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APPENDIX B. Additional robustness analyses and results.

In this appendix we present the results from several modeling analyses that were carried out in order to test the robustness of the presented phenomena. By analyzing eight additional model variants we test whether the major results, i.e., occurrence of alternative stable community states and the occurrence of deterministic extinction following initially successful invasion, as presented in the main text, are robust against changes of the default model. Six of these additional analyses pertain to the duration of the spawning event. One additional test reconsiders the form of the niche shift: we analyze a scenario where maturing predators can keep foraging on the intermediate resource for 10% of their time budget (instead of 0%, in the complete shift scenario, or 50%, in the partial shift scenario). Finally, we vary the size-dependent mortality constant for the predator, a parameter that is known to influence the cycle length through its effect on mortality and hence on somatic growth rates. In this test we use a value for the size-dependent mortality constant that is equal to twice the default value ($\beta\kappa_P$ is 0.06 as opposed to 0.03, see Table A3).

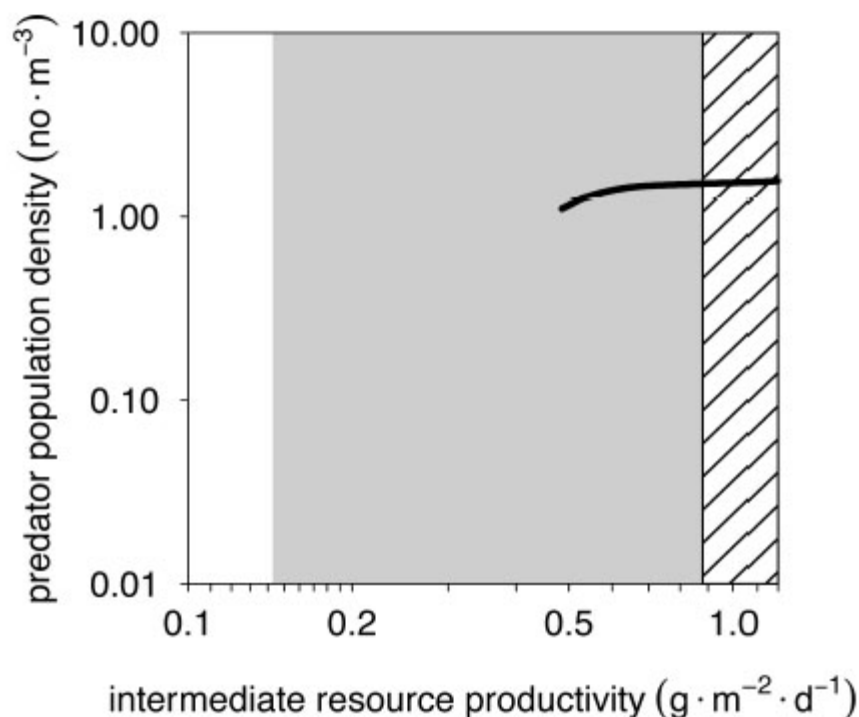


FIG. B1. Average total predator population density (black; average taken over the last 60% of the integration period, calculated for every productivity value) as a function of intermediate resource productivity ($\beta\kappa_P$) in the complete shift scenario with spawning occurring during a twenty-day period instead of in a one-day event. The gray region indicates $RO > 1.0$. The parameter range where invasion is possible, but persistence is not, leads to extinction following invasion ($\beta\kappa_P \sim 0.14-0.45$); the parameter range where persistence is possible but invasion is not leads to bistability (hatched area, $\beta\kappa_B \sim 0.8-1.2$) (Productivity of the prey resource and juvenile resource, $\beta\kappa_B$, is $0.28 \text{ g} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$).

Spawning period

In the default settings we model the yearly spawning event (of both predator and prey) as occurring on the first day of the season (see also Claessen et al. 2000, van de Wolfshaar et al. 2006). Commonly, marine fish species spawn over a more extended period of time (Bagge et al. 1994). To test robustness of our model results against deviations from the simplifying assumption of one-day spawning, we have carried out bifurcation analyses for six additional settings in which the spawning event was distributed over 5, 10, 20, 30, 60, or 90 days (results in Table B1).

