

How macroecology affects macroevolution: the interplay between extinction intensity and trait-dependent extinction in brachiopods.

Peter D. Smits^{1,*}

1. University of California – Berkeley, Berkeley, California 94720;

* Corresponding author; e-mail: psmits@berkeley.edu

Manuscript elements: Figure 1, figure 2, table 1, online appendices A and B (including figure A1 and figure A2). Figure 2 is to print in color.

Keywords: species selection, geographic range, environmental preference, paleobiology, Bayesian

Manuscript type: Article.

Prepared using the suggested L^AT_EX template for *Am. Nat.*

Abstract

As average species fitness decreases, do trait-based differences in species' fitness (selection) increase or decrease? Similarly, as taxonomic extinction intensity increases, how do the effects of species traits on taxonomic survival change? Do the selective differences associated with some traits change more than others? Here I analyze the relationships between biological traits and their effect on a taxon's extinction risk and how these effects can covary over time. With Paleozoic brachiopods as a model system, I analyzed genus duration as a function of multiple emergent traits: geographic range, affinity for epicontinental seas versus open ocean environments, and body size. Additionally, I estimate the effects of environmental generalization versus specialization on taxonomic survival by allowing environmental preference to have a nonlinear effect on duration. My analytical framework eschews the traditional distinction between background and mass extinction, and instead considers extinction intensity as a continuum. I find strong evidence for a non-linear relationship between environmental preference for epicontinental versus open-ocean environments and expected taxon duration, where taxa with intermediate or no environmental preference are expected to have greater durations than taxa which appear exclusively in either environmental end-member. I find evidence for a correlation between average cohort extinction risk and the effect of geographic range on extinction risk for that cohort where I estimate that as extinction intensity increases that the magnitude of the effect of geographic range on extinction risk increases, thus increasing the difference in extinction risk between small and large ranged taxa during periods of high extinction risk. I also find evidence a similar relationship between average cohort extinction risk and the effect of the linear aspect of environmental preference on expected duration, where cohorts' with above average estimates of extinction intensity increases are also expected to have above average estimates of the linear aspect of environmental preference. This result means that for taxa from those cohort's which preferentially appear in epicontinental environments will have a greater expected duration than those taxa which prefer open-ocean environments. These results support the conclusion that, for Paleozoic brachiopods

²⁷ and the effects of geographic range and environmental preference, as extinction intensity increases the magnitude of selection also increases.

Introduction

30 Extinction is one half of the diversification process (Raup, 1994; Stanley, 1975, 1979), second
only to speciation or origination in shaping changes to diversity; it can also be the ultimate
manifestation of selection as a taxon with a beneficial trait should persist for longer on average
33 than a taxon without that beneficial trait (Jablonski, 2008; Rabosky and McCune, 2010; Raup,
1994; Stanley, 1975). Species duration is a measure of species fitness (Cooper, 1984), and trait-
associated differences in fitness is the hallmark of (species) selection (Rabosky and McCune,
36 2010).

Jablonski (1986) observed that for bivalves at the end Cretaceous mass extinction event, previous
trait-associated differences in survival no longer mattered except for the case of geographic
39 range. Based on this evidence, Jablonski (1986) proposed the idea of "macroevolutionary modes"
and that mass extinction and background extinction are fundamentally different processes. How-
ever, based on estimates of extinction rates over time, there is no evidence of there being two or
42 more "types" of extinction (Wang, 2003). Instead, extinction rates for marine invertebrates are
unimodal with continuous variation. The apparent disconnect between the theory of macroevo-
lutionary modes and the observation of continuous variation in extinction rates implies the pos-
45 sibility of a relationship between the strength of selection (extinction intensity) and the associa-
tion between traits and differences in fitness (extinction selectivity) (Payne et al., 2016). As
extinction intensity increases, what happens to extinction selectivity? How do trait-associated
48 differences in fitness change as average extinction rate changes over time?

Here I develop a statistical model describing the relationship between brachiopod taxon du-
rations and multiple functional taxon traits in order to understand the relationship between ex-
51 tinction intensity and selectivity over time. Trait-dependent differences in extinction risk should
be associated with differences in taxon duration (Cooper, 1984; Rabosky and McCune, 2010). Bra-
chiopods are an ideal group for this study as they have an exceptionally complete fossil record
54 (Foote, 2000b; Foote and Raup, 1996). I focus on the brachiopod record from the post-Cambrian

Paleozoic, from the start of the Ordovician (approximately 485 My) through the end Permian (approximately 252 My) as this represents the time of greatest global brachiopod diversity (Alroy, 57 2010) which results in a large sample size.

