

# Density-dependent selection in evolutionary genetics: a lottery model of Grime's triangle

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## Abstract

[Needs to be revised but won't do that now in case it has to become Nature introductory paragraph] Fitness is typically represented in heavily simplified terms in evolutionary genetics, often using constant selection coefficients. This excludes fundamental ecological factors such as dynamic population size or density-dependence from the most genetically-realistic treatments of evolution, a problem that inspired MacArthur's influential but problematic  $r/K$  theory. Following in the spirit of  $r/K$ -selection as a general-purpose theory of density-dependent selection, but grounding ourselves empirically in "primary strategy" trait classification schemes like Grime's triangle, we develop a new model of density-dependent selection which revolves around territorial contests. To do so, we generalize the classic lottery model of territorial acquisition, which has primarily been used for studying species co-existence questions, to accommodate arbitrary densities. We use this density-dependent lottery model to predict the direction of trait evolution under different environmental conditions and thereby provide a mathematical underpinning for Grime's verbal scheme. We revisit previous concepts of density-dependent selection, including  $r$  and  $K$  selection, and argue that our model distinguishes between different aspects of fitness in a more natural and intuitive manner.

“...the concept of fitness is probably too complex to allow of a useful mathematical development. Since it enters fundamentally into many population genetics considerations, it is remarkable how little attention has been paid to it.” — Warren J. Ewens, *Mathematical Population Genetics I*, 2004 [Should be removed if we need space]

Evolutionary models differ greatly in their treatment of fitness. In models of genetic evolution, genotypes are typically assigned constant (or frequency-dependent) selection coefficients describing the change in their relative frequencies over time. This simplified treatment of selection facilitates genetic realism, and can be justified over sufficiently short time intervals (Ewens, 2004, p. 276). The emphasis here is to infer past selection, migration and demographic change given a sample of nucleotide sequences, or to predict how allele frequencies change over time based on their fitness effects, population structure, genetic drift and linkage. The resulting picture of evolution excludes basic elements of the ecological underpinnings of selection, including density dependence, and how selection affects population size. This complicates the inference of past selection, because demographic changes can look genealogically very similar to selective frequency changes (Barton, 1998).

By contrast, models of phenotypic trait evolution use absolute fitness functions to describe how some traits of interest affect survival and reproduction in particular ecological scenarios (Diekmann et al., 2004; Metz et al., 1992). These fitness functions can be quite problem-specific and often only account for a few traits at a time. The emphasis here is on the conditions for invasion from low frequencies and co-existence, rather than frequency or abundance trajectories over time. For instance, adaptive dynamics uses “invasion fitness” to explore the consequences of eco-evolutionary feedbacks (Diekmann et al., 2004).

It is challenging to generalize beyond particular traits or ecological scenarios to model fundamentally different forms of selection. Perhaps this is not surprising given that fitness is such a complex quantity, dependent on all of a phenotype’s functional traits (Violle et al., 2007) and its environment. A detailed, trait-based, predictive model of fitness would be enormously complicated and situation-specific. It is therefore easy to doubt the feasibility of a simplified, general

mathematical treatment of fitness (Ewens, 2004, p. 276). For example, MacArthur's famous  $r/K$   
45 scheme (MacArthur, 1962; MacArthur and Wilson, 1967) is now almost exclusively known as a  
framework for understanding life-history traits, and judged on its failure in that role (Boyce, 1984;  
Pianka, 1970; Reznick et al., 2002; Stearns, 1977). However, the  $r/K$  scheme's original purpose  
48 was to extend the existing population-genetic treatment of selection to account for population  
density (MacArthur, 1962). Few attempts have been made to develop it further along these lines.

Empirical trait classification studies have suggested the existence of a few "primary strate-  
51 gies", reflecting broadly distinct responses to selection (Winemiller et al., 2015). Grime famously  
considered (Grime, 1974, 1977, 1988; Westoby, 1998) two broad determinants of population den-  
sity: stress (persistent hardship e.g. due to resource scarcity or unfavorable temperatures) and  
54 disturbance (intermittent destruction of vegetation e.g. due to trampling, herbivory, pathogens,  
extreme weather or fire). The extremes of these two factors define three primary strategies de-  
noted by C/S/R respectively (Fig. 1): competitors "C" excel in low stress, low disturbance envi-  
57 ronments; stress tolerators "S" excel in high stress, low disturbance environments; and ruderals  
"R" excel in low stress, high disturbance environments. Population persistence is not possible in  
high-stress, high-disturbance environments. Grime showed that measures of C, S and R across  
60 a wide range of plant species are anti-correlated, so that strong C-strategists are weak S and R  
strategists, and so on, creating a triangular C/S/R ternary plot (Grime, 1974). Similar schemes  
were proposed for insects (Southwood, 1977), fishes (Winemiller and Rose, 1992), and zooplank-  
63 ton (Allan, 1976). More recently, modern hierarchical clustering techniques have revealed distinct  
trait clusters in corals analogous to Grime's primary strategies (Darling et al., 2012). These em-  
pirical findings suggest that functional traits contribute to fitness predominantly via a few key  
66 factors such as intrinsic reproductive rate or stress-tolerance.

Here we explore the interplay between some "key factors" of fitness in a simplified, terri-  
torial model of growth, dispersal and competition. This broadly follows the original spirit of  
69 MacArthur's  $r/K$  scheme. More specifically, our aim is to begin adding some ecological realism  
to population genetics' time-depedendent, genetically-focused view of evolution. We revisit the



Figure 1: Schematic of Grime's triangle. The two axes show increasing levels of environmental stress and disturbance, respectively. Population persistence is not possible if the combination of stress and disturbance is too large (dashed line). This creates a triangle, each corner of which corresponds to a "primary strategy".

classic lottery model of Chesson and Warner (1981), which has two features that make it well suited for this role, but one critical flaw that we rectify here.

The first feature is that the lottery representation of competition is particularly concise. Mature individuals ("adults") each require their own territory, whereas newborn individuals ("propagules") disperse to, and subsequently compete for, territories made available by the death of adults. Territorial contest among propagules leaves a single victorious adult per territory, the victor chosen at random from the propagules present, with probabilities weighted by a coefficient for each type representing competitive ability, akin to a lottery (Sale, 1977). By comparison, coefficients for the pairwise effects of types on each other (e.g. the  $\alpha$  coefficients in the generalized Lotka-Volterra equations and the associated concept of " $\alpha$ -selection"; Case and Gilpin 1974; Gill 1974; Joshi et al. 2001), or explicit resource consumption (Tilman, 1982), are much more complicated. The second feature is the close connection between the lottery model and one of the foundational models of population genetics, the Wright-Fisher model of genetic drift, which we discuss further below.

The critical flaw of the classic lottery model is that it breaks down at low densities (few propagules dispersing to each territory), precluding density-dependent behaviour. Our first task is to analytically extend the classic lottery model to correctly account for low density behavior

(sections “Model” and “Mean field approximation”).

Using our extended lottery model, we then revisit Grime’s C/S/R scheme, and evaluate how  
90 C/S/R manifests at the level of within-population genotypic evolution (as opposed to phenotypic  
divergence between species; sections “Invasion of rare genotypes and coexistence” and “Primary  
strategies and Grime’s triangle”). This represents a “sanity check” on our density-dependent  
93 lottery model. The resulting formulation of the C/S/R scheme is mathematical, in contrast  
to Grime’s original verbal and descriptive approach, which is a recognized hindrance to the  
evaluation or broader application of the C/S/R scheme (e.g. Tilman 2007).

96 We then explore some time-dependent behavior of our extended lottery model. Taking an  
example inspired by recent studies of rapid, seasonal evolution in *Drosophila* (Bergland et al.,  
2014), we discuss how environmental fluctuations might stabilize polymorphisms in the presence  
99 of cyclical population density.

## Model

We assume that reproductively mature individuals (“adults”) each require their own territory to  
102 survive and reproduce (Fig. 2). All territories are identical, and the total number of territories is  
 $T$ . Time  $t$  advances in discrete iterations, each representing the time from birth to reproductive  
maturity. In iteration  $t$ , the number of adults of the  $i$ ’th genotype is  $n_i(t)$ , the total number of  
105 adults is  $N(t) = \sum_i n_i(t)$ , and the number of unoccupied territories is  $U(t) = T - N(t)$ .

