Evolutionary rescue in one dimensional stepping stone models – Supplemental Material

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Appendix A: Demographic effects of migration

There are two demographic effects due to migration. The first one is a positive effect, caused by the net immigration of $\kappa m/2$ individuals at every generation. The other effect is negative, due to the emigration of $N_1 m/2$ individuals to the non-deteriorated part of the habitat (assuming that N_1 is the population in the lastly deteriorated deme; N_2 will be the density in the deme to its left, and so on).

Positive demographic effects of migration

In a two-deme model (equivalent to the island model), the total number of immigrants in the deteriorated area is

$$N_{\mathrm{IM}}^{(\mathrm{in})} = \kappa_{\mathrm{IM}} \frac{m_{\mathrm{IM}}}{2} \ . \tag{1}$$

Here we use the subscripts IM to indicate that these are the quantities that come into play to determine rescue in an island model. While κ_{IM} shrinks in time, on average its effect will be the same as having only two demes with $\kappa_{\mathrm{IM}} = K_{\mathrm{tot}}/2$, where K_{tot} is the number of individuals over the whole habitat (see table 1 in the main text). To obtain the same net positive effect in the stepping stone model, we require

$$N_{\mathrm{IM}}^{(\mathrm{in})} = N_{\mathrm{SSM}}^{(\mathrm{in})} = \kappa \frac{m_{\mathrm{SSM}}}{2} \tag{2}$$

If we remember that $\kappa = K_{\mathrm{tot}}/D$, and we equate equation (1) to (2), we find that

$$\frac{K_{\mathrm{tot}}}{D} \frac{m_{\mathrm{SSM}}}{2} = \frac{K_{\mathrm{tot}}}{2} \frac{m_{\mathrm{IM}}}{2} \ , \tag{3}$$

and thus,

$$\boxed{m_{\mathrm{SSM}} = m_{\mathrm{IM}} \frac{D}{2}} \ . \tag{4}$$

While equation (4) provides a good approximation for low to intermediate m, it is only valid as long as $m_{\mathrm{IM}}^2 D^2/4 \ll 1$ (see next subsection and main text).

Negative demographic effects of migration

We try a very rough approximation to calculate the number of individuals in each deme of the deteriorated region for the stepping stone model. At equilibrium, we have

$$N_i[t+1] = N_i[t](1-m-r) + \frac{m}{2}(N_{i-1}[t] + N_{i+1}[t]) \ . \tag{5}$$

For $i = 1$, we assume that $N_{i-1} = \kappa$. But since is a very rough approximation and we're looking for an equilibrium value, we just assume that $N_i[t+1] = N_i$. Granted, this isn't perfect. Besides that, we also assume that beyond a certain deme, the migrating population is so small to be negligible. For this example, we assume that $m/2N_i \ll 1 \;\forall i \geq 4$. This is a simple problem of substitution, solving first N_3, inserting it in the equation for N_2, and same until a form for N_1 is reached. This form is:

$$N_1 = \frac{\kappa\, m}{2\left(m + r - \frac{m^2}{4\left(m+r-\frac{m^2}{4\,(m+r)}\right)}\right)} \tag{6}$$

Thus, the net difference of individuals moving between the two demes is $(\kappa - N_1)m/2$. This difference is shown in the plot in figure S1. Thus, we conclude that the approximation $m_{\mathrm{IM}}D/2 = m_{\mathrm{SSM}}$ is valid only

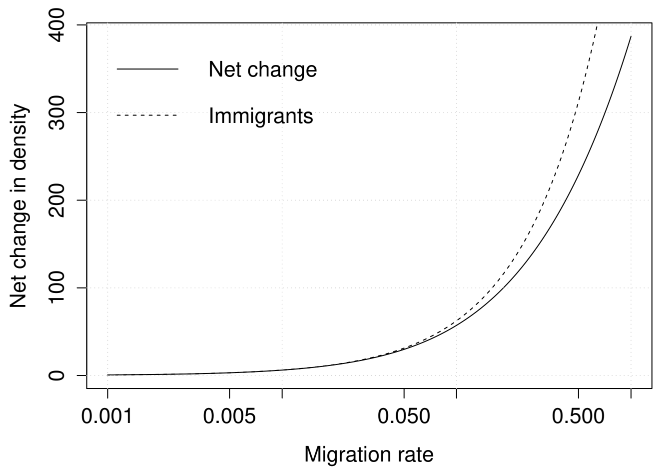

Figure S1: Net positive effect due to migration. Net change is $(\kappa - N_1)m/2$ (see main text). Parameters: $D = 16$, $r = 0.5$.

up to a certain value of m.