The analysis of taxon durations, or time from a taxon's origination till its extinction, falls under the purview of survival analysis, a field of applied statistics commonly used in health care 60 and engineering (Klein and Moeschberger, 2003) but has a long history in paleontology (Crampton et al., 2016; Simpson, 1944, 1953; Smits, 2015; Van Valen, 1973, 1979). I adopt a hierarchical Bayesian modeling approach (Gelman et al., 2013; Gelman and Hill, 2007) in order to unify the 63 previously distinct dynamic and cohort paleontological survival approaches (Baumiller, 1993; Crampton et al., 2016; Ezard et al., 2012; Foote, 1988; Raup, 1975, 1978; Simpson, 2006; Van Valen, 1973, 1979).

66 In order to test for an association between extinction intensity and extinction selectivity, extinction rate and trait-based differences in extinction rate need to be estimated. Previous work 69 has approached this problem by estimating the extinction intensity and selectivity at different time points or for different origination cohorts independently and then comparing those estimates (Payne et al., 2016). I find this approach problematic for a few reasons. First, by treating each time point or cohort as independent the estimates from each model are not relative to each 72 other and they do not represent the greatest compromise across all available data (Gelman et al., 2013). Second, by treating each time point or cohort as independent any and all post-hoc analyses 75 are at risk of false positive results because of multiple comparisons (Gelman et al., 2013). Third, post-hoc analysis of correlations between maximum likelihood estimates is much less satisfying or coherent than including those correlations as estimates of the initial model, something that is not possible when each time point or cohort is considered independent (Gelman et al., 2013).

78 While estimation of trait-dependent speciation and extinction rates from phylogenies of extant taxa has grown dramatically (Fitzjohn, 2010; Goldberg et al., 2011, 2005; Maddison et al., 2007; Rabosky et al., 2013; Stadler, 2011, 2013; Stadler and Bokma, 2013), there are two major 81 ways to estimate trait-dependent extinction: analysis of phylogenies, and analysis of the fossil

record. These two directions, phylogenetic comparative and paleobiological, are complementary and intertwined in the field of macroevolution (Hunt and Rabosky, 2014; Jablonski, 2008; Rabosky and McCune, 2010). In the case of extinction, analysis of the fossil record has the distinct advantage over phylogenies of only extant taxa because extinction is observable; this means that extinction rate is possible to estimate (Liow et al., 2010; Quental and Marshall, 2009; Rabosky, 2010). The approach used here is thus complementary to the analysis of trait-dependent extinction based on a phylogeny.

Factors affecting brachiopod survival

Conceptually, taxon survival can be considered an aspect of “taxon fitness” (Cooper, 1984; Palmer and Feldman, 2012). Traits associated with taxon survival are thus examples of species (or higher-level) selection, as differences in survival are analogous to differences in fitness. The traits analyzed here are all examples of emergent and aggregate traits (Jablonski, 2008; Rabosky and McCune, 2010); specifically I analyze genus-level traits. Emergent traits are those which are not measurable at a lower level (e.g. species versus individual organism) such as geographic range, or even fossil sampling rate. Aggregate traits, like body size or environmental preference, are the average of a shared trait across all members of a lower level.

Geographic range is widely considered the most important biological trait for estimating differences in extinction risk at nearly all times, with large geographic range associated with low extinction risk (Finnegan et al., 2012; Harnik et al., 2012; Jablonski, 1986, 1987, 2008; Jablonski and Roy, 2003; Payne and Finnegan, 2007). This stands to reason even if extinction is completely at random; a taxon with an unrestricted range is less likely to go extinct at random than a taxon with a restricted range.

Epicontinental seas are a shallow-marine environment where the ocean has spread over the continental interior or craton with a depth typically less than 100m. In contrast, open-ocean coastline environments have much greater variance in depth, do not cover the continental craton, and can persist during periods of low sea level (Miller and Foote, 2009). Because of this, a simple

108 hypothesis that taxa which favor epicontinental seas would be at great risk during periods of
low sea levels, such as during glacial periods, when epicontinental seas are drained. During
the Paleozoic (approximately 541–252 My), epicontinental seas were widely spread globally but
111 declined over the Mesozoic (approximately 252–66 My) and have nearly disappeared during
the Cenozoic (approximately 66–0 My) as open-ocean coastlines became the dominant shallow-
marine setting (Johnson, 1974; Miller and Foote, 2009; Peters, 2008; Sheehan, 2001). Taxa in
114 epicontinental environments could also have a greater extinction susceptibility than taxa in open-
ocean environments due to anoxic events due to enhanced water stratification or poor water
circulation (Peters, 2007).