TABLE B1. Productivity levels for which predator persistence and invasion boundaries occur in the system under different settings for the duration of the spawning period of both predator and prey. 'Persistence' indicates the boundary at low resource productivity level below which the predator is unable to persist in the system. 'Invasion' indicates the boundary at higher resource productivity level above which the predator is able to persist but unable to recover from low density (region of bistability). These boundaries are results from parameter bifurcations over juvenile and prey resource productivity, $\beta\kappa_B$.

	<u>Low</u> $\beta\kappa_B$			<u>High</u> $\beta\kappa_P$		
		Persistence	Invasion		Persistence	Invasion
Spawning period (d)	$\beta\kappa_B$	$\beta\kappa_B$	$\beta\kappa_B$	$\beta\kappa_B$	$\beta\kappa_P$	$\beta\kappa_P$
1	0.5	0.12	0.72	2.0	0.1	0.14
5	0.5	0.12	0.72	2.0	0.1	0.14
10	0.5	0.12	0.72	2.0	0.1	0.14
20	0.5	0.11	0.91	2.0	0.11	0.16
30	0.5	0.11	1.3	2.0	0.11	0.17
60	na			2.0	0.11	0.22
90	na			2.0	0.12	-

Note: 'na' indicates that the analysis for this setting is absent; '-' indicates that the boundary is absent

The time-distribution of hatching eggs is based on a truncated normal distribution, with the maximum or peak spawning occurring exactly at the midpoint of the spawning period.

Both the occurrence of alternative stable states as well as deterministic extinction following successful invasion are robust model results and show up for all but the 90-day spawning setting (Table B1 and Fig. B1). Figures B2 and B3 show that the single-cohort population dynamics is robust against extending the spawning event, including the characteristic cycle-length for predator and prey. In our study of variation in spawning period length, multiple cohorts were initiated every year (Figs. B2 and B3). But these within-year cohorts converge in size, due to the size-dependent scaling of intake and maintenance rates (small individuals are competitively superior over larger individuals). The size convergence is made visible in Fig. B4, by zooming in to the period over which multiple predator and prey cohorts are initiated and subsequently converge.

