specific rate by which juvenile biomass matures into adult biomass. From this equation system it is also clear that adults invest their entire net-biomass production into reproduction. If we want the model to obey the underlying individual-level assumptions that juvenile energetics is proportional to body size and that juveniles mature on reaching a size threshold, it can be shown that the rate by which juveniles mature into adults  $\gamma(v_j^+(R), d_j(R))$  should be defined as:

$$\gamma(v_j^+(R), d_j(R)) = \frac{v_j^+(R) - d_j(R)}{1 - z^{1-d_j(R)/v_j^+(R)}}$$

(De Roos and Persson 2013) where  $z$  is the ratio of birth mass to mass at maturation. This expression shows that an increase in juvenile net-biomass production will have a positive effect on maturation rate while an increase in mortality will have a negative effect, and that an increase in  $z$  will have a positive effect.

Under equilibrium conditions the system of 3 ordinary differential equations is fully identical to the fully size-structured presented before (De Roos et al. 2008). This reformulation of the model into ordinary differential equations significantly simplifies the analysis of the effects of food-dependent reproduction, mortality and development on community structure as it circumvents the use of the mathematically much more challenging partial differential equations while nonetheless providing exactly the same answers. Under ontogenetic symmetry ( $q=1$  and  $p=1$ ) juvenile and adult ingestion become identical,  $\omega_j(R) = \omega_A(R) = \omega_C(R) = M_C R / (H_C + R)$  (cf. eq.(1) in the main text), just like the juvenile and adult net-biomass production rates,  $v_j(R) = v_A(R) = v_C(R) = \sigma_C \omega_C(R) - T$  (cf. eq.(2) in main text), and the juvenile and adult mortality rate,  $d_j(R) = d_A(R) = d_C$ . Under these conditions the above system of ordinary differential equations can be rewritten into a system of 2 ordinary differential equations (eqs. (3) in main text) for total resource and total consumer biomass,  $C = J + A$ , which is identical to the Yodzis and Innes (1992) model.

## A.2 Domains of ontogenetic asymmetry and ontogenetic symmetry

Figure A1 shows the occurrence of overcompensation and cohort cycles as a function of ontogenetic asymmetry in net biomass production ( $q$ ) and mortality ( $p$ , left panel) and the birth/maturation size ratio ( $z = s_b/s_m$ , right panel). Overall, both panels show that overcompensation in either juvenile or adult biomass occurs widely whereas the parameter domain with predictions resembling ontogenetic symmetry (i.e., no overcompensation) is very restricted. The domains with adult overcompensation and adult-driven cycles decrease when mortality is increasingly biased toward juveniles ( $p < 1$ ), while the domains with juvenile overcompensation and without overcompensation increase. Varying the birth/maturation size ( $z$ ) ratio has no effect on the occurrence of overcompensation. The domain of adult-driven cycles is largely unaffected by  $z$ , whereas juvenile-driven cycles disappear for  $z \gtrsim 0.2$  as a consequence

of the decreased time delay between birth and maturation with increased  $z$  (De Roos and Persson 2013).

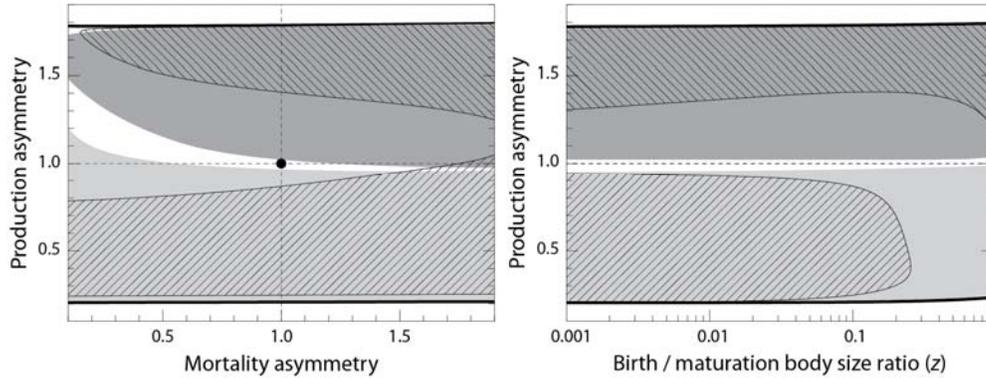


FIG. A1. Parameter domains with overcompensation in juvenile (light grey region) and adult biomass (dark grey region) as well as juvenile-driven (diagonally hatched region) and adult-driven cohort cycles (cross-diagonally hatched region) as a function of ontogenetic asymmetry in net biomass production ( $q$ ) and ontogenetic asymmetry in mortality ( $p$ , left panel) and with ontogenetic symmetry in mortality ( $p=1.0$ , right panel) as a function of ontogenetic asymmetry in net biomass production and the body size ratio at birth and maturation ( $z$ ). Thick black lines represent the consumer existence boundaries. Thin dashed lines reflect ontogenetic symmetry in net biomass production ( $q=1.0$ , left and right panels) and mortality ( $p=1.0$ , left panel only).  $z=0.1$  (left panel). Other parameters:  $s_b=0.1$ ,  $s_m=1.0$ ,  $H_C=3.0$ ,  $M_C=1.0$ ,  $T_C=0.1$ ,  $\sigma_C=0.5$ ,  $\mu=0.015$ ,  $\rho=0.1$  and  $R_{max} = 100$ .

#### LITERATURE CITED

- De Roos, A. M., J. A. J. Metz, and L. Persson. 2013. Ontogenetic symmetry and asymmetry in energetics. *Journal of Mathematical Biology*:(on line).
- De Roos, A. M., and L. Persson. 2013. *Population and Community Ecology of Ontogenetic Development*. Princeton University Press, Princeton, New Jersey, USA.
- De Roos, A. M., T. Schellekens, T. Van Kooten, K. Van De Wolfshaar, D. Claessen, and L. Persson. 2008. Simplifying a physiologically structured population model to a stage-structured biomass model. *Theoretical Population Biology* 73:47–62.
- Yodzis, P., and S. Innes. 1992. Body size and consumer resource dynamics. *American Naturalist* 139:1151–1175.