Here, we have shown that while negative effects due to removal of mutations increase linearly with m, demographic negative effects due to migration only play a role starting at a certain value of m. This means that while approximation (4) describes the change due to fragmentation well up to a certain point, it ultimately isn't sufficient to explain what goes on for larger values of D, when migration rates are high enough to result in a negative demographic effect.

Appendix B: Benchmark simulations

Details about how our simulations are performed can be found in the main text. We show that the simulation works for $m = 0$ (rescue occurring independently in D demes, figure S2) and $\theta = 0$ (equivalent to one big deteriorated deme, figure S3). We also show the probability of rescue for our simulation with

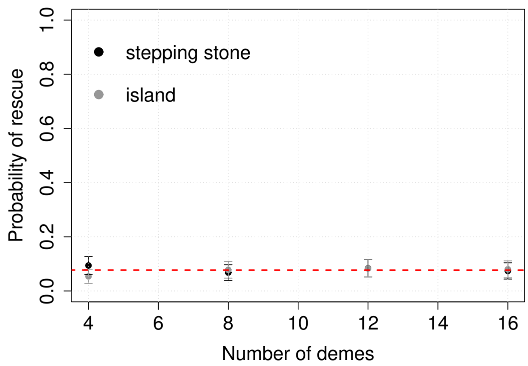

Figure S2: P_{rescue} as a function of the number of demes in the island model (black) and the stepping stone model (gray), with $m = 1$. The red line is the expected value of evolutionary rescue for one large deme. Other parameters are: $s = 1$, $r = 0.5$, $z = 0.02$, $K_{\text{tot}} = 2 \times 10^4$, 500 replicates.

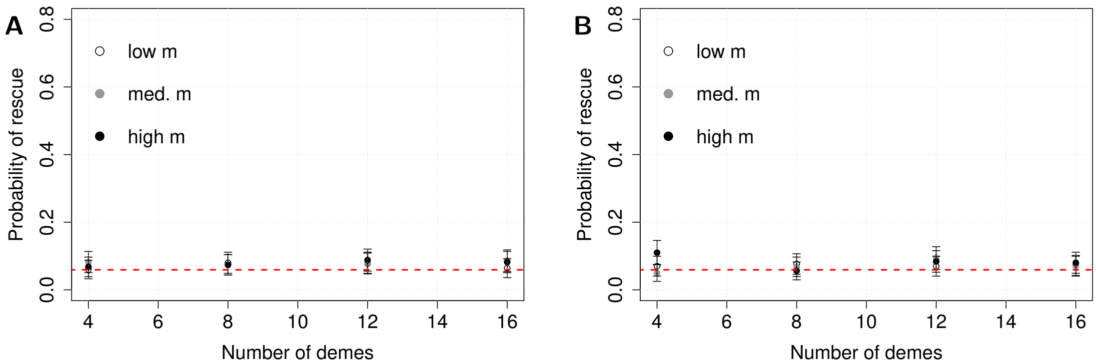

Figure S3: P_{rescue} as a function of the number of demes in (A) the island model and (B) the stepping stone model, in the case of $\theta = 0$. The red line is the expected value of evolutionary rescue for D independent demes. Low migration rate: $m = 3.2 \times 10^{-4}$; intermediate $m = 2.154 \times 10^{-2}$; high $m = 6.8129 \times 10^{-1}$. Other parameters are: $s = 1$, $r = 0.5$, $z = 0.02$, $\theta = 500$, 500 replicates.

only two demes (figure S4), compared to the approximation derived in Tomasini and Peischl [2020].