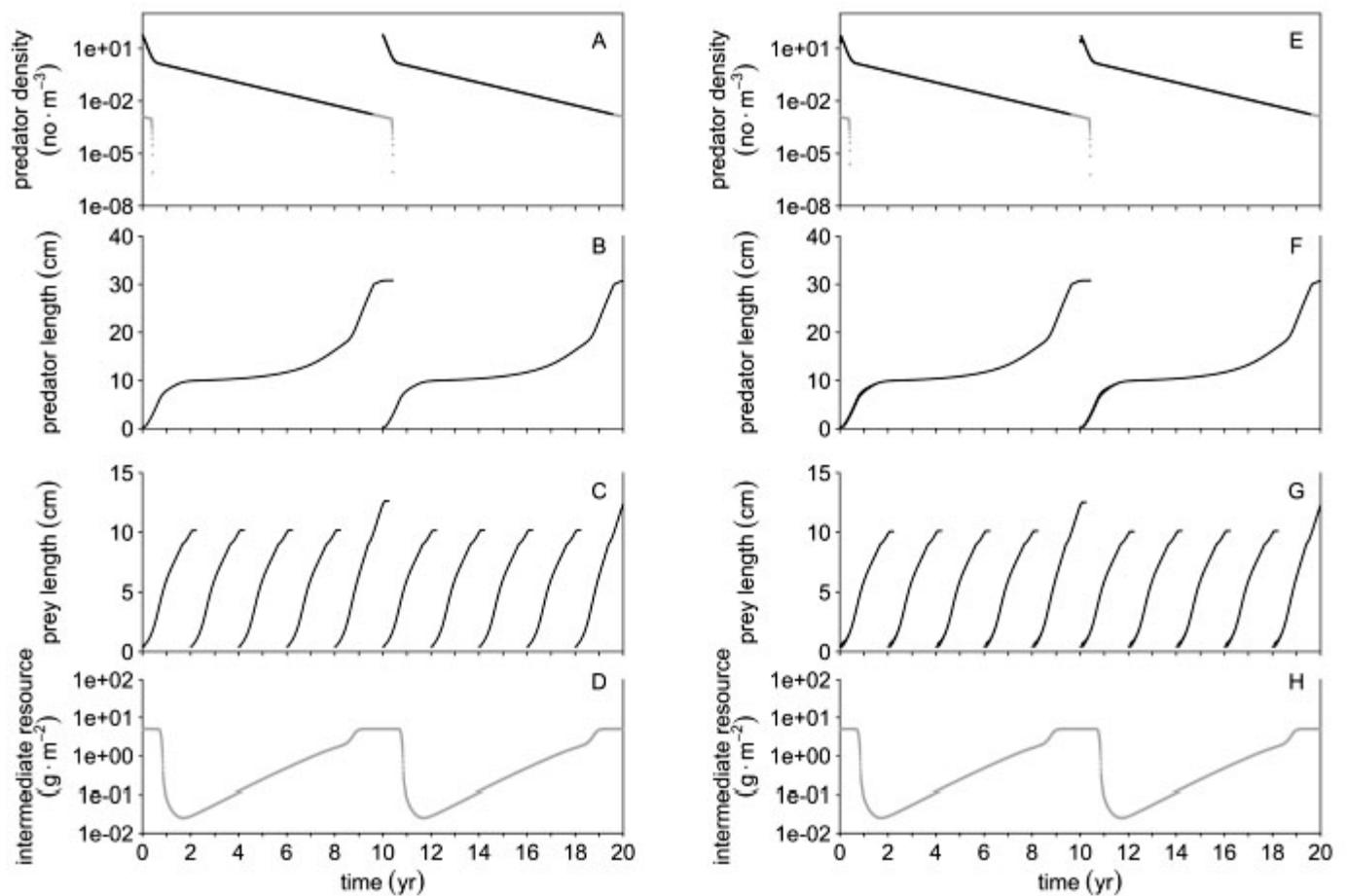


FIG. B2. Model dynamics at productivity levels with prey resource and juvenile resource productivity, $\beta\kappa_P$, of $0.24 \text{ g} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$, and productivity of the intermediate resource, $\beta\kappa_E$, of $0.5 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, showing the predator–prey dynamics in the complete shift scenario, for the default case with the spawning event on the first day of the season (A–D, cf main text Fig. 2E–H), and the case with a period of twenty days during which spawning occurs (E–H). 1st panel: Juvenile (black) and adult (gray) densities in the predator population (A, E); 2nd panel: Predator growth curves (B, F), showing predominantly single-cohort dynamics: continuously, as in the default case (B), or after convergence of the different cohorts that are born during the twenty-day spawning period (F); 3rd panel: Prey growth curves, showing single-cohort dynamics (C), with convergence similar to the predator growth curves in the case of twenty-day spawning period (G); 4th panel: Dynamics of the intermediate resource (D, H).