117 Miller and Foote (2009) demonstrated that during several mass extinctions taxa associated
with open-ocean environments tend to have a greater extinction risk than those taxa associated
with epicontinental seas. During periods of background extinction, however, they found no con-
120 sistent difference between taxa favoring either environment. Miller and Foote (2009) hypothesize
that open-ocean taxa may have a greater extinction rate because these environments would be
more strongly affected by waterborne hazards such as fallout from impacts or volcanic events
123 which would propagate more quickly than in epicontinental environments with sluggish circula-
tion. These two environment types represent the primary identifiable environmental dichotomy
observed in ancient marine systems (Miller and Foote, 2009; Sheehan, 2001). Given these find-
126 ings, I would hypothesize that as extinction risk increases, the extinction risk associated with
open-ocean environments should generally increase.

Because environmental preference is defined here as the continuum between occurring ex-
129 clusively in open-ocean environments versus epicontinental environments, intermediate values
are considered “generalists” in the sense that they favor neither end member. A long-standing
hypothesis is that generalists or unspecialized taxa will have greater survival than specialists
132 (Baumiller, 1993; Liow, 2004, 2007; Nürnberg and Aberhan, 2013, 2015; Simpson, 1944; Smits,
2015). Because of this, the effect of environmental preference was modeled as a quadratic func-
tion where a concave down relationship between preference and expected duration indicates that

¹³⁵ generalists are favored over specialists end-members.

Body size, measured as shell length, is also considered as a trait that may potentially influence extinction risk (Harnik, 2011; Payne et al., 2014). Body size is a proxy for metabolic activity and
¹³⁸ other correlated life history traits (Payne et al., 2014). Harnik et al. (2014) analyzed the effect of body size selectivity in Devonian brachiopods in a phylogenetic and non-phylogenetic context; finding that body size was not found to be associated with differences in taxonomic duration.
¹⁴¹ It has also been found that, at least in the case of some bivalve subclades, body size can be as important a factor as geographic range size in determining extinction risk (Harnik, 2011). Given these results, I expect that if body size has any effect on brachiopod taxonomic survival it is very
¹⁴⁴ small.

It is well known that, given the incompleteness of the fossil record, the observed duration of a taxon is an underestimate of that taxon's true duration (Alroy, 2014; Foote and Raup, 1996;
¹⁴⁷ Liow and Nichols, 2010; Solow and Smith, 1997; Wagner and Marcot, 2013; Wang and Marshall, 2004). Because of this, the concern is that a taxon's observed duration may reflect its relative chance of being sampled and not any of the effects of the covariates of interest. In this case, for
¹⁵⁰ sampling to be a confounding factor there must be consistent relationship between the quality of sampling of a taxon and its apparent duration (e.g. greater sampling, longer duration). If there is no relationship between sampling and duration then interpretation can be made clearly; while
¹⁵³ observed durations are obviously truncated true durations, a lack of a relationship would indicate that the amount and form of this truncation is not a major determinant of the taxon's apparent duration. By including sampling as a covariate in the model, this effect can be quantified and
¹⁵⁶ can be taken into account when interpreting the estimates of the effects of the other covariates.

Methods

The brachiopod dataset analyzed here was sourced from the Paleobiology Database (<http://www.paleodb.org>)
¹⁵⁹ and then filtered to a limited selection of higher taxonomic groups (Rhynchonelliformea: Rhyn-

chonellata, Chileata, Obolellida, Kutorginida, Strophomenida, Spiriferida). Additionally, samples were limited to those taxa present during the post-Cambrian Paleozoic. Temporal, stratigraphic, 162 and other relevant occurrence information used in this analysis was also downloaded. Analyzed occurrences were restricted to those with paleolatitude and paleolongitude coordinates, have been assigned to either epicontinental or open-ocean environment, and belonging to a genus 165 present in the body size dataset (Payne et al., 2014). Epicontinental versus open-ocean assignments for each fossil occurrence are based on those from previous analyses Foote and Miller (2013); Miller and Foote (2009); Ritterbush and Foote (2017). These filtering criteria are very 168 similar to those from Foote and Miller (2013) with an additional constraint of being present in the body size data set from Payne et al. (2014). In total, there 1130 genera were included in this analysis.