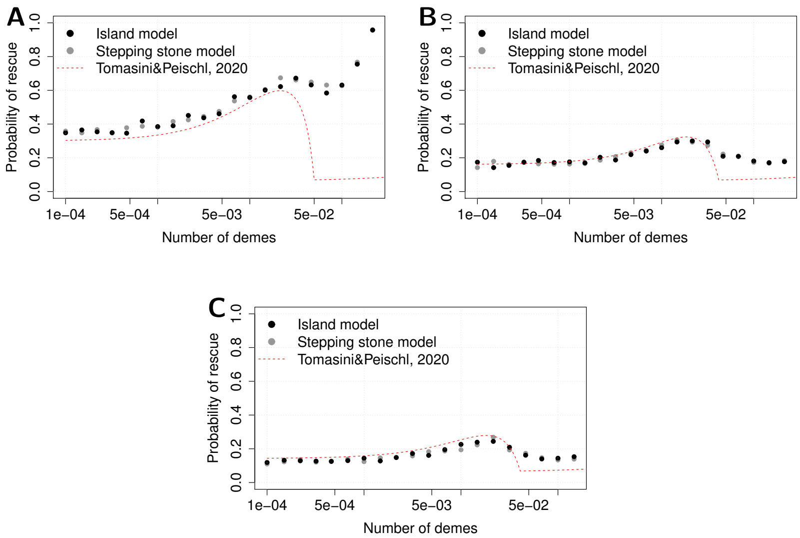

Figure S4: P_{rescue} as a function of the migration rate with only two demes; (A) $s = 0.1$, (B) $s = 0.5$, (C) $s = 1.0$. The red line is the expected value of evolutionary rescue as calculated in Tomasini and Peischl [2020]. Other parameters are: $r = 0.3$, $z = 0.02$, $\theta = 500$, 1000 replicates.

Appendix C: supplementary figures

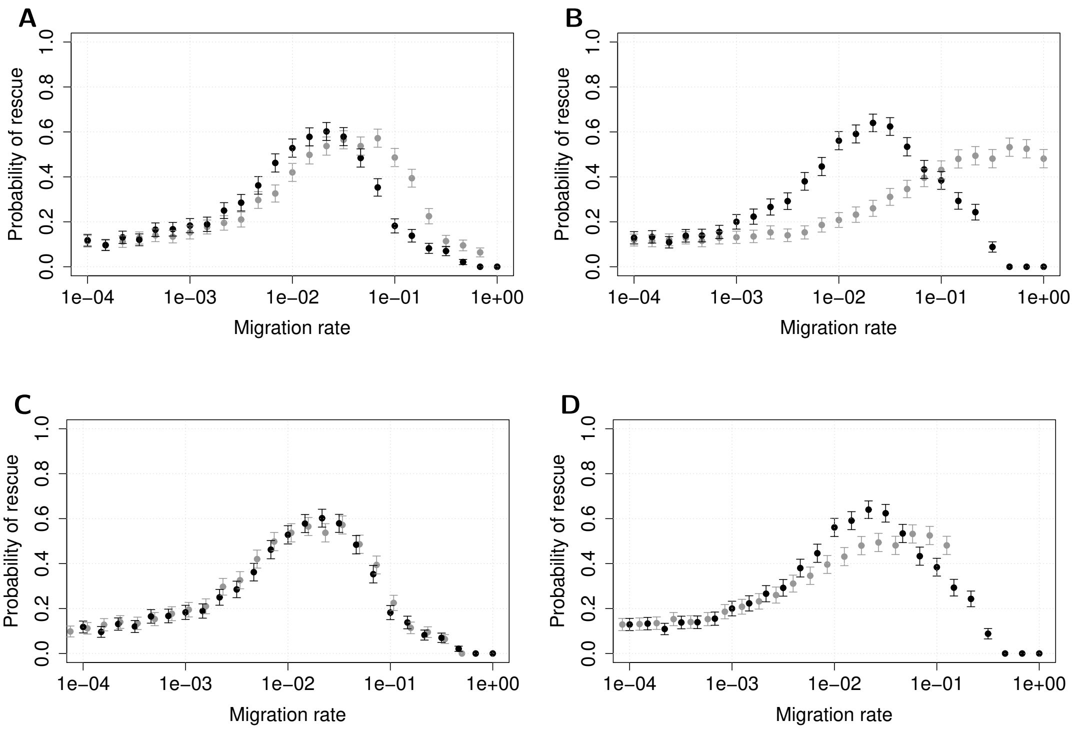

Figure S5: Comparison between stepping stone and island model. We show P_{rescue} as a function of migration rate for (A, C) $D = 4$ and (B, D) $D = 16$, with density regulation according to Beverton-Holt dynamics Beverton and Holt [1957]. For all figures, $s = 0.5$, $r = 0.5$, $z = 0.02$, and $\Theta = 4800$, and Beverton-Holt growth rate $\rho = 1.5$.