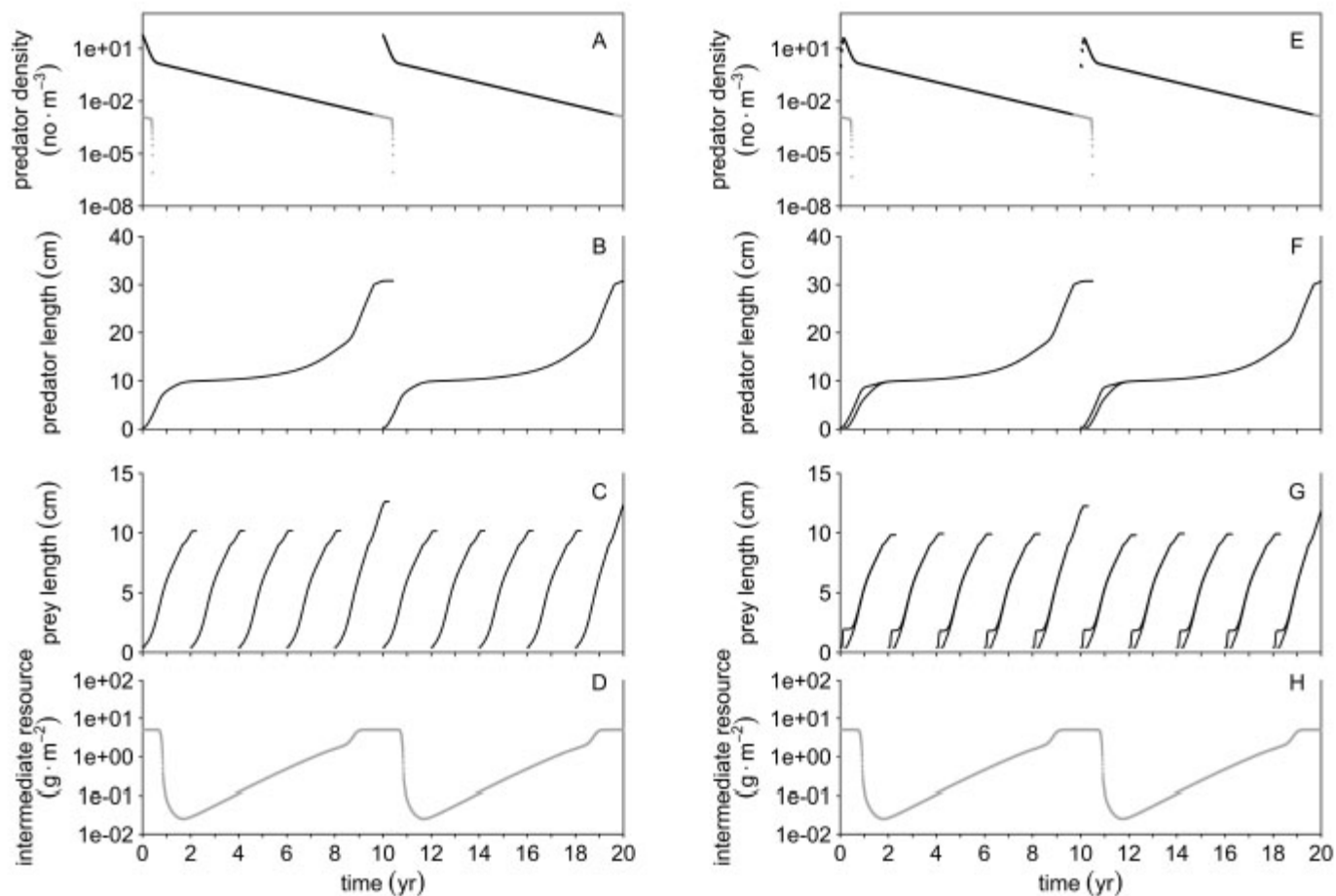


FIG. B3. Model dynamics at productivity levels with prey resource and juvenile resource productivity, $\beta\kappa_P$, of $0.24 \text{ g} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$, and productivity of the intermediate resource, $\beta\kappa_B$, of $0.5 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, showing the predator–prey dynamics in the complete shift scenario, for the default case with the spawning event on the first day of the season (A–D, cf main text Fig. 2E–H), and the case with a period of sixty days during which spawning occurs (E–H). All panels as in Fig. B2 (growth curves in F and G are shown only for the first and last cohort born during the spawning period of sixty days).