171 Fossil occurrences were analyzed at the genus level, a common proactice for paleobiological, macroevolutionary and macroecological studies of marine invertebrates (Alroy, 2010; Foote and Miller, 2013; Harnik et al., 2012; Kiessling and Aberhan, 2007; Miller and Foote, 2009; Nürnberg 174 and Aberhan, 2013, 2015; Payne and Finnegan, 2007; Ritterbush and Foote, 2017; Simpson and Harnik, 2009; Vilhena et al., 2013). While species diversity dynamics are frequently of much greater interest than those of higher taxa (though see Foote 2014; Hoehn et al. 2015), the nature 177 of the fossil record makes accurate, precise, and consistent taxonomic assignments at the species level difficult for all occurrences. As such, the choice to analyze genera as opposed to species was in order to assure a minimum level of confidence and accuracy in the data analyzed here.

180 Genus duration was calculated as the number of geologic stages from first appearance to last appearance, inclusive. Durations were based on geologic stages as opposed to millions of years because of the inherently discrete nature of the fossil record; dates are not assigned to individual 183 fossils themselves but instead fossils are assigned to a geological interval which represents some temporal range. In this analysis, stages are effectively irreducible temporal intervals in which taxa may occur. Genera with a last occurrence in or after Changhsingian stage (e.g. the final 186 stage of the study interval) were right censored at the Changhsingian.

The covariates of duration included in this analysis are geographic range size (r), environmental preference (v, v^2), shell length (m) and sampling (s).

189 Geographic range was calculated as relative occupancy corrected for incomplete sampling.

First, the paleolatitude-paleolongitude coordinates for all occurrences were projected onto an equal-area cylindrical map projection. Each occurrence was then assigned to one of the cells
192 from a 70×34 regular raster grid placed on the map. Each grid cell represents approximately 250,000 km². The map projection and regular lattice were made using shape files from
<http://www.naturalearthdata.com/> and the `raster` package for R (Hijmans, 2015). For each
195 stage, the total number of occupied grid cells was calculated. Then, for each temporal bin, the relative occurrence probability of the observed taxa was calculated using the JADE method developed by Chao et al. (2015). This method accounts for the fact that taxa with an occupancy of 0
198 cannot be observed which means that occupancy follows a truncated Binomial distribution. This correction is critical when comparing occupancies from different times with different geographic sampling. Finally, for each genus, the mean relative occurrence probability was calculated as
201 the average of that genus' occurrence probabilities for all stages it was sampled to yield relative occupancy, my proxy for geographic range.

Environmental preference was defined as probability of observing the ratio of epicontinental

204 occurrences to total occurrences ($\theta_i = e_i/E_i$) or greater given the background occurrence probability θ'_i as estimated from all other taxa occurring at the same time (e'_i/E'_i). This measure of environmental preference is expressed.

$$\begin{aligned} p(\theta'_i | e'_i, E'_i) &\propto \text{Beta}(e'_i, E'_i - e'_i) \text{Beta}(1, 1) \\ &= \text{Beta}(e'_i + 1, E'_i - e'_i + 1), \end{aligned} \tag{1}$$

207 where v is the percent of the distribution defined in equation 1 less than or equal to θ_i . The Beta distribution is used here because it is a continuous distribution bounded at 0 and 1, which is ideal for modeling percentages.

210 Body size, measured as shell length, was sourced directly from Payne et al. (2014). These measurements were made from brachiopod taxa figured in the *Treatise on Invertebrate Paleontology*

(Williams et al., 2007).

The sampling probability for individual taxa was calculated using the standard gap statistic (Foote, 2000a; Foote and Raup, 1996). The gap statistic is calculated as the number of stages in which the taxon was sampled minus two divided by the duration of the taxon minus two.

Subtracting two from the numerator and denominator is because the first and last appearance stages are by definition sampled. Because taxa that were right censored only include a first appearance, one was subtracted from the numerator and denominator instead of two.