We assume that the  $n_i$  and  $T$  are large enough that stochastic fluctuations in the  $n_i$  (“drift”) can  
be ignored. We derive deterministic equations for the expected change in the  $n_i$  over time, leaving  
108 the evaluation of drift for future work. In particular, we do not evaluate the initial stochastic  
behaviour of adaptive mutant lineages while they are at low abundance. When considering  
mutations, we restrict our attention to the earliest deterministic behavior of mutant lineages while  
111 they are still at low frequency (the transition to deterministic growth occurs at an abundance of  
order equal to their inverse expected absolute growth rate; Uecker and Hermisson 2011).

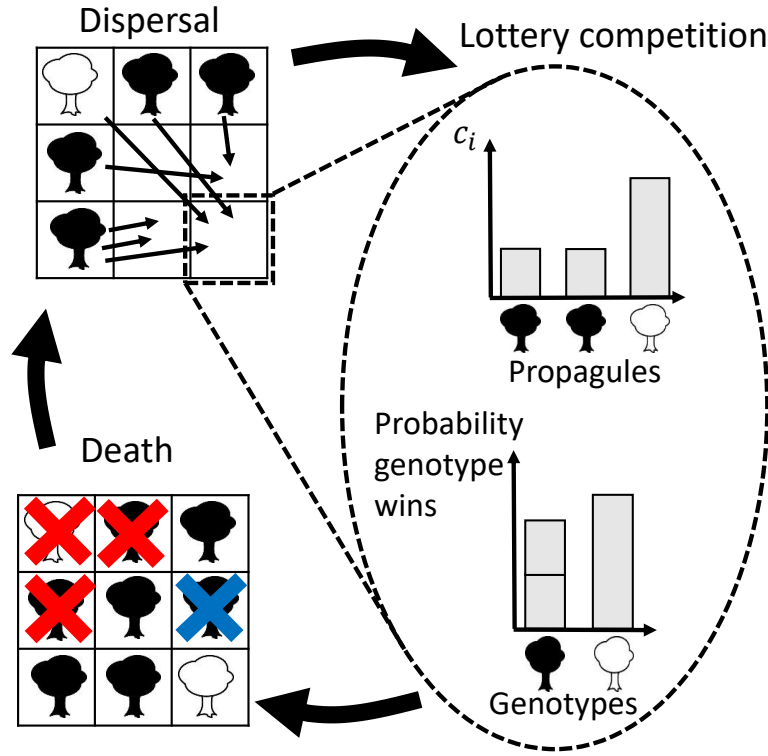


Figure 2: Each iteration of our lottery model has three main elements. First, propagules are produced by adults which are dispersed at random over the unoccupied territories (only propagules landing on unoccupied territories are shown). Lottery competition then occurs in each unoccupied territory (competition in only one territory is illustrated): each genotype has a probability proportional to  $b_i n_i c_i$  of securing the territory. Then occupied territories are freed up by adult mortality. In Eq. (3) and most of the paper, only adults can die (red crosses), but we will also consider the case where juveniles die (blue cross; section “Primary strategies and Grime’s triangle”).

Each iteration, adults produce new offspring (“propagules”),  $m_i$  of which disperse to un-  
 114 occupied territories. We assume that adults cannot be ousted from their territories, so that  $m_i$   
 only includes propagules landing on unoccupied territories. Propagules disperse at random over  
 the unoccupied territories, regardless of distance from their parents, and independently of each  
 117 other. There is no interaction between propagules (e.g. avoidance of territories crowded with  
 propagules). Loss of propagules during dispersal is subsumed into  $m_i$ .

In general,  $m_i$  will increase with  $n_i$ , and will depend on population density  $N$ . For example,  
 120 if  $b_i$  is the number of successfully dispersing propagules produced per genotype  $i$  adult, then  
 the loss of propagules due to dispersal to occupied territories implies  $m_i = b_i(1 - N/T)n_i$ , akin  
 to Levins’ competition-colonization model (Levins and Culver, 1971; Tilman, 1994). In section  
 123 “Cyclical birth and death rates” we evaluate Eq. (4) numerically using this functional form for  
 $m_i$ , with  $b_i$  assumed to be constant.

In the sections “Invasion of rare genotypes and coexistence” and “Primary strategies and  
 126 Grime’s triangle”, we assume the simpler form  $m_i = b_i n_i$ , with constant  $b_i$ , meaning that all  
 propagules land on unoccupied territories (a form of directed dispersal). This simplifies the  
 mathematics without affecting the results of those sections, which only depend on the low-  
 129 frequency invasion behavior of Eq. (4). Note that due to our assumption of uniform dispersal, the  
 parameter  $b_i$  can be thought of as a measure of “colonization ability”, which combines fecundity  
 and dispersal ability (Bolker and Pacala, 1999; Levins and Culver, 1971; Tilman, 1994).

The number of individuals of the  $i$ ’th genotype landing in any particular territory is denoted  
 132  $x_i$ . We assume that  $x_i$  follows a Poisson distribution  $p_i(x_i) = l_i^{x_i} e^{-l_i} / x_i!$ , where  $l_i = m_i / U$  is the  
 mean territorial propagule density. This only approximates uniform random dispersal, but is  
 135 essentially exact provided that the  $n_i$  are large enough that drift can be ignored (Appendix A).

When multiple propagules land on the same territory, the victor is determined by lottery  
 competition: genotype  $i$  wins a territory with probability  $c_i x_i / \sum_j c_j x_j$ , where  $c_i$  is a constant  
 138 representing relative competitive ability (Fig. 2).

In the classic lottery model (Chesson and Warner, 1981), unoccupied territories are assumed



to be saturated with propagules from every genotype  $l_i \gg 1$ . From the law of large numbers,  
 141 the composition of propagules in each territory will then not deviate appreciably from the mean  
 composition  $l_1, l_2, \dots, l_G$  ( $G$  is the number of genotypes present), and so the probability that geno-  
 type  $i$  wins any particular unoccupied territory is approximately  $c_i l_i / \sum_j c_j l_j$ . Let  $\Delta_+ n_i$  denote the  
 144 number of territories won by genotype  $i$ . Then  $\Delta_+ n_1, \Delta_+ n_2, \dots, \Delta_+ n_G$  follow a multinomial dis-  
 tribution with  $U$  trials and success probabilities  $\frac{c_1 l_1}{\sum_j c_j l_j}, \frac{c_2 l_2}{\sum_j c_j l_j}, \dots, \frac{c_G l_G}{\sum_j c_j l_j}$ , respectively. Genotype  $i$   
 is expected to win  $c_i l_i / \sum_j c_j l_j$  of the  $U$  available territories, and deviations from this expected  
 147 outcome are small (since  $T$  is large by assumption), giving

$$\Delta_+ n_i(t) = \frac{c_i l_i}{\sum_j c_j l_j} U(t) = b_i n_i \frac{1}{L} \frac{c_i}{\bar{c}}, \quad (1)$$

where  $\bar{c} = \sum_j c_j m_j / M$  is the mean propagule competitive ability for a randomly selected propa-  
 gule,  $L = M/U$  is the total propagule density and  $M = \sum_j m_j$  is the total number of propagules.

150 There is a close connection between the classic lottery model and the Wright-Fisher model of  
 genetic drift (Svardal et al., 2015). In the Wright-Fisher model, genotype abundances are sampled  
 each generation from a multinomial distribution with success probabilities  $w_i n_i / \sum_j w_j n_j$ , where  
 153  $w$  is relative fitness and the  $n_i$  are genotype abundances in the preceding generation. Population  
 size  $N$  remains constant. This is mathematically equivalent to the classic lottery model with non-  
 overlapping generations ( $d_i = 1$  for all  $i$ ) and  $w_i = b_i c_i$ . Thus, the classic lottery model allows  
 156 us to replace the abstract Wright-Fisher relative fitnesses  $w_i$  with more ecologically-grounded  
 fecundity, competitive ability and mortality parameters  $b_i$ ,  $c_i$  and  $d_i$ , respectively. Since birth and  
 death rates affect absolute abundances, this allows us to evaluate selection at different densities  
 159 (after appropriate extensions are made), in an otherwise very similar model to the canonical  
 Wright-Fisher. We therefore expect that drift in our extended lottery model should be similar to  
 that in the Wright-Fisher model, but we leave this for future work.