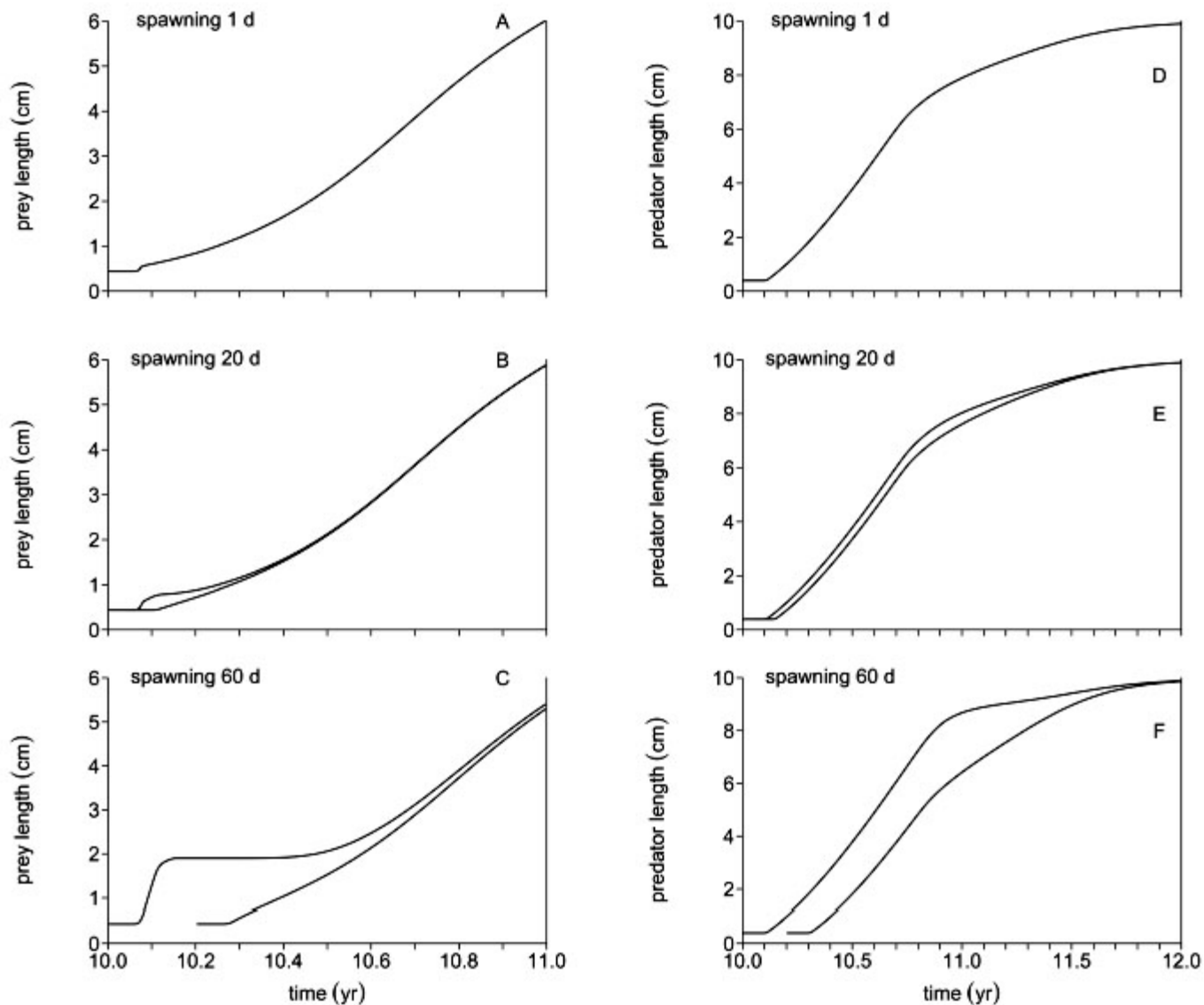


FIG. B4. Model dynamics with prey resource and juvenile resource productivity, β_{K_P} , of $0.24 \text{ g} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$, and productivity of the intermediate resource, β_{K_B} , of $0.5 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, showing length-age curves of prey (left) and predator (right) in the complete shift scenario, for the default case with the spawning event on the first day of the season (A, D, cf Fig. B2, B3), the case with a period of twenty days during which spawning occurs (C, E, cf Fig. B2), and the case with a period of sixty days during which spawning occurs (D, F, cf Fig. B3). For clarity, prey and predator growth curves are shown only for the first and last cohort born during the entire spawning period.

