A. van Leeuwen, M. Huss, A. Gårdmark, and A. M. de Roos. 2014. **Ontogenetic specialism in predators with multiple niche shifts prevents predator population recovery and establishment.** Ecology VOL: pp-pp.

APPENDIX A. **A size-structured predator-prey model with two ontogenetic niche shifts in the predator: Details of model variables, parameters and functions**

In this appendix we only give the formal definition of the discrete-continuous-time model since a detailed description and justification for the model structure and parameterization is given in Appendix A in van Leeuwen et al. (2013). The model variables are listed in Table A1, individual level model functions are given in Table A2, the model parameterization is given in Table A3, and dynamic equations are listed in Table A4.

TABLE A1. System variables, *i*-state variables and derived variables.

Symbol	Unit	Expression	Description/Note
System variables			
S_i	$nr \cdot m^{-3}$		Number of prey individuals in cohort *i*
C_j	$nr \cdot m^{-3}$		Number of predator individuals in cohort *j*
Z_S	$g \cdot m^{-3}$		Resource for prey
Z_C	$g \cdot m^{-3}$		Resource for juvenile predator
B	$g \cdot m^{-2}$		Intermediate resource for predator
***i*-state variables**			
a	d		Age
x	g		Irreversible mass
y_f	g		Fat reserves
y_g	g		Gonadal mass
Derived variables			
y	g	$y_f + y_g$	Total reversible mass
w	g	$x + y$	Total body weight
l	cm	$\lambda_1 \left(x\left(1+q_J\right)\right)^{\lambda_2}$	Total body length

Note: In the definition of *i*-state variables and derived variables the species indices are left out for notational clarity.

TABLE A2. Functions related to individual level processes. Index *i* refers to cohort *i* in the prey population; index *j* refers to cohort *j* in the predator population.

Nr	Description	Function	Note
	Predator		
1	Foraging time on prey	$t_P(l_j) = \begin{cases} 0 \\ \pi Q(l_j, \underline{l}_P, l_P) \end{cases}$	if $l_j < l_P$ otherwise
2	Foraging time on intermediate resource	$t_B(l_j) = \begin{cases} 0 \\ (1 - t_P(l_j))Q(l_j, \underline{l}_B, l_B) \end{cases}$	if $l_j < l_B$ otherwise
3	Attack rate juvenile resource	$A_{CZ}(l_j) = \chi_1 l_j^{\chi_2}$	
4	Attack rate intermediate resource	$A_{CB}(l_j) = \psi_1 l_j^{\psi_2}$	
5	Optimal prey attack rate on	$A_{CF}(l_j) = t_P(l_j)\gamma_1 l_i^{\gamma_2}$	
6	Digestion time	$H_C(l_j) = \xi_1 l_j^{\xi_2}$	
7	Maintenance requirements	$M_C(w_j) = \rho_1 w_j^{\rho_2}$	
8	Realized prey attack rate	$T_{CF}(l_j, l_i) = \begin{cases} A_{CF}(l_j)\dfrac{l_i - \delta l_j}{(\phi - \delta)l_j} \\ A_{CF}(l_j)\dfrac{\varepsilon l_j - l_i}{(\varepsilon - \phi)l_j} \\ 0 \end{cases}$	if $\delta l_j < l_i \leq \varphi l_j$ if $\varphi l_j < l_i < \varepsilon l_j$ otherwise
9	Encounter with juvenile resource	$E_{CZ}(l_j) = \begin{cases} A_{CZ}(l_j)Z_C \\ 0 \end{cases}$	if $l_j < l_P$ otherwise
10	Encounter intermediate resource	$E_{CB}(l_j) = \begin{cases} A_{CB}(l_j)B \\ (1 - t_P(l_j))A_{CB}(l_j)B \end{cases}$	if $l_j < l_P$ otherwise
11	Prey encounter	$E_{CF}(l_j) = \sum_i T_{CF}(l_j, l_i) w_i \dfrac{S_i}{V}$	
12	Total encounter	$E_C(l_j) = E_{CB}(l_j) + E_{CF}(l_j)$	
13	Intake juvenile resource	$I_{CZ}(l_j) = (1 - t_B(l_j))\dfrac{E_{CZ}(l_j)}{1 + H_C(l_j)E_{CZ}(l_j)}$	

