

# Supplementary Material

# **1 SUPPLEMENTARY METHODS**

### 1.1 Landscape generation and standardization

Abiotic factor matrices R, G, and C were generated using the midpoint displacement method with random successive additions (Saupe, 1988; Palmer, 1992). The midpoint displacement method specifies a target fractal dimension,  $D_{in}$ , that can vary from a perfect gradient ( $D_{in} = 2$ ) to a completely spatially random landscape ( $D_{in} = 3$ ). Because the actual fractal dimension of matrices produced by this method will vary somewhat, only matrices with a final fractal dimension  $D_{out}$  within the range  $D_{in} \pm 0.1$  were used to control for the effect of spatial autocorrelation (Palmer, 1992) (Table 1). Each abiotic factor matrix R, G, and C was standardized to have the same mean and standard deviation,  $\mu$  and  $\sigma$  (Table 1). By holding the landscape-scale spatial autocorrelation and standard deviation of abiotic variables constant across replicates with random spatial configurations, we were able to isolate the effect of plant community dynamics from the influence of idiosyncratic abiotic environments.

### 1.2 Modeling reproduction, dispersal, and mortality

After competition, remaining individuals reproduced. The number of seeds produced by annual species (j = 1, 3) was:

$$f_j(x,y) = F_a P_{Rj}(x,y) \tag{S1}$$

and the number of seeds produced by perennials (j = 2, 4) was:

$$f_j(x,y) = F_p P_{Rj}(x,y).$$
(S2)

 $P_{Rj}(x, y)$  gives the reproductive performance of each species with respect to abiotic factor R (eq. (1) with A(x, y) = R(x, y)). An individual of species j in a microsite (x, y) with  $R(x, y) = \mu_{Rj}$ , for example, would perform at its environmental optimum for this life stage, producing the maximum number of possible seeds,  $F_a$  (for annuals) or  $F_p$  (for perennials) (eqs. (S1) and (S2), respectively). If abiotic conditions resulted in a fraction of a seed produced, the viability of that fractional seed was determined by a random draw. A proportion of viable seeds p produced by each adult stayed in the parent's microsite, and the rest dispersed to randomly selected microsites within a specified distance.

In the three dispersal treatments, perennials could disperse to adjacent cells only (adjacent dispersal,  $d_p = 1$ ), to randomly chosen cells within 10 cells of the focal microsite (intermediate dispersal,  $d_p = 10$ ), or to randomly chosen cells across the entire landscape (universal dispersal,  $d_p = 65$ ). In all cases except universal dispersal, annuals were able to disperse twice as far as perennials ( $d_a = 2d_p$ ). Boundaries were absorbing (seeds that dispersed outside the landscape were lost). At the end of each year, individuals of all annual species died, and perennials died with probability 1/m (i.e. perennials lived an average of m years) (Table 1).

#### 1.3 Niche optima and spatial averages used to calculate fecundity

For the current study, fecundity was always independent of abiotic conditions. To calculate expected  $\overline{P_{Rj}}$  values for a particular landscape, individuals of each species were randomly placed over an abiotic factor matrix R distinct from matrices G and C in all simulations except when  $G \neq C$  (in which case R = C

 $\neq G$ ), and then allowed to reproduce according to eqs. (S1) and (S2). After one round of reproduction, we calculated  $\overline{P_{Rj}}$  as species j's average performance over space (in this case, number of seeds produced per microsite) and initial conditions. Values were adjusted to account for habitat availability as described for spatial averages in the main text, but sometimes exceeded the specified optimum (e.g. 20 seeds for annuals) when there was very low habitat availability. When this occurred, we reset the average value to the specified optimum (e.g. if an annual had a spatial average of 30 seeds after normalizing for habitat variability, we nevertheless only allowed those annuals to produce 20 seeds during the simulation).

#### 1.4 Statistical Models

All generalized linear mixed-effect models were fitted with the R package glmmTMB (Brooks et al., 2017). Model assumptions were tested using DHARMa (Hartig, 2019). The Anova function in the car package was used to evaluate all models (Fox and Weisberg, 2011), and estimated marginal means were extracted from model objects using emmeans (Lenth, 2018). For the relationship between abiotic heterogeneity and species richness, we rounded species richness values to the nearest integer and fitted the model using Poisson regression. Residuals were underdispersed, so we used the genpois family in all cases except those where this correction caused vertical imbalance of the residual values in residual v. predicted plots (model family used is noted in Table S3). Competitive balance had a strong left skew and was cubed before fitting a Gaussian distribution with abiotic heterogeneity as the predictor. For the relationship between competitive balance and species richness, we rounded species richness values to the nearest integer and fitted the model using Poisson regression. Residuals in these models were always underdispersed but correction with the genpois family resulted in strong correlative structure in the residual v. predicted plots. We thus present results from models using a truncated Poisson distribution, which did not fully correct residual dispersion. In all cases we opted to keep outliers in the final models because their removal did not qualitatively change conclusions drawn from the analysis.