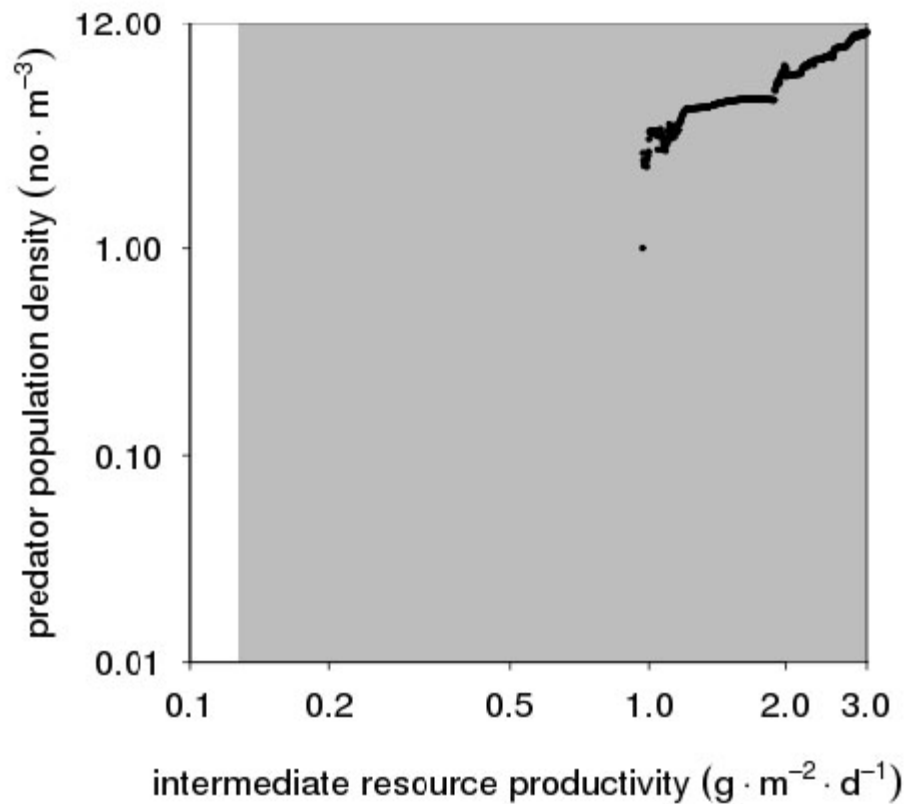


FIG. B5. Average total predator population density (black; average taken over the last 60% of the integration period, calculated for every productivity value) as a function of intermediate resource productivity ($\beta\kappa_B$), in the scenario in which maturing predators can keep foraging on the intermediate resource for 10% of their time budget (instead of 50%, in the partial shift scenario, or 0%, in the complete shift scenario). The grey region indicates $R_0 > 1.0$. (Productivity of the prey resource and juvenile resource, $\beta\kappa_P$, is $0.5 \text{ g} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$).

Form of the ontogenetic niche shift

We studied the scenario where the second niche shift is partial, and predator individuals continue foraging on the intermediate resource for 10% of their time, while they are switching to piscivory. In this scenario, the system dynamics are qualitatively different from the dynamics in the scenario with a complete niche shift. Alternative stable community states do not occur, in which sense the system resembles the partial shift scenario with 50% foraging on the intermediate resource in the predatory niche. Although this analysis points towards the question whether alternative stable community states only occur with a 100% niche-shift to predation, the outcome is still inconclusive, as more analyses are needed to conclude on the structural (in)stability of the alternative stable community states. Deterministic extinction following initially successful invasion does, however, occur also in this setting, in which sense the dynamics are comparable to the complete shift scenario (see Fig. B5). Overall, this scenario, with a partial niche shift, is an intermediate case between the partial and the complete niche shift scenarios as discussed in the main text.