14	Intake intermediate resource	$I_{CB}(l_j) = \begin{cases} t_B(l_j)\dfrac{E_{CB}(l_j)}{1+H_C(l_j)E_{CB}(l_j)} & \text{if } l_j < l_P \\ \dfrac{E_{CB}(l_j)}{1+H_C(l_j)E_C(l_j)} & \text{otherwise} \end{cases}$
15	Prey intake	$I_{CF}(l_j) = \dfrac{E_{CF}(l_j)}{1+H_C(l_j)E_C(l_j)}$
16	Total food intake	$I_C(l_j) = \begin{cases} I_{CZ}(l_j)+I_{CB}(l_j) & \text{if } l_j < l_P \\ I_{CB}(l_j)+I_{CF}(l_j) & \text{otherwise} \end{cases}$
17	Acquired biomass	$N_{CA}(l_j) = \theta_A\, I_C(l_j)$
18	Net biomass production	$N_{CE}(l_j, w_j) = N_{CA}(l_j) - M_C(w_j)$
19	Allocation factor	$k_C(x_j, y_j) = \begin{cases} \dfrac{1}{q+1} & \text{if } \dfrac{y_j}{x_j} > q \\ \left(\dfrac{y_j}{x_j}\right)^2 (1+q)q^2 & \text{otherwise} \end{cases}$
		with $q = q_J$ if $l_j < l_M$ and $q = q_A$ if $l_j \ge l_M$
20	Fecundity	$F_C(y_g) = \begin{cases} \dfrac{\theta_F y_g}{\left(\lambda_1 L_0^{\lambda_2}\right)} & \text{if } l_j > l_M \text{ and } y_j > q_J x_j \\ 0 & \text{otherwise} \end{cases}$
21	Starvation mortality	$d_{CY}(x_j, y_j) = \begin{cases} 0 & \text{if } \dfrac{y_j}{x_j} > q \\ \mu_Y\left(q_Y\dfrac{x_j}{y_j} - 1\right) & \text{otherwise} \end{cases}$
22	Size-dependent mortality	$d_{CJ}(l_j) = \mu_J\, e^{-\left(\frac{l_j}{l_D}\right)^{\lambda_2}}$
23	Total mortality	$d_C(x_j, y_j, l_j) = \begin{cases} \mu_E\, e^{-\frac{l_0}{l_D}} & \text{if } a < a_L \\ \mu_0 + d_{CY}(x_j, y_j) + d_{CJ}(l_j) & \text{otherwise} \end{cases}$