For the linear models, we were limited in our degrees of freedom, so we tested for single interaction effects separately (e.g. a model with route of abiotic influence x dispersal distance, a model with route of abiotic influence x strength of interspecific competition, and a model with dispersal distance x strength of interspecific competition, and a model with dispersal distance x strength of interspecific a main effect of the third process), and found that the only significant interaction was between route of abiotic influence and dispersal in models predicting species richness. The models reported in the main text therefore included main effects of route of abiotic influence, dispersal distance, and strength of interspecific competition, plus an interaction effect between route of influence and dispersal distance when predicting species richness.

# 2 SUPPLEMENTARY TABLES AND FIGURES

# 2.1 Tables

Table S1. Description of summary metrics. In the spatial statistics  $PROP_{con}(r)$  and ISAR(r),  $N_f$  is the total number of focal species within a sampling window, and the  $ISAR_i(r)$  and  $P_i(r)$  refer to an average taken over individuals of species i at radius r.

Metric	Abbreviation	Description
species richness	S	Number of unique species present in landscape $l$ and sampling unit $k, S_{kl}$
abiotic heterogeneity	v(A)	Variance in abiotic factor A in landscape $l$ and sampling unit $k$ , $var(A)_{kl}$
competitive balance	$C_{bal}$	The variability in average relative competition species experience in landscape $l$ and sampling unit $k$ , subtracted from the maximum value in the data, $max(var(\overline{r_j})) - var(\overline{r_j})_{kl}$
Individual Species Area Relationship	ISAR(r)	The average number of heterospecific individuals found around focal individuals across small to large radii within a sampling window, $\frac{1}{N_f} \sum_{i=1}^{N_f} \frac{ISAR_i(r)}{N_s}$ , (Wiegand and Moloney, 2013)
Proportion conspecifics	$PROP_{con}(r)$	The average proportion of conspecific individuals found around focal individuals across small to large radii within a sampling window, $\frac{1}{N_c} \sum_{i=1}^{N_f} P_i(r)$ , (Brown et al., 2016)

Table S2. Reducing niche space had no effect on species richness in the null model, but led to a statistically significant decrease when abiotic conditions determined interaction strengths. Results shown are from a type III ANOVA.

Terms	Sum Sq.	DF	F-value	P-value
Intercept	288.80	1	1644.10	< 0.001***
Route of abiotic influence (none v. interaction strengths)	0.00	1	0.00	1.00
landscape $\sigma$	0.025	1	0.14	0.71
Route:landscape $\sigma$	4.51	1	25.69	$< 0.001^{***}$
Residuals	13.35	76		

Table S3. Abiotic heterogeneity was always a statistically significant predictor of species richness when abiotic conditions affected initial densities (route 1), never when abiotic effects were absent (route none), and in only one case (when dispersal was limited to adjacent microsites and interspecific competition ( $\alpha_{ij}$ ) was strong) when abiotic conditions affected interaction strengths during competition (route 2).  $\alpha_{ij}$  is the strength of interspecific competition and dispersal is the distance seeds could travel away from their parent's microsite (Table 1). Family indicates the distribution used during regression. Results are from a type II ANOVA of generalized mixed-effect models.

Route of abiotic influence	coefficient (strength of the relationship)	ChiSq	DF	P-value	dispersal	$lpha_{ij}$	family
1	0.201	387.051	1	< 0.001***	adjacent	0.5	genpois
2	-0.002	0.657	1	0.418	adjacent	0.5	genpois
none	0.006	0.053	1	0.819	adjacent	0.5	poisson
1	0.207	425.626	1	< 0.001***	adjacent	1.0	genpois
2	0.007	1.771	1	0.183	adjacent	1.0	genpois
none	0.000	0.069	1	0.793	adjacent	1.0	genpois
1	0.205	418.221	1	< 0.001***	adjacent	1.5	genpois
2	0.035	24.166	1	< 0.001***	adjacent	1.5	genpois
none	0.000	0.000	1	0.983	adjacent	1.5	genpois
1	0.149	188.643	1	< 0.001***	intermediate	0.5	genpois
2	0.000	0.001	1	0.976	intermediate	0.5	genpois
none	0.000	0.000	1	0.984	intermediate	0.5	genpois
1	0.141	172.147	1	< 0.001***	intermediate	1.0	genpois
2	0.011	0.173	1	0.677	intermediate	1.0	poisson
none	-0.001	0.629	1	0.428	intermediate	1.0	genpois
1	0.146	194.614	1	< 0.001***	intermediate	1.5	genpois
2	0.002	0.363	1	0.547	intermediate	1.5	genpois
none	0.004	0.030	1	0.862	intermediate	1.5	poisson
1	0.168	266.745	1	< 0.001***	universal	0.5	genpois
2	0.008	0.091	1	0.763	universal	0.5	poisson
none	0.006	0.046	1	0.830	universal	0.5	poisson
1	0.181	332.621	1	< 0.001***	universal	1.0	genpois
2	0.004	0.982	1	0.322	universal	1.0	genpois
none	0.006	0.042	1	0.837	universal	1.0	poisson
1	0.173	314.472	1	< 0.001***	universal	1.5	genpois
2	0.006	0.045	1	0.832	universal	1.5	poisson
none	-0.002	0.263	1	0.608	universal	1.5	genpois

