

Parsing propagule pressure: Simulated and experimental disentanglement of introduction size and number of introductions for colonizing individuals

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ABSTRACT

Colonization of novel habitats is more likely with increasing propagule pressure—the total number of individuals introduced to a site. Two key components of propagule pressure are the number of introduction events and the size of those introduction events. It is unclear which of these components is more important for colonization success, or under what environmental conditions their relative importance might shift. Using demographic simulations paired with a *Tribolium* flour beetle microcosm experiment, we introduced 20 total individuals into replicated novel habitats of stable or fluctuating quality and manipulated the number and size of introduction events used to distribute them through time. After seven generations, we evaluated how different combinations of the number and size of introductions affected establishment probability, size of established populations, and whether effects depended on the variability of the recipient environment. We found no effect of biologically realistic environmental stochasticity on establishment probability or size of established populations in the demographic simulations. However, there was strong evidence that establishment probability was enhanced with more, smaller introductions. In the microcosm, we similarly found no effect of environmental stochasticity on establishment probability, but unlike the simulations found that populations that established were larger in the stable environment, especially with more introduction events. The microcosm experiment yielded greater overall establishment probability and larger populations compared to the demographic simulations. Genetic mechanisms likely underlie these differences in results and thus deserve more attention in efforts to parse propagule pressure. Our results highlight the importance of preventing further introductions of undesirable species to invaded sites, and suggest conservation efforts should focus on increasing the number of introductions or re-introductions of desirable species rather than increasing the size of those introduction events.

KEYWORDS: invasion, reintroduction, propagule pressure, biocontrol, conservation, microcosm, population dynamics, stochasticity, simulation

INTRODUCTION

Colonization is the ecologically fundamental process of population establishment in an unoccupied site, and it underlies the past, present, and future distributions of species. Colonization occurs naturally, but is increasingly prevalent due to anthropogenic influences (Sakai et al. 2001, Cassey et al. 2005, Ricciardi 2007). Incipient populations often face environments that are entirely novel, which is especially likely in the case of anthropogenic colonization (Cassey et al. 2005, Ricciardi 2007). Regardless of whether colonization events to novel habitats are natural (e.g., range expansion) or human-mediated (e.g., biological invasions, reintroductions of rare species, release of biological control agents), their successes or failures have significant implications for natural resource managers and society (Mack et al. 2000). Most introductions to novel habitats fail, and colonization success can be difficult to predict (Lockwood et al. 2005, Zenni and Nuñez 2013). Incipient populations are commonly small, and face threats from environmental, demographic, and genetic stochasticity (Lande 1988, 1993, Fauvergue et al. 2012). Furthermore, the success of any given population can be idiosyncratic with respect to taxonomy and geography (Lodge 1993, Lockwood et al. 2005). Thus, it is crucial to understand more general features of the colonization process beyond the particular invading organism or the particular invaded environment (Lockwood et al. 2005). Propagule pressure is one such general feature that is the only known consistent predictor of colonization success in novel habitats (Lockwood et al. 2005, Colautti et al. 2006, Simberloff 2009).

Propagule pressure is the total number of potentially reproductive individuals (e.g., adults, eggs, seeds, vegetative material) introduced to an area (Novak 2007). It is often described in this broad sense, which belies its complexity. Two important components of propagule pressure are the number of introduction events— sometimes termed propagule number, and the number of individuals per introduction event— sometimes termed propagule size (*sensu* Fauvergue et al. 2012). Here, we use “introduction regime” to refer to different combinations of the number of introduction events and the number of individuals introduced per event. The same total propagule pressure, N , can be achieved by different introduction regimes depending on how those N individuals are distributed in time or space (Haccou and Iwasa 1996). An introduction regime of N individuals lies on a continuum bounded by maximizing the number of individuals introduced per event (all N individuals introduced in one event to the same location) and maximizing the number of introduction events (one individual introduced in each of N sequential events through time or to each of N unique locations).

Colonization success increases with total propagule pressure, but it is unclear whether the correlation is driven by the number of individuals introduced per event or the number of introduction events (Lockwood et al. 2005, Colautti et al. 2006, Simberloff 2009). Historical data suggest that multiple introductions can facilitate population establishment, but conclusions from these studies are limited by the inability to control for the total number of individuals introduced (Hopper and Roush 1993, Blackburn and Duncan 2001, Grevstad et al. 2011, Fauvergue et al. 2012). Models that hold the total propagule pressure constant agree that multiple, small introductions distributed across space will lead to greater establishment probability compared to a single, large introduction when Allee effects are weak (Haccou and Iwasa 1996, Grevstad 1999, Schreiber and Lloyd-Smith 2009). However, both modeling and empirical approaches have

generated conflicting views on how an introduction regime affects colonization success when introductions are distributed through time and total propagule pressure is constant.

There is evidence from both models and experiments that colonization success can increase with more, smaller introduction events through time. Branching process models show that, in the long run, several, small introductions will always be more likely to successfully establish a population than a single, large introduction (Haccou and Iwasa 1996, Haccou and Vatutin 2003). This finding was corroborated by simulations with no Allee effects (Drolet and Locke 2016). In a *Daphnia* microcosm experiment, increasing introduction frequency (proportional to the number of introductions) positively affected population growth, but the number of individuals per introduction had no detectable effect. This pattern did not hold for establishment probability, which was only affected by total propagule pressure (Drake et al. 2005). However, Drake et al. (2005) did not continue scheduled introductions if a population went extinct, denying those populations one of the main benefits of repeated introductions and creating variability in the total propagule pressure. In a more recent experiment, several, small introductions led to a 65% increase in abundance of successfully colonizing invasive Pacific Oyster (*Crassostrea gigas*) compared to a single, large introduction (Hedge et al. 2012).