162 In our extension of the classic lottery model, we do not restrict ourselves to high propagule  
 densities. Eq. (1) is nonsensical at low densities ( $l_i \ll 1$ ): genotype  $i$  can win at most  $m_i$  territories,

yet Eq. (1) demands  $c_i l_i / \sum_j c_j l_j$  of the  $U$  unoccupied territories, for any value of  $U$ . Intuitively,  
 165 the cause of this discrepancy is that individuals are discrete. Genotypes with few propagules  
 depend on the outcome of contests in territories where they have at least one propagule present,  
 not some small fraction of a propagule as would be implied by small  $l_i$  in the classic lottery model.  
 168 In other words, deviations from the mean propagule composition  $l_1, l_2, \dots, l_G$  are important at  
 low density.

We expect that a fraction  $p_1(x_1) \dots p_G(x_G)$  of the  $U$  unoccupied territories will have the  
 171 propagule composition  $x_1, \dots, x_G$ . Genotype  $i$  is expected to win  $c_i x_i / \sum_j c_j x_j$  of these. Ignoring  
 fluctuations about these two expectations (due to our no-drift, large  $T$ , large  $n_i$  approximation),  
 genotype  $i$ 's territorial acquisition is given by

$$\Delta_+ n_i(t) = U(t) \sum_{x_1, \dots, x_G} \frac{c_i x_i}{\sum_j c_j x_j} p_1(x_1) \dots p_G(x_G), \quad (2)$$

174 in our extended lottery model, where the sum only includes territories with at least one propag-  
 ule present. Note that unlike the classic lottery model, not all unoccupied territories are claimed  
 each iteration, since under Poisson dispersal a fraction  $e^{-L}$  remain unoccupied.

177 For the majority of this manuscript we assume that mortality only occurs in adults (setting  
 aside the juvenile deaths implicit in territorial contest), and at a constant, genotype-specific per-  
 capita rate  $d_i$ , so that the overall change in genotype abundances is

$$\Delta n_i(t) = \Delta_+ n_i(t) - d_i n_i(t). \quad (3)$$

180 This seems reasonable in the absence of disturbances; when we come to consider the effects of dis-  
 turbances (Section "Primary strategies and Grime's triangle"), we will incorporate disturbance-  
 induced mortality in competing juveniles (Fig. 2).

## Results

### Mean Field Approximation

Eq. (2) involves an expectation over the time-dependent dispersal distributions  $p_i$ , and is thus too complicated to give intuition about the dynamics of density-dependent lottery competition. We now evaluate this expectation using a “mean field” approximation.

Similarly to the high- $l_i$  approximation of classic lottery model, we replace the  $x_i$  with appropriate mean values, although we cannot simply replace  $x_i$  with  $l_i$ . For a genotype with low propagule density  $l_i \ll 1$ , we have  $x_i = 1$  in the territories where its propagules land, and so its growth comes entirely from territories which deviate appreciably from  $l_i$ . To account for this, we separate Eq. (2) into  $x_i = 1$  and  $x_i > 1$  parts. Our more general mean field approximation only requires that there are no large discrepancies in competitive ability (i.e. we do not have  $c_i/c_j \gg 1$  for any two genotypes). We obtain (details in Appendix B)

$$\Delta_+ n_i(t) \approx b_i n_i \left[ e^{-L} + (R_i + A_i) \frac{c_i}{\bar{c}} \right], \quad (4)$$

where

$$R_i = \frac{\bar{c} e^{-l_i} (1 - e^{-(L-l_i)})}{c_i + \frac{L-1+e^{-L}}{1-(1+l_i)e^{-L}} \frac{\bar{c} L - c_i l_i}{L-l_i}}, \quad (5)$$

and

$$A_i = \frac{\bar{c}(1 - e^{-l_i})}{\frac{1-e^{-l_i}}{1-(1+l_i)e^{-L}} c_i l_i + \frac{1}{L-l_i} \left( L \frac{1-e^{-L}}{1-(1+L)e^{-L}} - l_i \frac{1-e^{-l_i}}{1-(1+l_i)e^{-L}} \right) \sum_{j \neq i} c_j l_j}. \quad (6)$$

To supplement our analytical mean field derivation, we verified that Eq. (4) closely approximates the exact behavior of our density-dependent lottery model using numerical simulations (Appendix B). Thus, Eq. (4) describes how type abundances change over time in a lottery model where population density can itself vary with time.

Comparing Eq. (4) to Eq. (1), the classic lottery per-propagule success rate  $c_i/\bar{c}L$  has been replaced by three separate terms. The first,  $e^{-L}$ , accounts for propagules which land alone on

unoccupied territories; these territories are won without contest. The second,  $R_i c_i / \bar{c}$  represents competitive victories when the  $i$  genotype is a rare invader in a high density population: from Eq. (5),  $R_i \rightarrow 0$  when the  $i$  genotype is abundant ( $l_i \gg 1$ ), or other genotypes are collectively rare ( $L - l_i \ll 1$ ). The third term,  $A_i c_i / \bar{c}$ , represents competitive victories when the  $i$  genotype is abundant:  $A_i \rightarrow 0$  if  $l_i \ll 1$ . The relative importance of these three terms varies with both the overall propagule density  $L$  and the relative propagule frequencies  $m_i / M$ . If  $l_i \gg 1$  for all genotypes, we recover the classic lottery model (only the  $A_i c_i / \bar{c}$  term remains, and  $A_i \rightarrow 1 / L$ ).

## Primary strategies and Grime's triangle

Here we describe how Grime's "disturbed", "stressful" and "ideal" environments can be captured mathematically in our scheme. To proceed, we need to map these verbally-defined environments to quantitative parameter regimes in our model.

The ideal environment is characterized by the near-absence of stress and disturbance:  $d \ll 1$ , whereas  $b$  is potentially much larger than 1.

Disturbed environments are characterized by short bursts of high extrinsic mortality  $d$  caused by physical destruction. We assume that in the disturbance extreme of Grime's triangle, many such bursts (which could each be spatially localized) will occur each iteration (i.e. over the time from birth to reproductive maturity), and so we can approximate extreme disturbance by high constant mortality rates  $d_i$ , which are now extended to affect juveniles as well. We assume that disturbances are equally damaging to adults and juveniles, so that only  $(1 - d_i) \Delta_+ n_i$  rather than  $\Delta_+ n_i$  territories are secured by genotype  $i$  each iteration. Heavily disturbed environments then correspond most adults and juveniles being killed every an iteration ( $d_i \approx 1$ ).

Stressful environments are more ambiguous, and have been the subject of an extensive debate in the plant ecology literature (the "Grime-Tilman" debate; Aerts 1999 and references therein). Severe stress inhibits growth and reproduction, so that  $b \ll 1$  (Grime, 1974, 1977). In Grime's view, this means that the rate at which propagules successfully develop to adulthood cannot appreciably exceed the mortality rate  $b / d \approx 1$ . In our model, this implies low propagule density

and little territorial contest.

The alternative view is that stressed environments are highly competitive. In spite of inhibited  
231 growth and reproduction, population density  $N/T$  is actually high since stressful environments  
also have lower environmental carrying capacity (Taylor et al., 1990). For example, if consumable  
resources are scarce, we expect intense resource competition (for empirical support, see Davis  
234 et al. 1998). In our model, territorial contests will then be important.

The mapping of different environments to our model parameters is summarized in the first  
two rows of Fig. 3. Also shown is the approximate dependence of  $\Delta_+ n_i$  on  $b_i$  and  $c_i$  for each  
237 environment (fourth row; details in Appendix). These can be used to infer the expected direction  
of evolution for the traits  $b$ ,  $c$  and  $d$  (fifth row) using a standard invasion analysis.

According to Haldane's formula, the probability that an adaptive mutant survives its initial  
240 low abundance phase and begins to grow deterministically is proportional to its expected ab-  
solute growth rate (Haldane, 1927; Uecker and Hermisson, 2011), with a proportionality factor  
typically of order one. The fixation of neutral mutations is exceedingly unlikely (probability of  
243 order  $1/N$ ). The direction of evolutionary change is determined by the mutational trait changes  
which are available and also confer an appreciable fitness benefit (Yampolsky and Stoltzfus, 2001),  
where availability is subject to constraints imposed by the environment.