	Prey	
24	Resource attack rate	$A_{SZ}(l_i) = \hat{A}\left(\left(\frac{l_i}{l_{opt}}\right)^{\lambda_2} \exp\left(1-\left(\frac{l_i}{l_{opt}}\right)^{\lambda_2}\right)\right)^{\alpha}$
25	Digestion time	$H_S(l_i) = \xi_1 l_i^{\xi_2}$
26	Maintenance	$M_S(w_i) = \rho_1 w_i^{\rho_2}$
27	Resource encounter	$E_{SZ}(l_i) = A_{SZ}(l_i) Z_S$
28	Acquired biomass	$N_{SA}(l_i) = \theta_A \frac{E_{SZ}(l_i)}{1+H_S(l_i)E_{SZ}(l_i)}$
29	Net biomass production	$N_{SE}(l_i, w_i) = N_{SA}(l_i) - M_S(w_i)$
30	Allocation factor	$k_S(x_i, y_i) = \begin{cases} \frac{1}{q+1} & \text{if } \frac{y_i}{x_i} > q \\ \left(\frac{y_i}{x_i}\right)^2 (1+q)q^2 & \text{otherwise} \end{cases}$ with $q = q_J$ if $l_i < l_M$ and $q = q_A$ if $l_i \geq l_M$
31	Fecundity	$F_S(y_g) = \begin{cases} \frac{\theta_F y_g}{\left(\lambda_1 L_0^{\lambda_2}\right)} & \text{if } l_i > l_M \text{ and } y_i > q_J x_i \\ 0 & \text{otherwise} \end{cases}$
32	Starvation mortality	$d_{SY}(x_i, y_i) = \begin{cases} 0 & \text{if } \frac{y_i}{x_i} > q \\ \mu_Y \left(q_Y \frac{x_i}{y_i} - 1\right) & \text{otherwise} \end{cases}$
33	Size-dependent mortality	$d_{SJ}(l_i) = \mu_J e^{-\left(\frac{l_i}{l_D}\right)^{\lambda 2}}$
34	Predation mortality	$d_{SP}(l_i) = \sum_j \frac{T_{CF}(l_j, l_i) C_j}{1+H_C(l_j)E_C(l_j)}$
35	Total mortality	$d_S(x_i, y_i, l_i) = \begin{cases} \mu_E e^{-\frac{l_0}{l_D}} & \text{if } a < a_L \\ \mu_0 + d_{SY}(x_i, y_i) + d_{SJ}(l_i) + d_{SP}(l_i) & \text{otherwise} \end{cases}$

	Resources	
36	Prey resource growth	$P_{SZ}\left(Z_S\right) = \beta\left(\kappa_P - Z_S\right)$
37	Juvenile resource growth	$P_{CZ}\left(Z_C\right) = \beta\left(\kappa_P - Z_C\right)$
38	Intermediate resource growth	$P_B\left(B\right) = \beta\left(\kappa_B - B\right)$
39	Grazing on prey resource	$G_{SZ}\left(l_i\right) = \sum_i \frac{E_{SZ}\left(l_i\right)}{1+H_S\left(l_i\right)E_{SZ}\left(l_i\right)} \frac{S_i}{V}$
40	Grazing on juvenile resource	$G_{CZ}\left(l_j\right) = \sum_j \frac{A_{CZ}\left(l_j\right)Z_C}{1+H_C\left(l_j\right)E_{CZ}\left(l_j\right)} \frac{C_j}{V}$
41	Grazing on intermediate resource	$G_{CB}\left(l_j\right) = \sum_j I_{CB}\left(l_j\right)\frac{C_j}{U}$

Continuous, differentiable, piecewise function

$$Q(n,\underline{n},\overline{n}) = \begin{cases} 0 & \text{for } f(n,\underline{n},\overline{n}) \le 0 \\ \frac{1}{6} f(n,\underline{n},\overline{n})^3 & \text{for } f(n,\underline{n},\overline{n}) \le 1 \\ -\frac{3}{2} f(n,\underline{n},\overline{n}) + \frac{3}{2} f(n,\underline{n},\overline{n})^2 - \frac{1}{3} f(n,\underline{n},\overline{n})^3 + \frac{1}{2} & \text{for } f(n,\underline{n},\overline{n}) \le 2 \\ \frac{9}{2} f(n,\underline{n},\overline{n}) - \frac{3}{2} f(n,\underline{n},\overline{n})^2 + \frac{1}{6} f(n,\underline{n},\overline{n})^3 - \frac{7}{2} & \text{for } f(n,\underline{n},\overline{n}) \le 3 \\ 1 & \text{otherwise} \end{cases}$$

Where: $f(n,\underline{n},\overline{n}) = \frac{3}{2}\frac{n-\underline{n}}{\overline{n}-\underline{n}}$

TABLE A3. Parameter symbols, descriptions, and values.