There is also evidence from both models and experiments that colonization success increases with fewer, larger introduction events through time. In simulations of bird invasions, a single, large introduction event always led to the greatest establishment probability (Cassey et al. 2014). When Drolet and Locke (2016) included Allee effects in their simulations, their previously observed pattern reversed and colonization success was instead more likely with fewer, larger introductions than with more, smaller introductions. In a field experiment with the psyllid biocontrol agent, *Arytainilla spartiophila*, the number of individuals per introduction event was a

better predictor of establishment success than the number of introduction events (Mommott et al. 2005). In this case however, the introduction regimes with the most individuals per event also had the highest total propagule pressure (Mommott et al. 2005). In an experiment that controlled total propagule pressure, a single, large introduction of the non-native mysid, *Hemimysis anomala*, led to larger populations and greater survival probabilities compared to several, small introductions through time (Sinclair and Arnott 2015).

Environmental stochasticity in the recipient environment may also affect which introduction regime is optimal for colonization. Branching process models show that a more variable environment can reduce the probability of population establishment for all introduction regimes (Haccou and Iwasa 1996, Haccou and Vatutin 2003), and simulations of introductions distributed in space suggest that greater environmental variability will magnify the benefit of multiple introductions (Grevstad 1999). However, simulations of introductions through time did not support either of these outcomes— a single, large introduction was most likely to establish a population even with extreme levels of environmental stochasticity (Cassey et al. 2014).

Thus, modeling and empirical approaches have not resolved how different introduction regimes with a fixed total propagule pressure will affect colonization success when introductions are distributed through time. Further, there has been no experimental test of whether variability in the recipient environment interacts with the introduction regime to affect colonization. We paired demographic simulations with a laboratory microcosm experiment using the red flour beetle, *Tribolium castaneum*, to reconcile conflicts in the literature and test how different introduction regimes implemented through time affected colonization success in novel habitats. We explicitly manipulated whether the novel habitat was stable or randomly fluctuating in quality to assess how the success of different introduction regimes may depend upon variability in the recipient

environment. With the total number of individuals introduced held constant at 20, we varied the size and number of introduction events used to distribute those individuals in four different introduction regimes. We evaluated establishment probability and population size over 7 discrete generations to ask: 1) does colonization success increase with more introduction events or with more individuals per introduction event?, and 2) does the effect of the introduction regime on colonization success depend on whether the recipient novel environment is stable or fluctuating through time?

METHODS

General Framework

In simulations and a microcosm experiment, we evaluated the outcome of introducing 20 total individuals to one of two environmental contexts (a stable or fluctuating novel environment), varying the number of introduction events used to distribute those individuals through time. This total was low enough to allow some population extinction within a reasonable timeframe, but high enough to be representative of documented introductions in the literature (Simberloff 1989, Simberloff 2009; Grevstad 1999; Berggren 2001; Taylor et al. 2005; Drake et al. 2005). The introduction regimes were: 20 individuals introduced in the first generation, 10 individuals introduced in each of the first 2 generations, 5 individuals introduced in each of the first 4 generations, and 4 individuals introduced in each of the first 5 generations. To create the fluctuating environment, we imposed a magnitude of variability corresponding to environmental stochasticity in nature, which leads to frequent, mild to moderate perturbations in population growth rate due to external forces (Lande 1993). Populations were tracked for seven generations following the initial introduction.

Establishment probability and the size of established populations were used as measures of colonization success. Populations were deemed ‘established’ for any time step in which they were extant and population size was noted for all extant populations in every time step. For analysis, establishment probability and mean population size were assessed in generation 7.

Study System

Our simulations and microcosm experiment use *Tribolium castaneum* (red flour beetles) to model the life history of organisms with discrete, non-overlapping generations (e.g., annual insects and fishes) following Melbourne and Hastings (2008). Individual simulated colonists were randomly sourced from a randomly mating, infinitely large population. Individual experimental colonists came from a thoroughly mixed source population maintained at 800 individuals in each of the 4 temporal blocks over which the experiment was replicated. To obtain colonists, beetles from the source population were mixed freely on a plate, selected from many sections of the plate, and introduced to subsets of the experiment populations in a random order (about 24 subsets per block). All migrant females were assumed to arrive mated from the source population. The strong maternal effects exhibited by *Tribolium* flour beetles were reduced by rearing individuals from the source population on novel growth medium for 1 generation prior to using them as colonists (Van Allen and Rudolf 2013, Hufbauer et al. 2015).

Simulations

Population dynamics were simulated with a Negative Binomial-Binomial gamma (NBBg) Ricker model (Melbourne and Hastings 2008) with an additional mating function of the form:

$$\begin{aligned}
 N_{t+1,i} &\sim \text{NegBinom}(\mu_i, k_D F_{mated(t,i)}) \\
 \mu_i &= \frac{F_{mated(t,i)}}{p} R_{Ei} e^{-\alpha N_{t,i}} \\
 R_{Ei} &\sim \text{Gamma}\left(k_E, \frac{R_0}{k_E}\right) \\
 N_{t,i} &= N_{migrants(t,i)} + N_{residents(t,i)} \\
 F_{mated(t,i)} &= \begin{cases} F_{migrants(t,i)}, & F_{migrants(t,i)} + F_{residents(t,i)} = N_{t,i} \\ F_{migrants(t,i)} + F_{residents(t,i)}, & F_{migrants(t,i)} + F_{residents(t,i)} < N_{t,i} \end{cases} \\
 F_{migrants(t,i)} &\sim \text{Binom}(N_{migrants(t,i)}, p) \\
 F_{residents(t,i)} &\sim \text{Binom}(N_{residents(t,i)}, p) \\
 p &= 0.5 \\
 R_0 &\sim \text{Gamma}(2.6, 1) \\
 \alpha &\sim \text{Gamma}(0.0037, 1) \\
 k_E &\sim \text{Gamma}(17.6, 1) \\
 k_D &\sim \text{Gamma}(1.07, 1)
 \end{aligned} \tag{Eq. 1}$$