246 For example, in Grime's interpretation of stressful environments,  $L$  is low, so competition is  
not important, and only mutants with greater  $b$  or lower  $d$  will have an appreciably greater  $\Delta n_i$ .  
Mutations in  $c$  are effectively neutral, and will rarely fix. However,  $b$  is constrained to be small.  
249 Thus, while some rare mutations may produce small improvements in  $b$ , it is much more likely  
that mutations lower  $d$ , making this the expected direction of evolutionary change.

Following Grime's original argument for a triangular scheme (Grime, 1977), Fig. 4 repre-  
252 sents each environmental extreme schematically as a vertex on a triangular space defined by  
perpendicular stress and disturbance axes. The ideal environment lies at the origin (no stress or  
disturbance), while the stressful and disturbed environments lie at the limits of survival on their  
255 respective axes. The hypotenuse connecting the stress and disturbance endpoints represents the

	Ideal	Disturbance*	Stress (G)	Stress (HD)
Constraints	$d \ll 1$	$d \approx 1$	$b \ll 1$	$b \ll 1$
Other parameters	$b \gg d$	$b \gg d$	$b \approx d$	$b > d$
Density $N/T$	High	Low	Low	High
Evolution for	$\uparrow b, \uparrow c$	$\uparrow b, \downarrow d$	$\downarrow d$	$\uparrow c, \downarrow d$

Figure 3: The realization of Grime’s three environmental extremes in our model, as well as the high-density variant of the stressful environment. Shown are the mapping of each environment to our parameters, the approximate dependence of  $\Delta_+ n_i$  on  $b_i$  and  $c_i$ , as well as the corresponding expected evolutionary changes in  $b_i$ ,  $c_i$  and  $d_i$ . \*Mortality affects both adults and juveniles in the disturbed environment, with  $\Delta_+ n_i$  replaced by  $(1 - d_i)\Delta_+ n_i$  in Eq. (3).

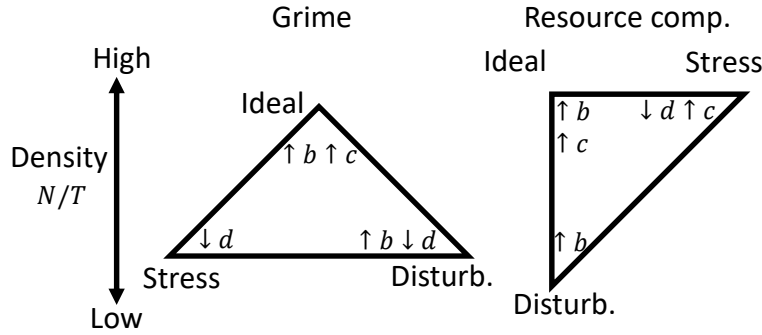


Figure 4: The realization of Grime’s triangle in our model. Schematic representation of the triangular space bounded by the low/high extremes of stress/disturbance. The low- $T$  interpretation of stress is also shown. The vertices of the triangles correspond to different environmental extremes. Selection favors different traits at each vertex, leading to different trait clusters.

limits of survival in the presence of a combination of stress and disturbance. The direction of evolutionary change is different at each vertex, leading to the emergence of different trait clusters or “primary strategies”.

## Coexistence in constant and cyclical environments

In the previous section we only considered how  $b$ ,  $c$  and  $d$  should respond in Grime’s environmental extremes. Here we further explore the low frequency behavior of Eq. (4) to determine which types can coexist in a constant environment, and then consider the full time-dependent behaviour of Eq. (4) in a cyclical environment.

In a population with a single genotype  $i$  which is in equilibrium,  $R_i = 0$ ,  $\bar{c} = c_i$  and  $\Delta n_i = 0$ ,

and Eq. (4) gives

$$b_i \left( e^{-L} + A_i \right) - d_i = 0, \quad (7)$$

where  $A_i = (1 - (1 + L)e^{-L})/L$ . Now suppose that a new genotype  $j$ , which is initially rare,  
 267 appears in the population. Then  $A_j \ll R_j$ ,  $l_j \approx 0$  and  $\bar{c} \approx c_i$ , and so, from Eq. (4),  $n_j$  will increase  
 if

$$b_j \left( e^{-L} + R_j \frac{c_j}{c_i} \right) - d_j > 0, \quad (8)$$

where  $R_j \approx (1 - e^{-L}) / \left( \frac{c_j}{c_i} + \frac{L-1-e^{-L}}{1-(1+L)e^{-L}} \right)$ .

270 Stable coexistence is possible between genotypes that are superior in different traits. Suppose  
 that  $j$  is better at securing territories ( $c_j > c_i$ ), that  $i$  is better at producing propagules ( $b_i > b_j$ ),  
 and that  $d_i = d_j$ . Coexistence occurs if  $j$  will invade an  $i$ -dominated population, but  $i$  will also  
 273 invade a  $j$ -dominated population (“mutual invasion”). If  $b_i$  is so large that  $L \gg 1$  when  $i$  is  
 dominant, and  $b_j$  is so small that  $L \ll 1$  when  $j$  is dominant, then, combining Eqs. (7) and (8),  
 we find that  $i$  invades  $j$  because  $b_i > b_j$ , while  $j$  invades  $i$  provided that

$$b_j c_j R_j - b_i c_i A_i > 0. \quad (9)$$

276 Thus, coexistence occurs if  $c_j/c_i$  is large enough. This is a version of the classic competition-  
 colonization trade-off (Levins and Culver, 1971; Tilman, 1994): the competitor ( $c$ -specialist) leaves  
 many territories unoccupied (low  $L$ ) due to its poor colonization ability (low  $b$ ), which the colo-  
 279 nizer ( $b$ -specialist) can then exploit. A similar argument applies for coexistence between high- $c$   
 and low- $d$  specialists; a “competition-longevity” trade-off (Tilman, 1994). These forms of co-  
 existence require density dependence, and are not present in the classic lottery model. Mutual  
 282 invasibility is not possible between  $b$ - and  $d$ -specialists.

Now suppose that birth and death rates vary periodically with amplitude sufficient to cause  
 large changes in population density. This example is inspired by natural *Drosophila* populations,  
 285 which expand rapidly in the warmer months when fruit is abundant, but largely die off in the

colder months. Within this seasonal population density cycle, hundreds of polymorphisms also cycle in frequency (Bergland et al., 2014). Some of these polymorphisms may be adaptive and potentially millions of years old, suggesting stable coexistence (Bergland et al., 2014; Messer et al., 2016). Selection on allele frequencies thus occurs on the same time scale as population demography, a situation vastly more complicated than classical sweeps in demographically stable populations (Messer et al., 2016).

The classical population genetic treatment of fluctuating selection suggests that environmental fluctuations do not promote coexistence. Allele frequencies are successively multiplied by relative fitness values for each environmental iteration, and so two alleles favored in different environments can only stably coexist if the product of fitnesses for one type exactly equals the product for the other (Dempster, 1955). Thus, stable coexistence still requires frequency-dependent selection or heterozygote advantage (as is required in a constant environment).

This classical argument overlooks two general effects that promote coexistence in fluctuating environments. The first is the storage effect, which occurs when part of the population is protected from selection (due to overlapping generations in the lottery model; Chesson and Warner 1981). The second is the bounded population size effect of Yi and Dean (2013), which occurs when each environmental cycle involves growth from low to high density, with the time spent growing each cycle dependent on the fitness of the types present.

Fig. 5a-c shows the behavior of Eq. (4) for an example where  $b$  and  $d$  cycle between zero and positive values (“summers” with rapid growth and no mortality, and “winters” with mortality and no growth). Both the storage effect (adults are sheltered from selection during the summer growth phase) and the bounded density effect (expansion to high density occurs every cycle) are operating. Two types are present, a  $b$  specialist, which is better at rapidly growing in the summer (higher  $b$ ), and a  $d$  specialist which is better at surviving the winter (lower  $d$ ). Neither type has an advantage over a full environmental cycle, and they stably coexist. This is due to a combination of the storage and bounded density effects (recall that stable coexistence between  $b$  and  $d$  specialists was not possible in a constant environment).



The classic lottery model (Eq. 1) gives dramatically different co-existence predictions because expansion to carrying capacity occurs immediately at the start of the summer (Fig. 5d-f). As a result, coexistence requires that the winter survivor's  $b$  must be about 5 times smaller than predicted when we properly account for the growth in the abundance of each type using Eq. (4) (keeping the other parameters the same). Previous models of the promotion of genetic variation via the storage effect (Ellner and Hairston Jr, 1994) similarly assume that the total number of offspring per iteration is constant, and would produce a similar error.