The minimum duration for which a gap statistic can be calculated is three stages, so I chose to impute the gap statistic for all observations with a duration less than 3. Imputation is the “filling in” of missing observations based on the observed values (Gelman and Hill, 2007; Rubin, 1996). This is fairly straight forward in a Bayesian framework because covariates and parameters are considered random variables, meaning that the missing values of sampling can be modeled as coming from some probability distribution.

Prior to analysis, geographic range was logit transformed and the number of samples was natural-log transformed; these transformations make these variables defined for the entire real line. Sampling probability was transformed as $(s(n - 1) + 0.5)/n$ where n is the sample size as recommended by Smithson and Verkuilen (2006); this serves to slightly shrink the range of the data so that there are no values of 0 or 1. All covariates except for sampling were standardized by subtracting the mean from all values and dividing by twice its standard deviation, which follows Gelman and Hill (2007). This standardization means that the associated regression coefficients are comparable as the expected change per 1-unit change in the rescaled covariates. Finally, D is defined as the total number of covariates, excluding sampling, plus one for the intercept term.

Details of model

Hierarchical modelling is a statistical approach which explicitly takes into account the structure of the observed data in order to model the within and the between group variances (Gelman et al., 2013; Gelman and Hill, 2007). The units of study (e.g. genera) each belong to a single

group (e.g. origination cohort). Each group is considered a draw from a shared probability distribution (e.g. prior) of all cohorts, observed and unobserved. The group-level parameters,
240 or the hyperparameters of this shared prior, are themselves given (hyper)prior distributions and
are also estimated like the other parameters of interest (e.g. covariate effects) (Gelman et al.,
2013). The subsequent estimates are partially pooled together, where parameters from groups
243 with large samples or effects remain large while those of groups with small samples or effects are
pulled towards the overall group mean. All covariate effects (regression coefficients), as well as
the intercept term (baseline extinction risk), were allowed to vary by group (origination cohort).

246 The covariance between covariate effects was also modeled.

Genus durations were assumed to follow a Weibull distribution which allows for age-dependent
extinction (Klein and Moeschberger, 2003): $y \sim \text{Weibull}(\alpha, \sigma)$. The Weibull distribution has two
249 parameters: scale σ , and shape α . When $\alpha = 1$, σ is equal to the expected duration of any taxon.
 α is a measure of the effect of age on extinction risk where values greater than 1 indicate that
extinction risk increases with age, and values less than 1 indicate that extinction risk decreases
252 with age. Note that the Weibull distribution is equivalent to the exponential distribution when
 $\alpha = 1$.

In the case of the right- and left-censored observations mentioned above, the probability
255 of those observations has a different calculation (Klein and Moeschberger, 2003). For right-
censored observations, the likelihood is calculated $p(y|\theta) = 1 - F(y) = S(y)$ where $F(y)$ is the
cumulative distribution function. Taxa that existed for only a single stage were left-censored,
258 which implies that that taxon went extinct at any point between 0 and 1 stages. In contrast to
right-censored data, the likelihood of a left-censored observation is calculated from $p(y|\theta) =$
 $F(y)$. This censoring strategy improves model fit greatly over treating these taxa as being fully
261 observed (see Appendix).

The scale parameter σ was modeled as a regression following Kleinbaum and Klein (2005)

with varying intercept and varying slopes and the effect of sampling; this is expressed

$$\sigma_i = \exp\left(\frac{-\mathbf{X}_i B_{j[i]} + \delta s_i}{\alpha}\right) \quad (2)$$

- 264 where i indexes across all observations where $i = 1, \dots, n$ where n is the total number of obser-
 265 vations, $j[i]$ is the cohort membership of the i th observation where $j = 1, \dots, J$ where J is the total
 266 number of cohorts, X is a $N \times D$ matrix of covariates along with a column of ones for the inter-
 267 cept term, B is a $J \times D$ matrix of cohort-specific regression coefficients, and δ is the regression
 coefficient for the effect of sampling s . δ does not vary by cohort.

Each of the rows of matrix B are modeled as realizations from a multivariate normal distri-
 270 bution with length D location vector μ and $J \times J$ covariance matrix Σ : $B_j \sim \text{MVN}(\mu, \Sigma)$. The
 271 covariance matrix was then decomposed into a length J vector of scales τ and a $J \times J$ correlation
 272 matrix Ω , defined $\Sigma = \text{diag}(\tau)\Omega\text{diag}(\tau)$ where “diag” indicates a diagonal matrix.