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177 Where $N_{t+1,i}$ is the size of population i at time $t+1$, k_D represents stochasticity due to
 178 demographic heterogeneity, μ_i is the expectation of the size of population i in the next time step,
 179 $F_{mated(t,i)}$ is the latent number of mated females in population i at time t , p is the probability of an
 180 individual being female, R_{Ei} is the latent density-independent population growth rate for
 181 environment E , α is the egg cannibalism rate, $N_{t,i}$ is the total size of population i at time t , k_E
 182 represents environmental stochasticity, R_0 is the density-independent population growth rate for
 183 the average environment, $N_{migrants(t,i)}$ is the total number of migrants to population i at time t , and
 184 $N_{residents(t,i)}$ is the total number of residents in population i at time t .

185 We imposed a mating function such that a population would deterministically go extinct if it
 186 comprised only non-migrant females. In cases with an all female population and a mixture of

residents and migrants, we only included the number of migrant females in the density-dependent effect of the demographic heterogeneity term $k_D * F_{mated(t,i)}$ because this effect manifests via the number of eggs laid by females and only migrant females, being pre-mated, would lay eggs. Weakly regularizing gamma priors were taken from Melbourne and Hastings (2008). The expected equilibrium population size for the model is:

$$K = \frac{\log(R_0)}{\alpha} \quad (\text{Eq. 2})$$

For each combination of the 4 introduction regimes and 2 recipient environment types (described above), we simulated 500,000 replicate populations for 7 generations. All simulations were performed in R (R Core Team 2016). This model captures the stochastic and deterministic ecological dynamics of the *Tribolium* system well, but does not include evolutionary processes (Melbourne and Hastings 2008, Hufbauer et al. 2015).

To parameterize the model, we censused 125 *Tribolium* populations one generation after establishing them at various, known densities (between 5 and 200 individuals) on the novel growth medium following the rearing procedure described in “Microcosm Experiment” below. We fit the hierarchical model (Eq. 1) to these data in a Bayesian framework to generate posterior distributions for each of the parameters using the nimble package in R (de Valpine et al. 2016). We used a Metropolis-Hastings random walk sampler with 3 chains having 50,000 samples each (including 10,000 samples that were removed for burn in). The chains converged (multivariate \hat{R} for the 4 key parameters = 1.01) and produced a sufficient number of effective samples (R_0 : 757, α : 548, k_E : 4103, k_D : 1703).

A single novel growth medium mixture was used for these 125 populations (mixture 5, Supplementary Table 1), so we treated the estimated environmental stochasticity parameter, k_E , as the expectation for a stable environment. We parameterized a fluctuating environment model by increasing the standard deviation of the density-independent per capita population growth rate by approximately 10% for any given population at any given time step. This was accomplished by multiplying all of the samples from the posterior distribution of the environmental stochasticity parameter, k_E , by 100/121 (derived by moment matching for the gamma distribution). By using random sets of parameters drawn from the samples of the posterior distributions, we were able to propagate the model uncertainty through the simulations and combine it with the deterministic and stochastic dynamics represented by the model itself.

Microcosm Experiment

We founded 842 *Tribolium* populations with different introduction regimes (20 individuals in the first generation, 10 individuals in the first 2 generations, 5 individuals in the first 4 generations, or 4 individuals in the first 5 generations) and environments (stable or fluctuating) with between 96 and 120 replicate populations per treatment combination (Supplemental Table 3). Each population was reared in a 4cm x 4cm x 6cm plastic box (AMAC Plastic Products) with 2 tablespoons (approximately 15 g) of freshly prepared growth medium that had been humidified for at least 24 hours. The growth medium used for the source population (the natal environment of the colonists) comprised 95% wheat flour (Pillsbury Co. or Gold Medal Products Co.) and 5% brewers' yeast (Sensient Flavors). Colonists were introduced into a novel growth medium comprising a small percentage of natal medium mixed with corn flour (Bob's Red Mill). All populations were reared in one of two dark incubators at 31° and approximately 70% relative humidity (standard conditions) and were haphazardly rotated between incubators weekly.

For each population in each generation, a known number of adults laid eggs for 24 hours in fresh medium, and were then removed. Offspring were given 35 days to develop, and adults were then censused. Censused adults laid eggs on freshly prepared growth medium for 24 hours, completing their laboratory life cycle. In censusing trials, we estimated the maximum observation error to be 4.6% (median: 0%, mean: 0.26%) with no detectable difference across observers or populations with different sizes.

Each replicate population experienced a novel environment that was either stable or randomly fluctuating through time. The same novel growth medium mixture containing 99.05% novel corn flour and 0.95% natal medium (mixture 5, Supplementary Table 1) was used for the stable environment for the duration of the experiment, which preliminary results indicated would yield a population growth rate of $\lambda = 1.2$ compared to a mean population growth rate of 3.36 on 100% natal medium. To create the fluctuating environment, we randomly selected a novel growth medium mixture from one of 9 possible media mixtures for each population in each generation. Each population in the fluctuating environment therefore experienced a unique series of environmental conditions. The 9 possible media mixtures represented a gradient of corn flour to natal medium ratios, and were designed to yield expected population growth rates between 0.88 and 1.33 (Supplementary Table 1). We chose this range to mimic environmental stochasticity measured in nature (Sæther and Engen 2002) while remaining within the bounds of biologically realistic population growth (λ between 0.5 and 1.5) (Morris et al. 2008). The random choice was constrained such that the expected geometric mean population growth rate for each population resembled expected growth of populations in the stable environment ($\lambda_{expected} = 1.2 \pm 0.05$).