## Discussion

In the introduction we mentioned the recurring difficulties with confounding selection and demography in population genetic inference. While we have not directly attempted to perform inference with our model, and Eq. (4) may not be appropriate for particular inference problems, it seems that something similar (and hopefully more analytically tractable) to our extension of the lottery model is unavoidable because, fundamentally, selective births and deaths affect both abundances and frequencies, not one or the other in isolation. Moreover, some aspects of allele frequency change are intrinsically density-dependent. In the classic lottery model, which as we have seen is essentially the Wright-Fisher model with overlapping generations,  $b_i$  and  $c_i$  are equivalent in the sense that the number of territorial victories only depends on the product  $b_i c_i$  (see "Model"). This is no longer the case in our extension, where  $b$  and  $c$  specialists can co-exist. This "colonization-competition trade-off" is well known in the co-existence literature (Tilman, 1994). It and similar forms of "spatial co-existence" in stable environments have previously been modeled either with Levin's qualitative representation of competition (Levins and Culver, 1971; Tilman, 1994), as opposed to the quantitative  $c$  of lottery competition, or with a more sophisticated treatment of space (non-uniform dispersal; Bolker and Pacala 1999; Shmida and Ellner 1984). In cyclical environments, polymorphisms can be stabilized by the bounded density effect which is completely lost if there is an exclusive focus on allele frequencies (Yi and Dean, 2013).

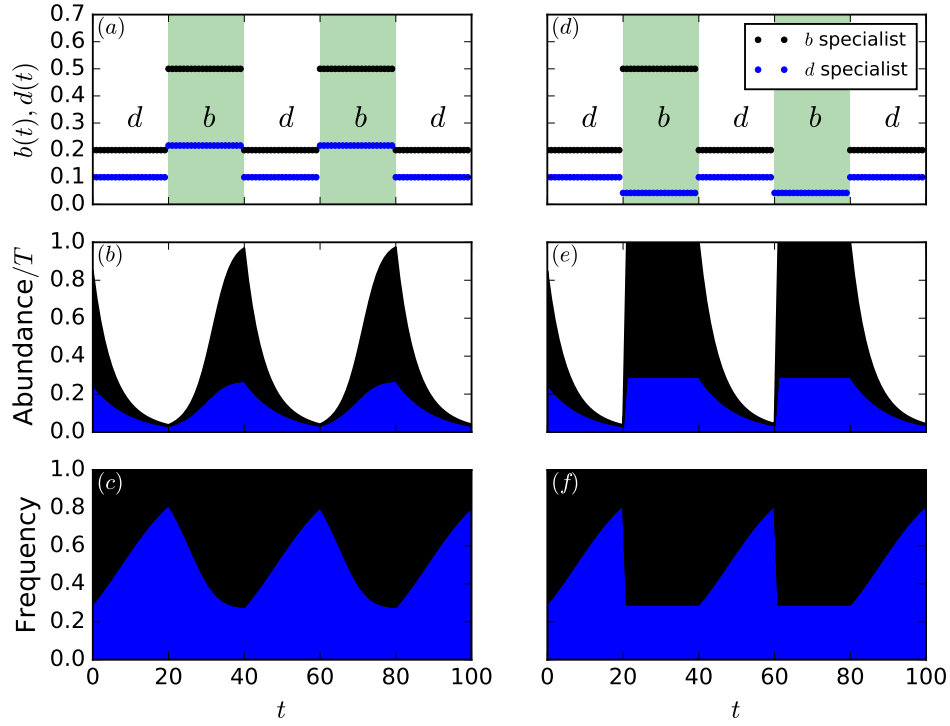


Figure 5: Stable coexistence between  $b$  and  $d$  specialists in a fluctuating environment. (a) Birth and death rates seasonally alternate being nonzero (white for winter, green for summer). The  $b$  specialist (black) has higher  $b$  and  $d$  ( $b = 0.5, d = 0.2$ ) than the  $d$  specialist ( $b = 0.217, d = 0.1$ ) (blue). (b) Both types grow during the positive  $b$  phase, and decline during the positive  $d$  phase, but the  $d$  specialist does so at a lower rate. Total height (blue+black) is population density  $N/T$ . (c) Summer favors the  $b$  specialist, winter the  $d$  specialist, and they stably coexist. (d-f) Same as (a-c) for the classic lottery model, where coexistence now requires  $b \approx 0.0421$  for the  $d$  specialist. For illustration, the propagule abundances are assumed to have the form  $m_i = b_i(1 - N/T)n_i$ , reflecting non-directed dispersal.

We leave the details of how our model might be applied in inference, including the crucial issue  
339 of its genetic drift predictions, for future work.

It is interesting to compare the predictions of the extended lottery model with earlier approaches, such as the  $r/K$  scheme, where  $r = b - d$  is the maximal, low-density growth rate (Pianka, 1972). Confusingly, the term “ $K$ -selection” sometimes refers generally to selection at high  
342 density (Pianka, 1972), encompassing both selection for higher saturation density (MacArthur and Wilson, 1967) and competitive ability (Gill, 1974). Contrary to an  $r/K$  dichotomy, empirical  
345 studies have shown that maximal growth rate and saturation density (measured by abundance) are positively correlated, both between species/strains (Fitzsimmons et al., 2010; Hendriks et al., 2005; Kuno, 1991; Luckinbill, 1979), and as a result of experimental evolution (Luckinbill, 1978,  
348 1979). From the perspective of our model, this correlation is not surprising since the saturation density, which is determined by a balance between births and deaths, increases with  $b$ .

There is support for a negative relationship between competitive success at high density  
351 and maximal growth rate (Luckinbill, 1979), consistent with an  $r/K$  dichotomy. This could be driven by a tradeoff between individual size and reproductive rate. To avoid confusion with other forms of “ $K$ -selection”, selection for competitive ability has been called “ $\alpha$ -selection” after  
354 the competition coefficients in the Lotka-Volterra equation (Case and Gilpin, 1974; Gill, 1974; Joshi et al., 2001). However, competitive success as measured by  $\alpha$  (i.e. the per-capita effect of one genotype on another genotype’s growth rate) is only partly determined by individual  
357 competitive ability — in the presence of age-structured competition and territoriality, it also includes the ability of each genotype to produce contestants i.e.  $b$  in our model. Our  $c$  is strictly competitive ability only — as such, changes in  $c$  do not directly affect population density (the  
360 total number of territories occupied per iteration is  $\Delta_+ N = U(1 - e^{-L})$ , which does not depend directly on the  $c_i$ ). The clean separation of a strictly-relative  $c$  parameter is particularly useful from an evolutionary genetics perspective, essentially embedding a zero-sum relative fitness trait  
363 within a non-zero-sum fitness model. This could have interesting applications for modeling the impacts of intra-specific competition on species extinction, for example due to clonal interference

(Desai and Fisher, 2007; Gerrish and Lenski, 1998) between *c*-strategists on the one hand, and *b*-  
and *d*- strategists on the other.

*K*-selection in the narrow logistic sense of selection for a greater environmental carrying  
capacity for given birth and death rates, sometimes referred to as “efficiency” (MacArthur and  
Wilson, 1967), could be represented in our model by smaller individual territorial requirements.  
To a first approximation, two co-occurring genotypes which differ by a small amount in their  
territorial requirements only should have the same fitness since the costs or benefits of a change in  
the amount of unoccupied territory is shared equally among genotypes via the propagule density  
per territory  $L$ . The situation is more complicated when the differences in territorial requirements  
become large enough that territorial contests can occur on different scales for different genotypes.  
We leave these complications for future work.