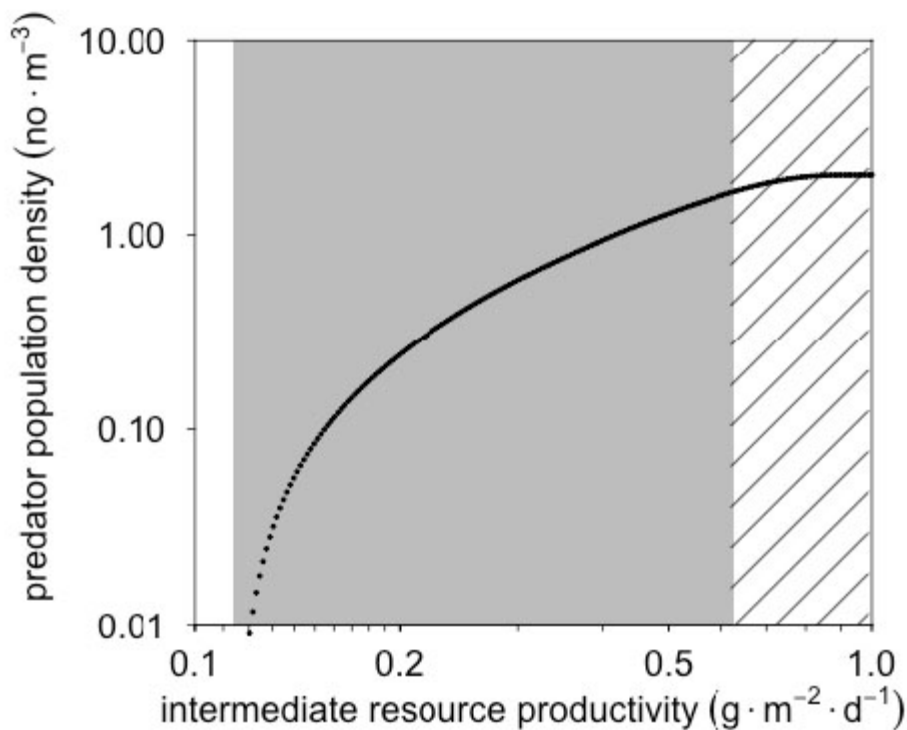


FIG. B6. Average total predator population density (black; average taken over the last 60% of the integration period, calculated for every productivity value) as a function of intermediate resource productivity ($\beta\kappa_B$) in the complete niche shift scenario with increased size-dependent mortality for the predator. The gray region indicates the range of intermediate resource productivity levels where predator invasion is possible, i.e., $R_0 > 1.0$. The parameter range where persistence is possible, but invasion is not, leads to bistability (hatched area, $\beta\kappa_B \sim 0.63-1.0$). (Productivity of the prey resource and juvenile resource, $\beta\kappa_P$, is $0.4 \text{ g} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$).

Size-dependent mortality

Using a higher level of size-dependent mortality for the predator did not qualitatively change the system dynamics (Fig. B6), meaning that both bistability as well as the occurrence of deterministic extinction following initially successful invasion are robust phenomena. Figure B6 shows a thin parameter region with extinction following invasion, because under this parameterization the phenomenon has a stronger dependence on the basal resource productivity (of the prey resource and juvenile resource) than on the intermediate resource productivity. Higher size-dependent mortality changes the cycle length of the predator (Fig. B7), which is due to increased growth rates for small individuals. The time series presented here show that this change in the dynamics does not disrupt the qualitative outcomes of the model.