We estimated the amount of environmental stochasticity that we achieved in the fluctuating environment as the difference in mean total stochasticity between populations in the fluctuating

and stable environments (Sæther and Engen 2002). We assumed that total stochasticity was a combination of demographic and environmental stochasticity for populations in the fluctuating environment, and that demographic stochasticity was the sole contributor to total stochasticity for populations in the stable environment. Total stochasticity (demographic plus environmental) of each population that did not experience extinction ($n=667$) was calculated as the variance of the natural logarithms of its population growth rates through 7 generations:

$$s_{total} = s_{demographic} + s_{environmental} = var(\log(\lambda_t)) \quad (\text{Eq. 3})$$

where, for a particular population, s_{total} is its total stochasticity, $s_{demographic}$ is its demographic stochasticity, $s_{environmental}$ is its environmental stochasticity (assumed to be 0 for populations in the stable environment), and λ_t is its per capita population growth rate between generation $t-1$ and generation t ($t=1, 2, \dots, 7$). We only calculated total stochasticity for populations that did not experience any extinction in order to capture the full temporal extent of environmental fluctuations and because extinctions would have an infinite effect on this measure of stochasticity.

Statistical analyses

We evaluated how our environment treatment affected variability in population growth rate (total stochasticity from Eq. 3) using a linear mixed effects model with environment (stable or fluctuating) as a fixed effect and block as a random intercept effect.

We used a mixed effects logistic regression with a logit link to predict the binary response of establishment, and a mixed effects Poisson regression with a log link to analyze population size. In both models, introduction regime, environment treatment, and their interaction were treated as fixed effects, and block was treated as a random intercept effect.

We assessed the effect of temporary extinctions on the establishment probability and mean population size by fitting the generalized linear mixed effects models described above to data from the multiple introduction regimes (i.e. not the 20x1 regime) and with additional predictor variables. To assess the effect of the presence of a temporary extinction, we included an additional Boolean predictor for whether a population went temporarily extinct or not. To assess the role of the total propagule pressure, we included a numeric predictor representing the number of beetles introduced after the latest temporary extinction.

Group-level significance of fixed effects was tested using likelihood ratio tests on nested models, and least-squares contrasts were used to compare levels of the fixed effects. All statistical analyses were performed in R, version 3.3.2 (R Core Team 2016). Generalized linear mixed models were fit using the lme4 package, version 1.1-12 (Bates et al. 2015) and pairwise comparisons were made using the lsmeans package, version 2.25 (Lenth 2016).

Data availability

The raw experiment data, simulated population trajectories, R code for the simulations, R code fitting the NBBg model, samples from the posterior distributions of the NBBg parameters, and R code fitting the mixed effects models are available as supplemental material, on Figshare (<https://doi.org/10.6084/m9.figshare.4648865.v1>), and on GitHub (<https://github.com/mikoontz/ppp-establishment>).

Note on egg contamination

Laboratory procedures after generation 3 resulted in occasional egg contamination between replicate populations of the same treatment. Some populations of 1 individual persisted when

they should have deterministically gone extinct, so we manually edited those population trajectories such that they went extinct in the generation after having only 1 individual.

RESULTS

Simulations

Summary statistics for the posterior distributions of the four NBBg model parameters are given in Supplementary Table 2.

Our simulations showed introduction regimes with more introduction events were more likely establish a population by the seventh generation (Figure 1). Introductions into a stochastically fluctuating environment resulted in slightly lower population establishment for all introduction regimes (difference of ~1%), but did not favor any particular regime (not shown). The mean population sizes for each introduction regime/environment combination were approximately equal in simulations. Mean population sizes only incorporated extant populations, so they were slightly larger than the expectation for the equilibrium population size (Figure 2).

Microcosm experiment

Mean environmental stochasticity of populations in the fluctuating environment was 0.052 (95% CI = 0.0073 to 0.0966; $p = 0.023$). This value is near the median value of 0.055 measured in nature by Sæther and Engen (2002) in a metaanalysis of 35 avian populations, indicating that we achieved biologically realistic fluctuations in population growth rate.

We found no evidence that the probability of establishment was affected by a main effect of environment ($\chi^2=0.72$, $df=1$, $p=0.40$), nor by an interaction between environment and

introduction regime ($\chi^2=3.49$, $df=3$, $p=0.32$). However, there was strong support for an effect of introduction regime on establishment probability ($\chi^2=59.76$, $df=3$, $p<0.0001$). Pairwise comparisons of the different introduction regimes averaged across the environment treatments revealed that the 4x5 regime was the most likely to establish populations, with a probability of about 0.98, whereas the 20x1 and 10x2 regimes were the least likely to establish populations, with a probability reduced to about 0.8 (Figure 1).

The mean size of populations that persisted until generation 7 was shaped by significant effects of introduction regime ($\chi^2=91.65$, $df=3$, $p<0.0001$), environment treatment ($\chi^2=117.83$, $df=3$, $p<0.0001$), and their interaction ($\chi^2=44.62$, $df=3$, $p<0.0001$). Populations established via more introduction events were larger when averaged across the environment treatments. Extant populations in the stable environment were larger than those in the fluctuating environment when averaged across the introduction regimes. The interaction manifests as the benefit of a stable environment increases with more, smaller introduction events (Figure 2).