Subject	**Symbol**	**Unit**	**Description/ Interpretation**	**Value**	**Prey value**	***ref***	**Predator value**	***ref***
Global/ species independent	V	m^3	System volume	1				
	$V:U$	m	Ratio of volume to surface, i.e. average depth	50				
Season	$year$	d	Duration of growing season	250				
	σ	-	Spawning decision date (spawnset)		200		200	
Resources	β	d^{-1}	Resource growth rate	0.1				
	κ_P	$g \cdot m^{-3}$	Carrying capacity prey resource and juvenile resource	varied				
	κ_B	$g \cdot m^{-2}$	Carrying capacity intermediate resource	varied				
Length-weight	λ_1	$g \cdot cm^{-\lambda_2}$	Length-weight conversion constant		5.4	*1*	4.64	*2*
	λ_2	-	Length-weight conversion exponent		0.33	*1*	0.33	*2*
Form of 2nd niche shift	π	-	Partial (1/2) vs complete (1) shift scenario				1 or 1/2	
Ontogeny (and reproduction)	θ_F	-	Gonad – offspring conversion		0.5	*3*	0.5	*3*
	l_0	cm	Size at birth		0.44	*4*	0.39	*5*
	l_D	cm	Characteristic size in size-dependent mortality rate		4.30	*6*	3.68	*6*
	l_M	cm	Length at maturation		9	*7*	30	*8*
	$l_{\underline{B}}$	cm	Length at start foraging on the intermediate resource				5	*9*
	l_B	cm	Length at 50% switch to intermediate resource				10	*9*
	$l_{\underline{P}}$	cm	Length at start predation				15	*9*
	l_P	cm	Length at 50% switch to predation				20	*10*
	a_E	d	Duration of egg stage		6	*11*	15	*5*
	a_L	d	Duration of yolk-sac stage		8	*11*	7	*5*
	a_J	d	Age at first feeding		14	*4*	22	*5*
	q_J	-	Juvenile condition target		0.9	*12-15*	0.7	*16*

	q_A	-	Adult condition target	1.4	*17*	1.4	*18*
	q_G	-	Minimum spawning condition	0.9		0.7	
Handling	ξ_1	$d \cdot g^{-1} \cdot cm^{-\xi_2}$	Allometric scalar for digestion time	167.6	*19*	364.1	*20*
	ξ_2	-	Allometric exponent for digestion time	-1.91	*19*	-2.34	*20*
Metabolism	ρ_1	$g^{(1-\rho_2)} \cdot d^{-1}$	Allometric scalar for maintenance rate	0.03	*21*	0.03	*5,22*
	ρ_2	-	Allometric exponent for maintenance rate	0.8	*21*	0.8	*5,22*
	θ_A	-	Food assimilation efficiency	0.5	*11*	0.6	*23*
Juvenile resource	$\hat{A}$	$m^3 \cdot d^{-1}$	Maximum attack rate juvenile resource	150	*24*		
	l_{opt}	cm	Length at which resource attack rate is maximum	20	*24*		
	α	-	Allometric exponent in juvenile resource attack rate	0.5	*24*		
	χ_1	$m^3 \cdot d^{-1} \cdot cm^{-\chi_2}$	Attack rate scaling constant			0.3	*25*
	χ_2	-	Attack rate scaling exponent			1.8	*25*
Intermediate resource	ψ_1	$m^2 \cdot d^{-1} \cdot cm^{-\psi_2}$	Attack rate scaling constant			0.4	*25*
	ψ_2	-	Attack rate scaling exponent			0.6	*25*
Predation	γ_1	$m^3 \cdot d^{-1} \cdot cm^{-\gamma_2}$	Prey attack rate scaling constant			1.6	*26*
	γ_2	-	Prey attack rate scaling exponent			0.6	*26*
	δ	cm/cm	Minimum prey-predator length ratio			0.08	*27-30*
	φ	cm/cm	Optimum prey-predator length ratio			0.26	*27-30*
	ε	cm/cm	Maximum prey-predator length ratio			0.5	*27-30*
Mortality	μ_E	d^{-1}	Egg and yolk-sac mortality	0.03		0.03	
	μ_J	d^{-1}	Size-dependent mortality	0.03		0.03	
	μ_0	d^{-1}	Background mortality	0.005		0.003	
	μ_Y	d^{-1}	Starvation mortality	0.2	*6*	0.2	
	q_Y	-	Minimum/ starvation condition	0.2	*6*	0.2	*26*