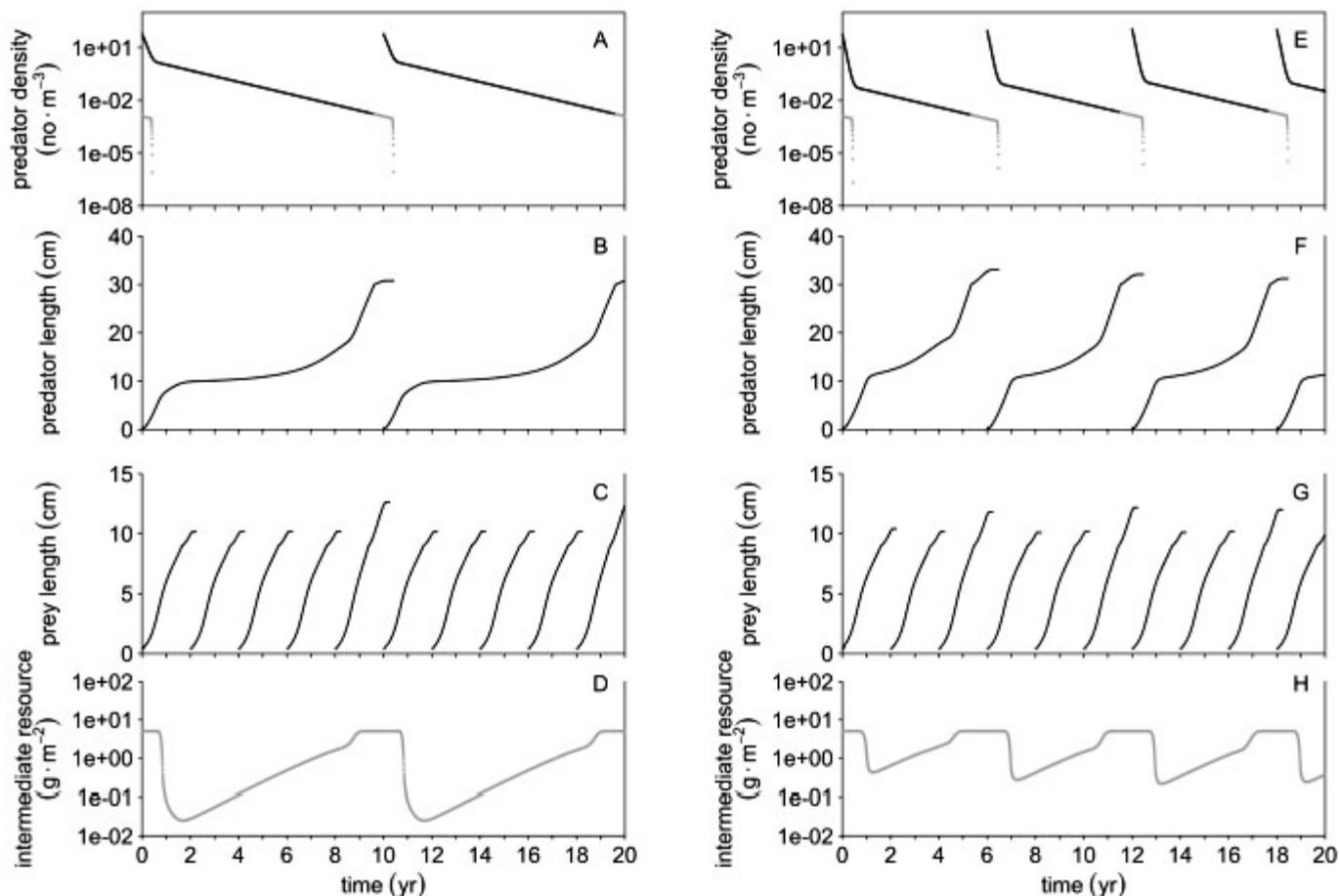


FIG. B7. Model dynamics for two different size-dependent mortality levels in the predator. Left is the default case ($\kappa_z = 0.03$), with default productivity levels (prey resource and juvenile resource productivity, $\beta\kappa_P$, is $0.28 \text{ g} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$; productivity of the intermediate resource, $\beta\kappa_B$, is $0.6 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$); right the case with increased size-dependent predator mortality ($\kappa_z = 0.06$), where prey resource and juvenile resource productivity, $\beta\kappa_B$, is $0.4 \text{ g} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$ and productivity of the intermediate resource, $\beta\kappa_P$, is $0.5 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$). The panels depict the same variables as in Fig. B2.

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