Extinctions accumulated regularly throughout the experiment period, with 101 out of 842 populations (12.0%) going extinct by generation 7 (Supplementary Figure 2). The additional introductions that some populations received often restored a population that had temporarily gone extinct. Out of 602 populations that received more than 1 introduction (i.e. not the 20x1 introduction regime), 104 of them (17.3%) temporarily went extinct at least once before being replenished by additional colonizing individuals. Twelve populations were rescued in this way at least twice, and one population was rescued in this way three times.

Temporary extinctions significantly affected colonization success. The presence of a temporary extinction significantly reduced average establishment probability from 92.4% to 82.1%

(difference = -1.13 on logit scale, 95% CI = -0.22 to -2.04, $\chi^2 = 5.44$, df = 1, p = 0.020) and mean population size from 47.8 to 45.4 (difference = -0.052 on log scale, 95% CI = -0.02 to -0.09, $\chi^2 = 9.42$, df = 1, p=0.0021). Each additional colonist contributing to a population after the latest temporary extinction significantly increased the mean population size (estimate = 0.005 on the log scale, 95% CI = 6.4e-05 to 0.01, $\chi^2 = 3.94$, df = 1, p=0.047).

Results from the simulations are expected to represent the dynamics in the microcosm experiment if the assumption of the model on which the simulations were built holds—that only demographic processes are responsible for the dynamics observed in the experiment. However, establishment probability at generation 7 was equal to or greater than that expected from the simulations (Figure 1) and mean population sizes were much larger in the experiment than in the simulations (Figure 2), together suggesting an influence of non-demographic mechanisms.

DISCUSSION

We assessed how the number and size of introduction events through time drive colonization success in a novel environment when the total number of individuals introduced to a site is fixed. We considered novel environments that were either stable or randomly fluctuating in quality through time, and evaluated populations through 7 discrete generations. We approached this question in two ways: 1) stochastic simulations of a demographic population dynamics model parameterized with empirical data, and 2) a highly replicated laboratory microcosm experiment. By coupling these approaches, we were able to expand and test the theoretical understanding of how the introduction regime affects colonization in stable and fluctuating environments as well as to develop new avenues for research when observations did not align with predictions. We

found that several, small introductions increase colonization success and that demographic processes alone are insufficient to explain the dynamics observed in the experiment.

We found minimal to no effect of a biologically realistic level of environmental stochasticity on establishment probability in demographic simulations. This finding is inconsistent with the prediction made by Grevstad (1999) who found with simulations that several, small introductions would produce an especially high establishment probability compared to a single, large introduction in a variable environment. The difference in findings is perhaps due to a difference in the kinds of introduction regimes modeled: Grevstad (1999) simulated multiple introductions distributed in space, while we focused on introductions separated in time. Additionally, we may not have detected the same effect of environmental stochasticity that Grevstad (1999) noted because of differences in the magnitude of environmental variation imposed. At the highest levels of simulated environmental variation imposed in Grevstad's study, over 65% of environments would result in population decline and over 40% of environments would result in population loss of greater than 90%. This kind of environmental variability might be characterized as random catastrophes—major events causing immediately disastrous effects to the population, rather than a level of environmental stochasticity leading to more moderate fluctuations in growth rates (Lande 1993). Our simulations and microcosm results do corroborate the results from simulations by Cassey et al. (2014) who also used introductions through time and found a minimal effect of environmental stochasticity on establishment probability. Cassey et al. (2014) further found a minimal effect of random, infrequent catastrophes and bonanzas, suggesting that increasing environmental variability through time in the broadest sense (i.e., encompassing environmental stochasticity, random catastrophes, and bonanzas) does not

magnify the benefit of several, small introductions through time in the same way that Grevstad (1999) found with several, small introductions across space.

There also did not appear to be a strong effect of environmental stochasticity on population size in the demographic simulations. All treatments in the simulations reached similar mean population size by generation 7, which was slightly higher than the equilibrium size due to our measure only including extant populations. This suggests that strong density dependence in the demographic simulations was the primary influence on population size.

We observed striking differences in the measures of colonization success between the demographic simulations and the microcosm experiment. We found that establishment probability increased with the number of introduction events (as in the simulations), but that all microcosm establishment probabilities equaled or exceeded expectations from simulations. In the microcosm, mean population size in stable environments was greater than in fluctuating environments. There was also an interaction between environment and introduction regime, whereby the mean population size was increasingly greater in stable compared to fluctuating environments as the number of introductions increased. Furthermore, populations grew larger by generation 7 in the microcosm experiment than in the simulations.

Departures from the simulation expectations in the microcosm experiment suggest that the demographic processes captured by the model do not account for all of the biological processes that occurred in the microcosm. Recent work shows that adaptation to the novel, harsh environment from standing variation is possible in this species (Hufbauer et al. 2015), and likely explains the greater establishment probability and population sizes in the microcosm compared to expectations derived from demographic simulations which do not include adaptation.

The rescue effect of immigration can act demographically by increasing the size of populations (Brown and Kodric-Brown 1977). Certainly, demographic rescue played a critical role for the 104 populations that went extinct temporarily until another introduction event revived them. Those temporary extinctions had lasting effects on colonization success. Colonization success declined for populations that experienced a temporary extinction, and the mean population size significantly increased if more colonists contributed to the population after a temporary extinction. These results reflect the overarching importance of total propagule pressure regardless of introduction regime.