Table 54. Abiotic heterogeneity was always a statistically significant predictor of competitive balance when abiotic conditions affected initial densities during germination (route 1). Route 2 is the effect of the same abiotic conditions on interaction strengths during competition and route "none" indicates the null model simulation where abiotic conditions affected neither life stage.  $\alpha_{ij}$  is the strength of interspecific competition and dispersal is the distance seeds could travel away from their parent's microsite (Table 1). Results are from a type II ANOVA of generalized mixed-effect models.

Route of abiotic influence	coefficient (slope of the relationships)	ChiSq	DF	P-value	dispersal	$lpha_{ij}$
1	0.016	97.803	1	< 0.001***	adjacent	0.5
2	0.000	0.182	1	0.670	adjacent	0.5
none	0.000	2.688	1	0.101	adjacent	0.5
1	0.015	91.446	1	< 0.001***	adjacent	1.0
2	0.000	0.028	1	0.867	adjacent	1.0
none	0.000	0.097	1	0.755	adjacent	1.0
1	0.016	107.196	1	< 0.001***	adjacent	1.5
2	0.000	1.179	1	0.278	adjacent	1.5
none	0.000	0.000	1	0.997	adjacent	1.5
1	0.015	111.175	1	< 0.001***	intermediate	0.5
2	0.000	1.140	1	0.286	intermediate	0.5
none	0.000	0.048	1	0.827	intermediate	0.5
1	0.016	114.386	1	< 0.001***	intermediate	1.0
2	0.000	2.683	1	0.101	intermediate	1.0
none	0.000	0.150	1	0.699	intermediate	1.0
1	0.016	125.327	1	< 0.001***	intermediate	1.5
2	0.001	6.021	1	0.014*	intermediate	1.5
none	0.000	0.263	1	0.608	intermediate	1.5
1	0.015	133.102	1	< 0.001***	universal	0.5
2	0.001	3.313	1	0.069.	universal	0.5
none	0.000	0.086	1	0.769	universal	0.5
1	0.016	134.001	1	< 0.001***	universal	1.0
2	0.001	4.786	1	0.029*	universal	1.0
none	0.001	1.205	1	0.272	universal	1.0
1	0.016	145.793	1	< 0.001***	universal	1.5
2	0.002	13.502	1	< 0.001***	universal	1.5
none	0.001	5.591	1	0.018*	universal	1.5

Table 55. Competitive balance was always a statistically significant predictor of species richness when abiotic conditions affected initial densities during germination (route 1). When abiotic conditions affected interaction strengths during competition (route 2), competitive balance was always a statistically significant predictor of species richness when dispersal was restricted to adjacent microsites. When abiotic conditions affected neither life stage in the null model (route none), competitive balance was always a statistically significant predictor of species richness except when dispersal was universal.  $\alpha_{ij}$  is the strength of interspecific competition and dispersal is the distance seeds could travel away from their parent's microsite (Table 1). Results are from a type II ANOVA of generalized mixed-effect models.