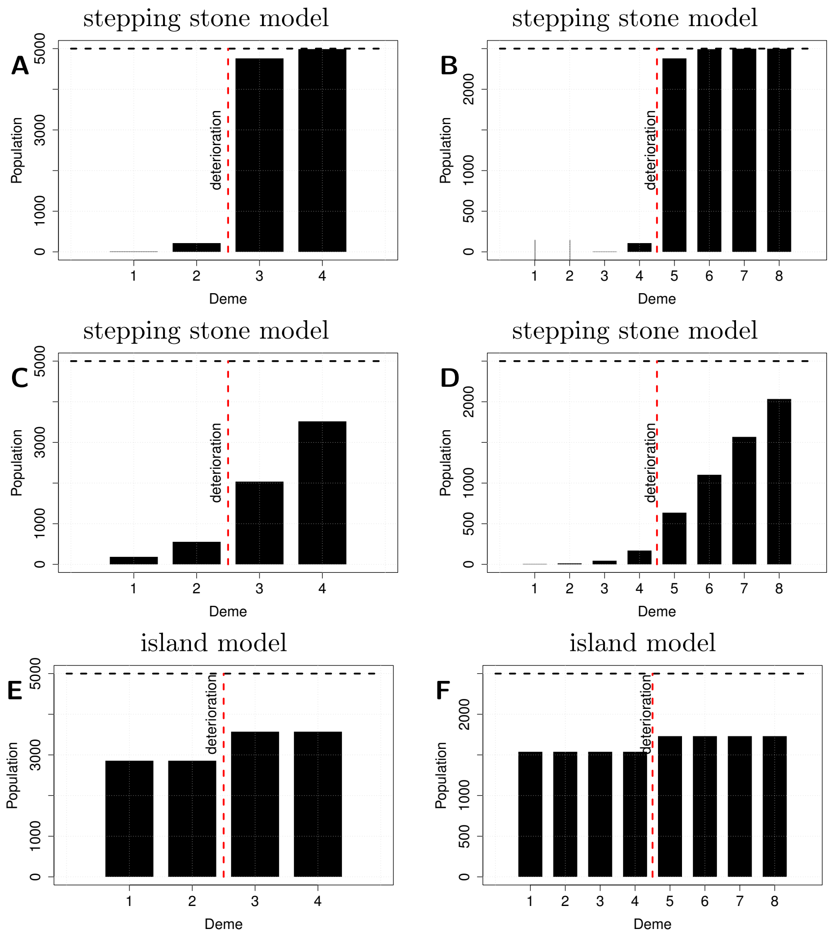

Figure S6: Deterministic populations densities before density regulation in demes at halfway of the habitat deterioration, for $D = 4$ (panels A, C and E) and for $D = 8$ (panels B, D and F). Panels A–D show the population in the stepping stone model, with panels A and B showing intermediate migration rate ($m = 0.1$) and panels C and D showing high migration rate ($m = 1$). Panels E and F show how population dynamics behave in the island model, with $m = 1$. Black dotted line is the carrying capacity per deme, red dotted line is the limit of the deteriorated area (left part). We can see how in the stepping stone model, demes are affected far away from the deterioration limit when migration is higher, thus prompting much stronger relaxed competition. In the island model, all demes are affected in the same way depending on their environment. Other parameters are $K_{\text{tot}} = 20000$, and $r = 0.5$, and $\Theta = 4800$. Halfway is then $t = 2399$, (the generation before deterioration of the next deme).

References

R. J. H. Beverton and S. J. Holt. *On the dynamics of exploited fish populations*, volume 19. Ministry of Agriculture, Fisheries and Food, 1957.

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