The rescue effect can also act genetically by increasing the fitness of populations (Brown and Kodric-Brown 1977, Frankham 2015, Whiteley et al. 2015). The immigrants all came from the same large external source population, so it is unlikely that gene flow from migrants produced novel genetic combinations on which selection could act (Novak 2007). Thus, a more likely mechanism by which immigration increased mean population size was by relieving inbreeding depression or counteracting drift-induced allele loss. Small populations are more prone to experiencing increased homozygosity and inbreeding depression, which can reduce population growth rates and increase extinction risk (McCauley and Wade 1981, Saccheri et al. 1998, O'Grady et al. 2006, Szűcs et al. 2014, 2017). Even small amounts of gene flow can alleviate these effects, so the additional small introductions of mated individuals from the external source population were well-suited to bring about longer-term relief (Slatkin 1985, Mills and Allendorf 1996). However, Cassey et al. (2014) found that simulated inbreeding depression was especially detrimental for several, small introductions through time, so other mechanisms might be at play. Sustained immigration may affect adaptation of the incipient population. Introductions to a harsh, novel habitat can result in adaptive evolution with the right amount of gene flow if additional

immigrants to a declining population prevent extinction long enough to allow for adaptation to occur (Holt and Gomulkiewicz 1997). However, too much gene flow can lead to genetic swamping whereby the homogenizing effects of gene flow overpowers ongoing local adaptation (Mills and Allendorf 1996, Lenormand 2002). This may have been the case for populations in the 10x2 introduction regime, which had the highest average migration rate, lowest establishment probability, and lowest mean population size. Alternatively, negative density dependence may have reduced population fitness when migration rates were high, reducing population growth rates and hampering the spread of adaptive alleles (Holt and Gomulkiewicz 1997). Though not significant, the lower establishment probability and mean population size in the 10x2 introduction regime warrants further work to assess whether they exemplify the yet-unseen scenario described by Blackburn et al. (2015) in which maladaptive gene flow from multiple introductions hampers population establishment in a novel range. More broadly, further study is necessary to evaluate how immigration affected adaptation in this system, if at all (Gomulkiewicz and Holt 1995, Boulding and Hay 2001).

CONCLUSION

Our experimental results suggest that several, small introductions through time lead to greater colonization success in a novel habitat, and that introductions into a stable recipient environment lead to larger population sizes, but not greater establishment probability. Further, introductions to a stable recipient environment are especially beneficial to populations established with more introduction events. These results defied our expectations derived from parallel simulations of a model that included demographic processes but not evolutionary ones, so we suspect a genetic mechanism might be at work. Genetic mechanisms are rarely incorporated when simulating the effect of introduction regime on colonization (but see Cassey et al. 2014), and our multi-

generation microcosm is unique in bringing evolutionary processes to bear on parsing two key components of propagule pressure in an experimental setting.

For invasions, our results highlight the importance of preventing further introductions to the same location, even for established species. For conservation and biological control, our results suggest that emphasis should be placed on increasing the number of introductions or re-introductions to a location, rather than increasing the size of those events if Allee effects are weak. Sustained introduction efforts should also bring about concomitant benefits in the form of longer-term monitoring, increased data collection, and more opportunities for experimentation and adaptive management (Lockwood et al. 2005, Godefroid et al. 2011).

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REFERENCES

- Van Allen, B. G., and V. H. W. Rudolf. 2013. Ghosts of habitats past: Environmental carry-over effects drive population dynamics in novel habitat. *The American Naturalist* 181:596–608.
- Bates, D., M. Maechler, B. Bolker, and S. Walker. 2015. Fitting linear mixed-effects models

469 using lme4. Journal Of Statistical Software 67:1–48.

470 Berggren, A. 2001. Colonization success in Roesel’s bush-cricket *Metrioptera roeseli*: The
471 effects of propagule size. Ecology 82:274–280.

472 Blackburn, T. M., and R. P. Duncan. 2001. Establishment patterns of exotic birds are constrained
473 by non-random patterns in introduction. Journal of Biogeography 28:927–939.

474 Blackburn, T. M., J. L. Lockwood, and P. Cassey. 2015. The influence of numbers on invasion
475 success. Molecular Ecology:1–12.

476 Boulding, E. G., and T. Hay. 2001. Genetic and demographic parameters determining population
477 persistence after a discrete change in the environment. Heredity 86:313–24.

478 Brown, J. H., and A. Kodric-Brown. 1977. Turnover rates in insular biogeography: Effect of
479 immigration on extinction. Ecology 58:445–449.

480 Cassey, P., T. M. Blackburn, R. P. Duncan, and S. L. Chown. 2005. Concerning invasive
481 species: Reply to Brown and Sax. Austral Ecology 30:475–480.

482 Cassey, P., T. A. A. Prowse, and T. M. Blackburn. 2014. A population model for predicting the
483 successful establishment of introduced bird species. Oecologia 175:417–428.

484 Colautti, R. I., I. A. Grigorovich, and H. J. MacIsaac. 2006. Propagule pressure: A null model for
485 biological invasions. Biological Invasions 8:1023–1037.

486 Drake, J. M., P. Baggenstos, and D. M. Lodge. 2005. Propagule pressure and persistence in
487 experimental populations. Biology Letters 1:480–3.

488 Drolet, D., and A. Locke. 2016. Relative importance of propagule size and propagule number for

establishment of non-indigenous species: A stochastic simulation study. *Aquatic Invasions*
11.

Fauvergue, X., E. Vercken, T. Malausa, and R. A. Hufbauer. 2012. The biology of small,
introduced populations, with special reference to biological control. *Evolutionary*
Applications 5:424–43.

Frankham, R. 2015. Genetic rescue of small inbred populations: Meta-analysis reveals large and
consistent benefits of gene flow. *Molecular Ecology* 24:2610–2618.

Godefroid, S., C. Piazza, G. Rossi, S. Buord, A.-D. Stevens, R. Aguraiuja, C. Cowell, C. W.
Weekley, G. Vogg, J. M. Iriondo, I. Johnson, B. Dixon, D. Gordon, S. Magnanon, B.
Valentin, K. Bjureke, R. Koopman, M. Vicens, M. Virevaire, and T. Vanderborght. 2011.
How successful are plant species reintroductions? *Biological Conservation* 144:672–682.