Our realization of Grime’s triangle (Fig. 4) differs from approaches which identify primary  
strategies as trait combinations which can co-exist (Bolker and Pacala, 1999), referring instead to  
the direction of adaptive trait evolution under different regimes of stress and disturbance, which  
is closer in spirit to Grime’s arguments (Grime, 1974, 1977). In addition, we have not assumed any  
kind of trade-offs or pleiotropy between *b*, *c* and *d*, only constraints imposed by the environment  
on the order of magnitude of *b* and *d*. As an example of a trade-off, corals which rapidly out-  
shade neighbors have a tall, branched morphology which is vulnerable to disturbances, and so,  
all else being equal, ideal environment *c*-strategists will suffer higher mortality from disturbances  
(Darling et al., 2012). Fig. 4 gives the same conclusion without invoking trade-offs; mutations  
which reduce disturbance vulnerability are essentially neutral under ideal conditions, leading  
to no improvements in mortality from disturbances, whereas *c* will tend to increase over time.  
Thus, while trade-offs may amplify specialization, and are sometimes invoked to explain primary  
strategy schemes (Aerts, 1999; MacArthur and Wilson, 1967; Winemiller and Rose, 1992), they are  
not necessary for it.

One limitation of our model as a general-purpose model of density-dependent selection is  
the restriction of competition to interference competition between juveniles for durable resources

(lottery recruitment to adulthood), analogous to the ubiquitous assumption of viability selection  
393 in population genetics (Ewens, 2004, p. 45). In some respects this is the complement of resource  
competition models, which restrict their attention to exploitation competition, typically without  
age structure (Tilman, 1982). In the particular case that resources are spatially localized (e.g. due  
396 to restricted movement through soils), resource competition and territorial acquisition effectively  
coincide, and in principle resource competition could be represented by a competitive ability  $c$  (or  
conversely,  $c$  should be derivable from resource competition). The situation is more complicated  
399 if the resources are well-mixed, since, in general, resource levels then need to be explicitly tracked.  
It seems plausible that explicit resource tracking may not be necessary when the focus is on the  
evolution of similar genotypes rather than the stable co-existence of widely differing species  
402 (Ram et al., 2016). We are not aware of any attempts to delineate conditions under which explicit  
resource tracking is unnecessary even if it is assumed that community structure is ultimately  
determined by competition for consumable resources. More work is needed connecting resource  
405 competition models to the density-dependent selection literature, since most of the former has  
to date been focused on narrower issues of the role of competition at low resource availability  
(Aerts, 1999; Davis et al., 1998; Tilman, 2007).

408 While our model can be applied to species rather than genotypes (e.g. ecological invasions),  
our focus is genotype evolution i.e. the change in allele frequencies over time. Our assumption  
that there are no large  $c$  discrepancies (section “Mean field approximation”) amounts to a restric-  
411 tion on the amount of genetic variation in  $c$  in the population. Since beneficial mutation effect  
sizes will typically not be much larger than a few percent, large  $c$  discrepancies can only arise if  
the mutation rate is extremely large, and so the assumption will not be violated in most cases.  
414 However, this restriction could become important when looking at species interactions rather  
than genotype evolution.

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## 525 **Appendix A: Poisson approximation**

For simplicity of presentation, we have assumed a Poisson distribution for the  $x_i$  as our model of dispersal. Strictly speaking, the total number of  $i$  propagules  $\sum x_i$  (summed over unoccupied  
528 territories) is then no longer a constant  $m_i$ , but fluctuates between generations for a given mean

$m_i$ , which is more biologically realistic. Nevertheless, since we do not consider the random fluctuations in type abundances here, and for ease of comparison with the classic lottery model, we ignore the fluctuations in  $m_i$ . Instead we focus, on Poisson fluctuations in propagule composition in each territory.

In the exact model of random dispersal, the counts of a genotype's propagules across unoccupied territories follows a multinomial distribution with dimension  $U$ , total number of trials equal to  $m_i$ , and equal probabilities  $1/U$  for a propagule to land in a given territory. Thus, the  $x_i$  in different territories are not independent random variables. However, for sufficiently large  $U$  and  $m_i$ , this multinomial distribution for the  $x_i$  across territories is closely approximated by a product of independent Poisson distributions for each territory, each with rate parameter  $l_i$  (Arenbaev, 1977, Theorem 1). Since we are ignoring finite population size effects, we effectively have  $T \rightarrow \infty$ , in which case  $U$  can be only be small enough to violate the Poisson approximation if there is vanishing population turnover, and then the dispersal distribution is irrelevant anyway. Likewise, in ignoring stochastic finite population size for the  $n_i$ , we have effectively already assumed that  $m_i$  is large enough to justify the Poisson approximation (the error scales as  $1/\sqrt{m_i}$ ; Arenbaev 1977).

## Appendix B: Derivation of growth equation

We separate the right hand side of Eq. (2) into three components  $\Delta_+ n_i = \Delta_u n_i + \Delta_r n_i + \Delta_a n_i$  which vary in relative magnitude depending on the propagule densities  $l_i$ . Following the notation in the main text, the Poisson distributions for the  $x_i$  (or some subset of the  $x_i$ ) will be denoted  $p$ , and we use  $P$  as a general shorthand for the probability of particular outcomes.

### Growth without competition

The first component,  $\Delta_u n_i$ , accounts for territories where only one focal propagule is present  $x_i = 1$  and  $x_j = 0$  for  $j \neq i$  ( $u$  stands for "uncontested"). The proportion of territories where this

occurs is  $l_i e^{-L}$ , and so

$$\Delta_u n_i = U l_i e^{-L} = m_i e^{-L}. \quad (10)$$

### Competition when rare

555 The second component,  $\Delta_r n_i$ , accounts for territories where a single focal propagule is present along with at least one non-focal propagule ( $r$  stands for “rare”) i.e.  $x_i = 1$  and  $X_i \geq 1$  where  $X_i = \sum_{j \neq i} x_j$  is the number of nonfocal propagules. The number of territories where this occurs  
558 is  $U p_i(1) P(X_i \geq 1) = b_i n_i e^{-l_i} (1 - e^{-(L-l_i)})$ . Thus

$$\Delta_r n_i = m_i e^{-l_i} (1 - e^{-(L-l_i)}) \left\langle \frac{c_i}{c_i + \sum_{j \neq i} c_j x_j} \right\rangle_{\tilde{p}}, \quad (11)$$

where  $\langle \rangle_{\tilde{p}}$  denotes the expectation with respect to  $\tilde{p}$ , and  $\tilde{p}$  is the probability distribution of nonfocal propagule abundances  $x_j$  *after* dispersal, in those territories where exactly one focal  
561 propagule, and at least one non-focal propagule, landed.

Our “mean field” approximation is to replace  $x_j$  with its mean in the last term in Eq. (11),

$$\left\langle \frac{c_i}{c_i + \sum_{j \neq i} c_j x_j} \right\rangle_{\tilde{p}} \approx \frac{c_i}{c_i + \sum_{j \neq i} c_j \langle x_j \rangle_{\tilde{p}}}. \quad (12)$$

Below we justify this replacement by arguing that the standard deviation  $\sigma_{\tilde{p}}(\sum_{j \neq i} c_j x_j)$  (with  
564 respect to  $\tilde{p}$ ), is much smaller than  $\langle \sum_{j \neq i} c_j x_j \rangle_{\tilde{p}}$ .

We first calculate  $\langle x_j \rangle_{\tilde{p}}$ . Let  $X = \sum_j x_j$  denote the total number of propagules in a territory and  $\mathbf{x}_i = (x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_G)$  denote the vector of non-focal abundances, so that  $p(\mathbf{x}_i) =$

$p_1(x_1) \dots p_{i-1}(x_{i-1})p_{i+1}(x_{i+1}) \dots p_G(x_G)$ . Then,  $\tilde{p}$  can be written as

$$\begin{aligned}\tilde{p}(\mathbf{x}_i) &= p(\mathbf{x}_i | X \geq 2, x_i = 1) \\ &= \frac{P(\mathbf{x}_i, X \geq 2 | x_i = 1)}{P(X \geq 2)} \\ &= \frac{1}{1 - (1 + L)e^{-L}} \sum_{X=2}^{\infty} P(X) p(\mathbf{x}_i | X_i = X - 1),\end{aligned}\tag{13}$$

and so

$$\begin{aligned}\langle x_j \rangle_{\tilde{p}} &= \sum_{\mathbf{x}_i} \tilde{p}(\mathbf{x}_i) x_j \\ &= \frac{1}{1 - (1 + L)e^{-L}} \sum_{X=2}^{\infty} P(X) \sum_{\mathbf{x}_i} p(\mathbf{x}_i | X_i = X - 1) x_j.\end{aligned}\tag{14}$$

The inner sum over  $\mathbf{x}_i$  is the mean number of propagules of a given nonfocal type  $j$  that will be found in a territory which received  $X - 1$  nonfocal propagules in total, which is equal to  $\frac{l_j}{L - l_i}(X - 1)$ . Thus,

$$\begin{aligned}\langle x_j \rangle_{\tilde{p}} &= \frac{l_j}{1 - (1 + L)e^{-L}} \frac{1}{L - l_i} \sum_{k=2}^{\infty} P(X)(X - 1) \\ &= \frac{l_j}{1 - (1 + L)e^{-L}} \frac{L - 1 + e^{-L}}{L - l_i},\end{aligned}\tag{15}$$

where the last line follows from  $\sum_{X=2}^{\infty} P(X)(X - 1) = \sum_{X=1}^{\infty} P(X)(X - 1) = \sum_{X=1}^{\infty} P(X)X - \sum_{X=1}^{\infty} P(X)$ .