Sources:
1) (ICES 2010)
2) (Coull et al. 1989)
3) (Persson et al. 1998)
4) (Arrhenius and Hansson 1993)
5) (Finn et al. 2002)
6) (Huss et al. 2012)
7) (Grygiel and Wyszynski 2003)
8) (Vainikka et al. 2009)
9) (Hussy et al. 1997)
10) (Sparholt 1994)
11) (Daewel et al. 2008)
12) (Mathers et al. 1994, Folkvord et al. 2000)
13) (Mathers et al. 1994)
14) (Folkvord et al. 2000)
15) (Hjelm et al. 2006)
16) (Siikavuopio et al. 2008)
17) (Rajasilta et al. 2001)
18) (Kjesbu et al. 1996)
19) (De Silva and Balbontin 1974)
20) (Bjornsson et al. 2007)
21) (Peters 1983, Opalinski et al. 2004)
22) (Luna 2008)
23) (Peters 1983)
24) (Hjelm and Persson 2001)
25) Persson, L. 2011 - personal communication
26) (Claessen et al. 2000)
27) (Johansen 2003, Juanes 2003, Pinnegar et al. 2003, Scharf et al. 2000)
28) (Juanes 2003)
29) (Pinnegar et al. 2003)
30) (Scharf et al. 2000)

TABLE A4. Dynamics for the discrete-continuous-time predator-prey model

Predator cohorts	**Within-season processes, taking place in continuous time**	
		Note
Mortality	$\frac{dC_j}{dt} = -d_C(x_j, y_j, l_j)C_j$	
Growth in *x*	$\frac{dx_j}{dt} = \begin{cases} k_C(x_j, y_j)N_{CE}(l_j, w_j) \\ 0 \end{cases}$	if $N_{CE}(l_j, w_j) > 0$ otherwise
Growth in *y*	$\frac{dy_j}{dt} = \begin{cases} \left(1 - k_C(x_j, y_j)\right) N_{CE}(l_j, w_j) \\ N_{CE}(l_j, w_j) \end{cases}$	if $N_{CE}(l_j, w_j) > 0$ otherwise
	Between-season reproduction, taking place in discrete time	
Number of newborns added to new cohort	$F_C(y_g) \cdot C_j$	
Prey cohorts	**Within-season processes, taking place in continuous time**	
		Note
Mortality	$\frac{dS_i}{dt} = -d_S(x_i, y_i, l_i)S_i$	
Growth in *x*	$\frac{dx_i}{dt} = \begin{cases} k_S(x_i, y_i)N_{SE}(l_i, w_i) \\ 0 \end{cases}$	if $N_{SE}(l_i, w_i) > 0$ otherwise
Growth in *y*	$\frac{dy_i}{dt} = \begin{cases} \left(1 - k_S(x_i, y_i)\right)N_{SE}(l_i, w_i) \\ N_{SE}(l_i, w_i) \end{cases}$	if $N_{SE}(l_i, w_i) > 0$ otherwise
	Between-season reproduction, taking place in discrete time	
Number of newborns added to new cohort	$F_S(y_g) \cdot S_i$	
Resources	**Within-season processes, taking place in continuous time**	
Changes in prey resource, Z_S	$\frac{dZ_S}{dt} = P_{SZ}(Z_S) - G_{SZ}(l_i)$	
Changes in juvenile resource, Z_C	$\frac{dZ_C}{dt} = P_{SZ}(Z_S) - G_{CZ}(l_j)$	
Changes in intermediate resource, *B*	$\frac{dB}{dt} = P_B - G_{CB}(l_j)$	

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