Gomulkiewicz, R., and R. D. Holt. 1995. When does evolution by natural selection prevent
extinction? *Evolution* 49:201–207.

Grevstad, F. S. 1999. Factors influencing the chance of population establishment: Implications
for release strategies in biocontrol. *Ecological Applications* 9:1439–1447.

Grevstad, F. S., E. M. Coombs, and P. B. McEvoy. 2011. Revisiting release strategies in
biological control of weeds: Are we using enough releases? XIII International Symposium
on Biological Control of Weeds:368–376.

Haccou, P., and Y. Iwasa. 1996. Establishment probability in fluctuating environments: A
branching process model. *Theoretical Population Biology* 50:254–280.

Haccou, P., and V. Vatutin. 2003. Establishment success and extinction risk in autocorrelated

510 environments. *Theoretical Population Biology* 64:303–314.

511 Hedge, L. H., W. A. O’Connor, and E. L. Johnston. 2012. Manipulating the intrinsic parameters
512 of propagule pressure: Implications for bio-invasion. *Ecosphere* 3:art48.

513 Holt, R. D., and R. Gomulkiewicz. 1997. How does immigration influence local adaptation? A
514 reexamination of a familiar paradigm. *The American Naturalist* 149:563–572.

515 Hopper, K. R., and R. T. Roush. 1993. Mate finding, dispersal, number released, and the success
516 of biological control introductions. *Ecological Entomology* 18:321–331.

517 Hufbauer, R. A., M. Szűcs, E. Kasyon, C. Youngberg, M. J. Koontz, C. Richards, T. Tuff, and B.
518 A. Melbourne. 2015. Three types of rescue can avert extinction in a changing environment.
519 *Proceedings of the National Academy of Sciences* 112:10557–10562.

520 Lande, R. 1988. Genetics and demography in biological conservation. *Science* 241:1455–1460.

521 Lande, R. 1993. Risks of population extinction from demographic and environmental
522 stochasticity and random catastrophes. *The American Naturalist* 142:911–927.

523 Lenormand, T. 2002. Gene flow and the limits to natural selection. *Trends in Ecology and*
524 *Evolution* 17:183–189.

525 Lenth, R. V. 2016. Least-squares means: The R package lsmeans. *Journal Of Statistical Software*
526 69:1–33.

527 Lockwood, J. L., P. Cassey, and T. Blackburn. 2005. The role of propagule pressure in
528 explaining species invasions. *Trends in Ecology and Evolution* 20:223–8.

529 Lodge, D. M. 1993. Biological invasions: Lessons for ecology. *Trends in Ecology and Evolution*

530 8:133–137.

531 Mack, R. N., D. Simberloff, W. M. Lonsdale, H. Evans, M. Clout, and F. A. Bazzaz. 2000.

532 Biotic invasions: Causes, epidemiology, global consequences, and control. *Ecological*

533 *Applications* 10:689–710.

534 McCauley, D. E., and M. J. Wade. 1981. The populational effects of inbreeding in *Tribolium*.

535 *Heredity* 46:59–67.

536 Melbourne, B. A., and A. Hastings. 2008. Extinction risk depends strongly on factors

537 contributing to stochasticity. *Nature* 454:100–3.

538 Memmott, J., P. G. Craze, H. M. Harman, P. Syrett, and S. V Fowler. 2005. The effect of

539 propagule size on the invasion of an alien insect. *Journal of Animal Ecology* 74:50–62.

540 Mills, L. S., and F. W. Allendorf. 1996. The one-migrant-per-generation rule in conservation and

541 management. *Conservation Biology* 10:1509–1518.

542 Morris, W. F., C. A. Pfister, S. Tuljapurkar, C. V Haridas, C. L. Boggs, M. S. Boyce, E. M.

543 Bruna, D. R. Church, T. Coulson, D. F. Doak, S. Forsyth, J.-M. Gaillard, C. C. Horvitz, S.

544 Kalisz, B. E. Kendall, T. M. Knight, C. T. Lee, and E. S. Menges. 2008. Longevity can

545 buffer plant and animal populations against changing climatic variability. *Ecology* 89:19–25.

546 Novak, S. J. 2007. The role of evolution in the invasion process. *Proceedings of the National*

547 *Academy of Sciences* 104:3671–2.

548 O’Grady, J. J., B. W. Brook, D. H. Reed, J. D. Ballou, D. W. Tonkyn, and R. Frankham. 2006.

549 Realistic levels of inbreeding depression strongly affect extinction risk in wild populations.

550 *Biological Conservation* 133:42–51.

551 R Core Team. 2016. R: A language and environment for statistical computing. [http://www.r-](http://www.r-project.org/)
552 [project.org/](http://www.r-project.org/). Vienna, Austria.

553 Ricciardi, A. 2007. Are modern biological invasions an unprecedented form of global change?
554 *Conservation Biology* 21:329–36.

555 Saccheri, I., M. Kuussaari, M. Kankare, P. Vikman, and I. Hanski. 1998. Inbreeding and
556 extinction in a butterfly metapopulation. *Nature* 392:491–494.

557 Sæther, B.-E., and S. Engen. 2002. Pattern of variation in avian population growth rates.
558 *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*
559 357:1185–95.

560 Sakai, A. K., F. W. Allendorf, J. S. Holt, D. M. Lodge, J. Molofsky, K. A. With, S. Baughman, R.
561 J. Cabin, J. E. Cohen, N. C. Ellstrand, D. E. McCauley, P. O. Neil, I. M. Parker, J. N.
562 Thompson, and S. G. Weller. 2001. The population biology of invasive species. *Annual*
563 *Review of Ecology and Systematics* 32:305–332.