The exact analysis of the fluctuations in  $\sum_{j \neq i} c_j x_j$  is complicated because the  $x_j$  are not independent with respect to  $\tilde{p}$ . These fluctuations are part of the “drift” in type abundances which we leave for future work. Here we use the following approximation to give some insight into the magnitude of these fluctuations and also the nature of the correlations between the  $x_j$ . We replace  $\tilde{p}$  with  $\tilde{q}$ , defined as the  $\mathbf{x}_i$  Poisson dispersal probabilities conditional on  $X_i \geq 1$  (which are independent). The distinction between  $\tilde{p}$  with  $\tilde{q}$  will be discussed further below. The  $\tilde{q}$  approximation

gives  $\langle x_j \rangle_{\tilde{q}} = \langle x_j \rangle_p / C = l_j / C$ ,

$$\begin{aligned}
\sigma_{\tilde{q}}^2(x_j) &= \langle x_j^2 \rangle_{\tilde{q}} - \langle x_j \rangle_{\tilde{q}}^2 \\
&= \frac{1}{C} \langle x_j^2 \rangle_p - \frac{l_j^2}{C^2} \\
&= \frac{1}{C} (l_j^2 + l_j) - \frac{l_j^2}{C^2} \\
&= \frac{l_j^2}{C} \left( 1 - \frac{1}{C} \right) + \frac{l_j}{C},
\end{aligned} \tag{16}$$

and

$$\begin{aligned}
\sigma_{\tilde{q}}(x_j, x_k) &= \langle x_j x_k \rangle_{\tilde{q}} - \langle x_j \rangle_{\tilde{q}} \langle x_k \rangle_{\tilde{q}} \\
&= \frac{1}{C} \langle x_j x_k \rangle_p - \frac{l_j l_k}{C^2} \\
&= \frac{l_j l_k}{C} \left( 1 - \frac{1}{C} \right),
\end{aligned} \tag{17}$$

567 where  $C = 1 - e^{-(L-l_i)}$  and  $j \neq k$ .

The exact distribution  $\tilde{p}$  assumes that exactly one of the propagules present in a given site after dispersal belongs to the focal type, whereas  $\tilde{q}$  assumes that there is a focal propagule present before non-focal dispersal commences. As a result,  $\tilde{q}$  predicts that the mean propagule density is greater than  $L$  (in sites with only one focal propagule is present) when the focal type is rare and the propagule density is high. This is erroneous, because the mean number of propagules in every site is  $L$  by definition. Specifically, if  $L - l_i \approx L \gg 1$ , then the mean propagule density predicted by  $\tilde{q}$  is approximately  $L + 1$ . The discrepancy causes rare invaders to have an intrinsic rarity disadvantage (territorial contests under  $\tilde{q}$  are more intense than they should be). In contrast, Eq. (15) correctly predicts that there are on average  $\sum_{j \neq i} \langle x_j \rangle_{\tilde{p}} \approx L - 1$  nonfocal propagules because  $\tilde{p}$  accounts for potentially large negative covariances between the  $x_j$  “after dispersal”. By neglecting the latter covariences,  $\tilde{q}$  overestimates the fluctuations in  $\sum_{j \neq i} c_j x_j$ ; thus  $\tilde{q}$  gives an upper bound on the fluctuations. The discrepancy between  $\tilde{q}$  and  $\tilde{p}$  will be largest

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when  $L$  is of order 1 or smaller, because then the propagule assumed to already be present under  $\tilde{q}$  is comparable to, or greater than, the entire propgaule density.

582 Decomposing the variance in  $\sum_{j \neq i} c_j x_j$ ,

$$\sigma_{\tilde{q}}^2(\sum_{j \neq i} c_j x_j) = \sum_{j \neq i} \left[ c_j^2 \sigma_{\tilde{q}}^2(x_j) + 2 \sum_{k > j, k \neq i} c_j c_k \sigma_{\tilde{q}}(x_j, x_k) \right], \quad (18)$$

and using the fact that  $\sigma_{\tilde{q}}(x_j, x_k)$  and the first term in Eq. (16) are negative because  $C < 1$ , we obtain an upper bound on the relative fluctuations in  $\sum_{j \neq i} c_j x_j$ ,

$$\frac{\sigma(\sum_{j \neq i} c_j x_j)}{\langle \sum_{j \neq i} c_j x_j \rangle} = C^{1/2} \frac{\left( \sum_{j \neq i} c_j^2 l_j + (1 - 1/C) \left( \sum_{j \neq i} c_j l_j \right)^2 \right)^{1/2}}{\sum_{j \neq i} c_j l_j} < C^{1/2} \frac{\left( \sum_{j \neq i} c_j^2 l_j \right)^{1/2}}{\sum_{j \neq i} c_j l_j}. \quad (19)$$

585 Suppose that the  $c_j$  are all of similar magnitude (their ratios are of order one). Then Eq. (19) is  $\ll 1$  for the case when  $L - l_i \ll 1$  (due to the factor of  $C^{1/2}$ ), and also for the case when at least some of the nonfocal propagule densities are large  $l_j \gg 1$  (since it is then of order  $1/\sqrt{L - l_i}$ ).  
 588 The worst case scenario occurs when  $L - l_i$  is of order one. Then Eq. (19) gives a relative error of approximately 50%, which from our earlier discussion we know to be a substantial overestimate when  $L$  is of order 1. Our numerical results (Fig. 6) confirm that the relative errors are indeed  
 591 small.

However, the relative fluctuations in  $\sum_{j \neq i} c_j x_j$  can be large if some of the  $c_j$  are much larger than the others. Specifically, in the presence of a rare, extremely strong competitor ( $c_j l_j \gg c_{j'} l_{j'}$  for all other nonfocal genotypes  $j'$ , and  $l_j \ll 1$ ), then the RHS of Eq. (19) can be large and we  
 594 cannot make the replacement Eq. (12).

Substituting Eqs. (12) and (15) into Eq. (11), we obtain

$$\Delta_r n_i \approx m_i R_i \frac{c_i}{\bar{c}}, \quad (20)$$

597 where  $R_i$  is defined in Eq. (5).

## Competition when abundant

The final contribution,  $\Delta_a n_i$ , accounts for territories where two or more focal propagules are present ( $a$  stands for “abundant”). Similarly to Eq. (11), we have

$$\Delta_a n_i = U(1 - (1 + l_i)e^{l_i}) \left\langle \frac{c_i x_i}{\sum_j c_j x_j} \right\rangle_{\hat{p}} \quad (21)$$

where  $\hat{p}$  is the probability distribution of both focal and nonfocal propagule abundances *after* dispersal in those territories where at least two focal propagules landed.