Route of abiotic influence	regression coefficient (slope of the relationships)	ChiSq	DF	P-value	dispersal	$lpha_{ij}$
1	2.294	163.083	1	< 0.001***	adjacent	0.5
2	3.039	4.115	1	0.043*	adjacent	0.5
none	4.216	5.843	1	0.016*	adjacent	0.5
1	2.301	156.795	1	< 0.001***	adjacent	1.0
2	3.204	6.882	1	0.009**	adjacent	1.0
none	4.285	6.023	1	0.014*	adjacent	1.0
1	2.405	161.240	1	< 0.001***	adjacent	1.5
2	5.235	29.150	1	< 0.001***	adjacent	1.5
none	4.426	6.665	1	0.010*	adjacent	1.5
1	2.878	228.871	1	< 0.001***	intermediate	0.5
2	3.000	4.155	1	0.042*	intermediate	0.5
none	3.862	6.315	1	0.012*	intermediate	0.5
1	3.093	241.253	1	< 0.001***	intermediate	1.0
2	2.717	3.403	1	0.065.	intermediate	1.0
none	3.654	4.876	1	0.027*	intermediate	1.0
1	3.026	233.237	1	< 0.001***	intermediate	1.5
2	2.425	3.379	1	0.066.	intermediate	1.5
none	4.420	6.821	1	0.009**	intermediate	1.5
1	3.874	257.738	1	< 0.001***	universal	0.5
2	1.045	2.148	1	0.143	universal	0.5
none	1.023	1.975	1	0.160	universal	0.5
1	3.860	253.362	1	< 0.001***	universal	1.0
2	0.661	0.754	1	0.385	universal	1.0
none	0.949	1.505	1	0.220	universal	1.0
1	4.239	269.429	1	< 0.001***	universal	1.5
2	0.088	0.015	1	0.904	universal	1.5
none	1.034	1.801	1	0.180	universal	1.5

# 2.2 Figures



Figure S1. Hypothetical results to illustrate how we partitioned contributions from the two routes of abiotic influence to changes in species richness, relative to the null model. This graphic summarizes the method presented in Ellner et al. (2019). In (a), black bars show average species richness produced by each of the five simulated scenarios (no effect of abiotic conditions in the null model), effect of abiotic conditions on initial densities (route 1), effect of abiotic conditions on per capita interaction strengths during competition (route 2), routes 1 and 2 according to the same abiotic conditions G = C, and routes 1 and 2 according to independent, uncorrelated abiotic conditions  $G \neq C$ ). Bars in color show average differences in species richness compared to null model simulations, with species losses indicated with a dotted outline and species gains indicated with a solid outline. For single-effect simulations route 1 and route 2, average species richness was always lower than in the null model, indicated by the r1 and r2 components under the black dashed line. The gray  $r_{1+r_{2}}$  bar shows what the combined effect of routes 1 and 2 would be if they were strictly additive and sets the baseline against which the remaining simulations are compared. The orange bar is therefore an interaction effect arising from the combined effects of routes 1 and 2 when abiotic conditions during germination and competition were identical (G = C). This interaction can be broken down into two component effects: one arising from independent variation in routes 1 and 2, r1#r2; and one arising from covariance in routes 1 and 2, (r1r2), which is calculated by subtracting r1#r2 from r1r2. Results are summarized by stacking contributions relative to 0, which we do showing the interaction between route 1 and 2 in (b), and again with the interaction effect broken into its component effects in (c).



# radius

**Figure S2.** Differences in *ISAR* values for routes 1 and 2 held across combinations of dispersal and strength of interspecific competition. A notable exception is some ability to distinguish route 2 from null model simulations when dispersal was adjacent and the strength of interspecific competition was strong ( $\alpha_{ij} = 1.5$ ). Values close to 1 indicate strong interspecific mingling, values close to 0 indicate strong interspecific segregation.



**Figure S3.** Differences in  $PROP_{con}$  values for routes 1 and 2 held across combinations of dispersal and strength of interspecific competition. A notable exception is some ability to distinguish route 2 from null model simulations when dispersal was adjacent and the strength of interspecific competition was strong ( $\alpha_{ij} = 1.5$ ). Values close to 1 indicate strong intraspecific clumping, values close to 0 indicate strong intraspecific overdispersion.



**Figure S4.** Number of landscapes (out of 20 total) that had an extinction event at least once over initial conditions. Results are shown for adjacent, intermediate, and universal dispersal. Panels show results for low to high strengths of interspecific competition. No more than a single species ever went extinct.



**Figure S5.** Relationships between (A) abiotic heterogeneity and species richness and (B) abiotic heterogeneity and competitive balance when dispersal was restricted to adjacent microsites and interspecific competition was strong ( $\alpha_{ij} = 1.5$ ). Panel (C) shows the relationship between competitive balance and species richness when dispersal was universal and interspecific competition was equal to intraspecific competition ( $\alpha_{ij} = 1.0$ ). Shading around predicted values are 95% confidence intervals. Route 1 is the effect of abiotic conditions on initial densities during germination, route 2 is the effect of the same abiotic conditions strengths during competition, and route "none" indicates the null model simulation where abiotic conditions affected neither life stage.



**Figure S6.** Results from single microsites were qualitatively similar to results from small (5x5 microsite) sampling units. In large (13x13 microsite) sampling units, contributions from the interaction, r1r2, led to more species losses than in microsite and small sampling units (shown in (A)) because the uncorrelated component switched from a positive to a negative effect (shown in (B)).

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