564 Schreiber, S. J., and J. O. Lloyd-Smith. 2009. Invasion dynamics in spatially heterogeneous
565 environments. *The American Naturalist* 174:490–505.

566 Simberloff, D. 1989. Which insect introductions succeed and which fail? Pages 61–75 *in* J. A.
567 Drake et al., editor. *Biological Invasions: A Global Perspective*. John Wiley & Sons Ltd.

568 Simberloff, D. 2009. The role of propagule pressure in biological invasions. *Annual Review of*
569 *Ecology, Evolution, and Systematics* 40:81–102.

570 Sinclair, J. S., and S. E. Arnott. 2015. Strength in size not numbers: Propagule size more
571 important than number in sexually reproducing populations. *Biological Invasions*.

- Slatkin, M. 1985. Gene flow in natural populations. *Annual Review of Ecology and Systematics* 16:393–430.
- Szűcs, M., B. A. Melbourne, T. Tuff, and R. A. Hufbauer. 2014. The roles of demography and genetics in the early stages of colonization. *Proceedings of the Royal Society B Biological Sciences* 281:1–7.
- Szűcs, M., B. A. Melbourne, T. Tuff, C. Weiss-Lehman, and R. A. Hufbauer. 2017. Genetic and demographic founder effects have long-term fitness consequences for colonising populations. *Ecology Letters*.
- Taylor, S. S., I. G. Jamieson, and D. P. Armstrong. 2005. Successful island reintroductions of New Zealand robins and saddlebacks with small numbers of founders. *Animal Conservation* 8:415–420.
- de Valpine, P., C. Paciorek, D. Turek, C. Anderson-Bergman, and D. Temple Lang. 2016. nimble: Flexible BUGS-compatible system for hierarchical statistical modeling and algorithm development. R package version 0.6-2.
- Whiteley, A. R., S. W. Fitzpatrick, W. C. Funk, and D. A. Tallmon. 2015. Genetic rescue to the rescue. *Trends in Ecology and Evolution* 30:42–49.
- Zenni, R. D., and M. A. Nuñez. 2013. The elephant in the room: The role of failed invasions in understanding invasion biology. *Oikos* 122:801–815.

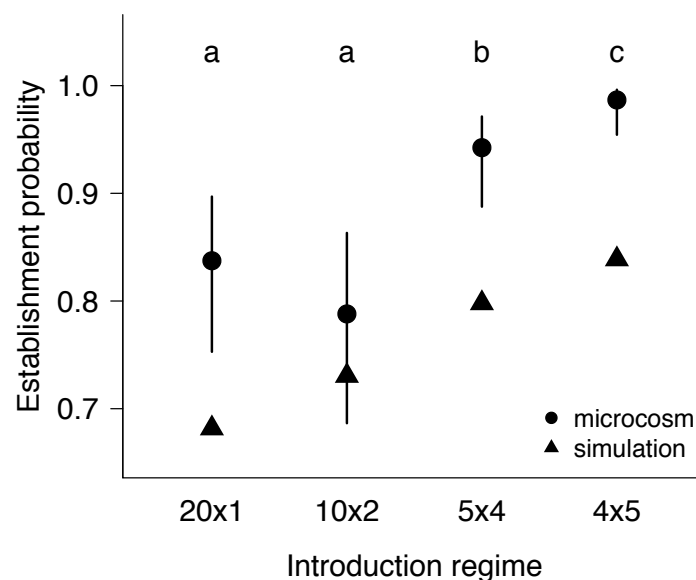


Figure 1. Establishment probabilities for each introduction regime assessed at generation 7. Triangles represent results from simulations. Dot-whiskers represent estimates and 95% confidence intervals from the mixed effects logistic regression model fit to data from the microcosm experiment. Different letters over dot-whiskers represent introduction regimes with significantly different establishment probabilities.

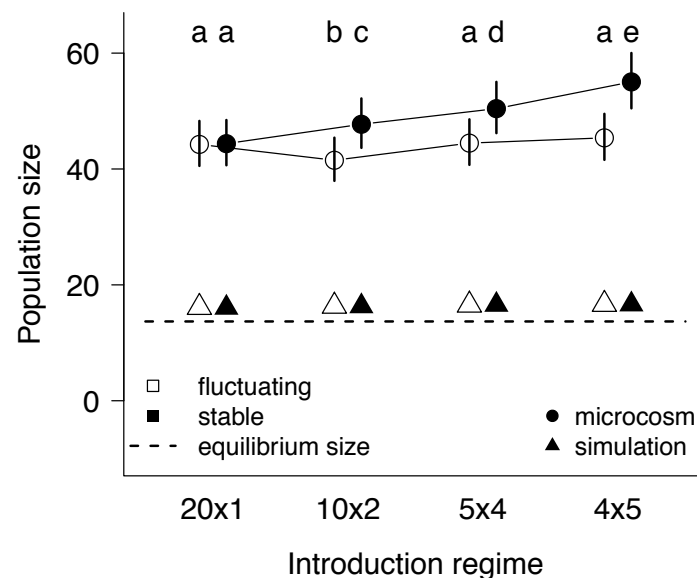


Figure 2. Mean sizes of extant populations for each introduction regime/environment combination in generation 7. Triangles represent results from simulations. Dot-whiskers represent estimates and 95% confidence intervals from the mixed effects Poisson regression model fit to data from the microcosm experiment. Different letters over dot-whiskers represent introduction regimes with significantly different mean population sizes. The dashed line represents the theoretical equilibrium population size derived from the NBBg model, which includes extinction and is therefore lower than the mean population size from the simulations.