Again, we argue that the relative fluctuations in  $\sum c_j x_j$  are much smaller than 1 (with respect to  $\hat{p}$ ), so that,

$$\left\langle \frac{c_i x_i}{\sum_j c_j x_j} \right\rangle_{\hat{p}} \approx \frac{c_i \langle x_i \rangle_{\hat{p}}}{\sum_j c_j \langle x_j \rangle_{\hat{p}}}. \quad (22)$$

Following a similar procedure as for  $\Delta_r n_i$ , where the vector of propagule abundances is denoted  $\mathbf{x}$ , the mean focal genotype abundance is,

$$\begin{aligned} \langle x_i \rangle_{\hat{p}} &= \sum_{\mathbf{x}} x_i p(\mathbf{x} | x_i \geq 2) \\ &= \sum_{x_i} x_i p(x_i | x_i \geq 2) \\ &= \frac{1}{1 - (1 + l_i)e^{-l_i}} \sum_{x_i \geq 2} p(x_i) x_i \\ &= l_i \frac{1 - e^{-l_i}}{1 - (1 + l_i)e^{-l_i}}. \end{aligned} \quad (23)$$



For nonfocal genotypes  $j \neq i$ , we have

$$\begin{aligned}
\langle x_j \rangle_{\hat{p}} &= \sum_{\mathbf{x}} x_j p(\mathbf{x} | x_i \geq 2) \\
&= \sum_X P(X | x_i \geq 2) \sum_{\mathbf{x}} x_j p(\mathbf{x} | x_i \geq 2, X) \\
&= \sum_X P(X | x_i \geq 2) \sum_{x_i} p(x_i | x_i \geq 2, X) \sum_{\mathbf{x}_i} x_j p(\mathbf{x}_i | X_i = X - x_i) \\
&= \sum_X P(X | x_i \geq 2) \sum_{x_i} p(x_i | x_i \geq 2, X) \frac{l_j(X - x_i)}{L - l_i} \\
&= \frac{l_j}{L - l_i} \left[ \sum_X P(X | x_i \geq 2) X - \sum_{x_i} p(x_i | x_i \geq 2) x_i \right] \\
&= \frac{l_j}{L - l_i} \left( L \frac{1 - e^{-L}}{1 - (1 + L)e^{-L}} - l_i \frac{1 - e^{-l_i}}{1 - (1 + l_i)e^{-l_i}} \right). \tag{24}
\end{aligned}$$

To calculate the relative fluctuations in  $\sum_{j \neq i} c_j x_j$ , we use a similar approximation as for  $\Delta_r n_i$ :  $\hat{p}$  is approximated by  $\hat{q}$ , defined as the  $\mathbf{x}$  dispersal probabilities in a territory conditional on  $x_i > 2$  (that is, treating the  $x_j$  as independent). All covariances between nonfocal genotypes are now zero, so that  $\sigma_{\hat{q}}^2(\sum c_j x_j) = \sum c_j^2 \sigma_{\hat{q}}^2(x_j)$ , where  $\sigma_{\hat{q}}^2(x_j) = l_j$  for  $j \neq i$ , and

$$\sigma_{\hat{q}}^2(x_i) = \frac{l_i}{D} \left( l_i + 1 - e^{-l_i} - \frac{l_i}{D} (1 - e^{-l_i})^2 \right), \tag{25}$$

where  $D = 1 - (1 + l_i)e^{-l_i}$ , and

$$\frac{\sigma_{\hat{q}}(\sum c_j x_j)}{\langle \sum c_j x_j \rangle} = \frac{\left( \sum_{j \neq i} c_j^2 l_j + c_i^2 \sigma_{\hat{q}}^2(x_i) \right)^{1/2}}{\sum_{j \neq i} c_j l_j + c_i l_i (1 - e^{-l_i}) / D}. \tag{26}$$

Similarly to Eq. (19), the RHS of Eq. (26) is  $\ll 1$  for the case that  $L \ll 1$  (due to a factor of  $D^{1/2}$ ), and also for the case when at least some of the propagule densities (focal or nonfocal) are large — provided that  $c_i$  and the  $c_j$  are all of similar magnitude. Again, the worst case scenario occurs when  $l_i$  and  $L - l_i$  are of order 1, in which case Eq. (26) is around 35%, which is again where the  $\hat{q}$  approximation produces the biggest overestimate of the fluctuations in  $\mathbf{x}$ . Similarly

615 to Eq. (19), the RHS of (26) will not be  $\ll 1$  in the presence of a rare, extremely strong competitor.

Combining Eqs. (21) and (22), we obtain

$$\Delta_a n_i = m_i A_i \frac{c_i}{\bar{c}}, \quad (27)$$

where  $A_i$  is defined in Eq. (6).

## 618 **Comparison with simulations**

Fig. 6 shows that Eq. (4) and its components closely approximate our density-dependent lottery model over a wide range of propagule densities (the latter is evaluated by direct simulations of  
621 uniform random dispersal and lottery competition). Two genotypes are present, one of which is at low frequency. The growth of the low-frequency genotype relies crucially on the low-density competition term  $R_i c_i / \bar{c}$ , and also to a lesser extent on the high density competition term  $A_i c_i / \bar{c}$   
624 if  $l_1$  is large enough (Fig. 6b). On the other hand,  $R_i c_i / \bar{c}$  is negligible for the high-frequency genotype, which depends instead on high density territorial victories (Fig. 6d). Fig. 3 also shows the breakdown of the classic lottery model at low propagule densities.

## 627 **Appendix C: Direction of evolution under different environmental extremes**

Summing Eq. (4) over genotypes,  $N$  obeys

$$\Delta N = U(1 - e^{-L}) - \sum_i d_i n_i, \quad (28)$$

630 where  $U = \sum_i b_i n_i / L$ . In equilibrium ( $\Delta N = 0$ ), Eq. (28) implies  $L / (1 - e^{-L}) = \sum_i b_i n_i / \sum_i d_i n_i$ , and so  $L$  only depends on the ratio of population mean birth rate to population mean death rate..

and so the propagule density is high  $L \approx b_i / d_i \gg 1$ , and every unoccupied territory will  
633 be heavily contested. The population density is also high  $N / T \approx 1$  (since  $L = b_i N / (N - T) =$

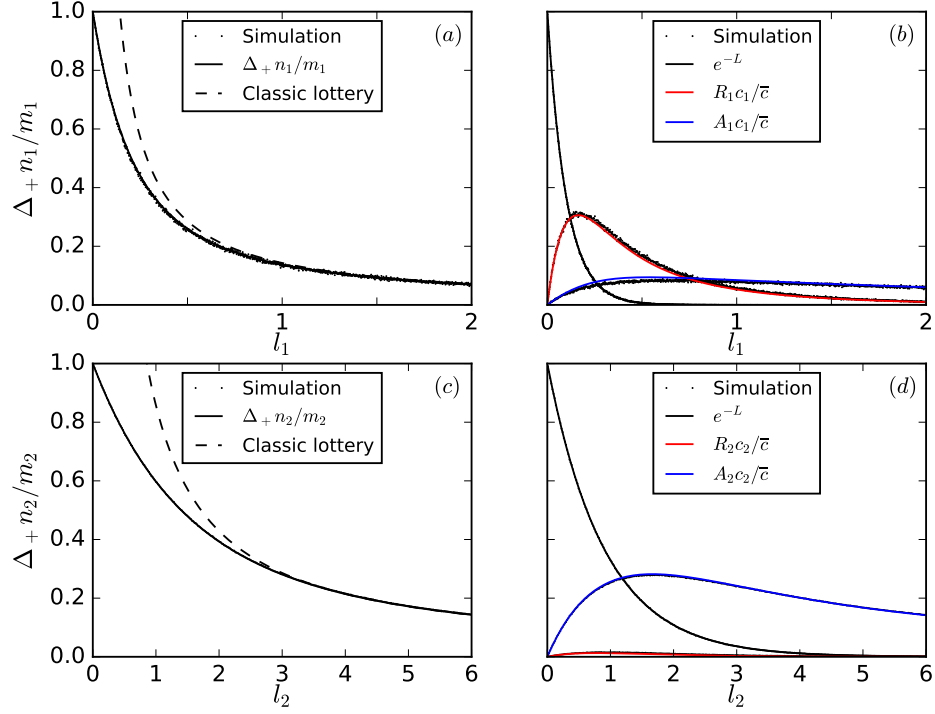


Figure 6: The change in genotype abundances in a density dependent lottery model is closely approximated by Eq. (4).  $\Delta_+ n_i / m_i$  from Eq. (4) (and its separate components) are shown, along with direct simulations of random dispersal and lottery competition over one iteration over a range of propagule densities ( $U$  is varied between  $5 \times 10^3$  and  $10^6$  with  $m_1 = 10^4$  and  $m_2 = 9 \times 10^4$ ). Two genotypes are present. (a) and (b) show the low-frequency genotype with  $c$ -advantage ( $c_1 = 1.5$ ), (c) and (d) show the high-frequency predominant genotype ( $c_2 = 1$ ). Simulation points are almost invisible in (c) and (d) due to near exact agreement with Eq. (4). Dashed lines in (a) and (c) show the breakdown of the classic lottery model.

$$b_i/(1 - T/N)).$$