273 The elements of μ were given independent normally distributed priors. The effects of geo-
 274 graphic range size and the breadth of environmental preference were given informative priors
 275 reflecting the previous findings while the others were given weakly informative favoring no ef-
 276 fect. The correlation matrix Ω was given an LKJ distributed prior (Lewandowski et al., 2009) that
 277 slightly favors an identity matrix as recommended by Team (2017). These priors are defined

$$\begin{aligned} \mu^0 &\sim \mathcal{N}(0, 5) \\ \mu^r &\sim \mathcal{N}(-1, 1) \\ \mu^v &\sim \mathcal{N}(0, 1) \\ \mu^{v^2} &\sim \mathcal{N}(1, 1) \\ \mu^m &\sim \mathcal{N}(0, 0.5) \\ \delta &\sim \mathcal{N}(1) \\ \tau &\sim C^+(1) \\ \Omega &\sim \text{LKJ}(2). \end{aligned} \quad (3)$$

The log of the shape parameter α was given a weakly informative prior $\log(\alpha) \sim \mathcal{N}(0, 1)$

²⁷⁹ centered at $\alpha = 1$, which corresponds to the Law of Constant Extinction (Van Valen, 1973).

Imputation of sampling probability

The vector sampling s has two parts: the observed part s^o , and the unobserved part s^u . Of the
²⁸² 1130 total observations, 539 have a duration of 3 or more and have an observed gap statistic. The
gap statistic for the remaining 591 observations was imputed. As stated above, the unobserved
part is the imputed, or filled in, based on the observed part s^o . Because sampling varies between
²⁸⁵ 0 and 1, I chose to model it as a Beta regression with matrix W being a $N \times (D - 3)$ matrix of
covariates (i.e. geographic range size, environmental preference, body size; no interactions) as
predictors of sampling; this assumes that the sampling value for all taxa come from the same
²⁸⁸ distribution. Importantly, I make no assumptions of causal structure.

Predicting sampling probability using the other covariate that are then included in the model
of duration is acceptable and appropriate in the case of imputation where the sample goal is
²⁹¹ accurate prediction (Gelman and Hill, 2007; Rubin, 1996). Not including these covariates can
lead to biased estimates of the imputed variable; if the covariates themselves are related, not
including them will bias this correlation towards zero which then leads to improper imputation
²⁹⁴ and inference (Rubin, 1996).

The Beta regression is defined

$$s^o \sim \text{Beta}(\phi = \text{logit}^{-1}(X^o\gamma), \lambda), \quad (4)$$

where γ is a length D vector of regression coefficients, and X defined as above. The Beta distribution used in the regression is reparameterized in terms of a mean parameter
²⁹⁷

$$\phi = \frac{\alpha}{\alpha + \beta} \quad (5)$$

and total count parameter

$$\lambda = \alpha + \beta \quad (6)$$

where α and β are the characteristic parameters of the Beta distribution (Gelman et al., 2013).

300 The next step is to then estimate $s^u | s^o, X^o, X^u, \gamma$, the posterior distribution of which are folded back into s and used as a covariate of duration (Eq. 2). All the elements of γ , δ (Eq. 2), and λ (Eq. 4) were given weakly informative priors as recommended by Team (2017):

$$\begin{aligned}\gamma &\sim \mathcal{N}(0, 1) \\ \delta &\sim \mathcal{N}(0, 1) \\ \lambda &\sim \text{Pareto}(0.1, 1.5).\end{aligned}\tag{7}$$

303 *Posterior inference and posterior predictive checks*

The joint posterior was approximated using a Markov-chain Monte Carlo routine that is a variant of Hamiltonian Monte Carlo called the No-U-Turn Sampler (Hoffman and Gelman, 2014) as 306 implemented in the probabilistic programming language Stan (Stan Development Team, 2014). The posterior distribution was approximated from four parallel chains run for 40,000 steps, split 309 half warm-up and half sampling and thinned to every 20th sample for a total of 4000 posterior samples. Starting conditions for sampling were left at defaults for CmdStan interface except for the following changes: adapt delta was set 0.95 to ensure no divergent samples, and initial value was set to 0 which allows for stable initial samples. Posterior convergence was assessed using 312 standard MCMC diagnostics such as the scale reduction factor \hat{R} (target < 1.1) and effective sample size or ESS (target eff/steps < 0.0001), and HMC specific criteria such as energy (target > 0.2), presence and number of divergent samples and number of samples that saturated the 315 maximum trajectory length for avoiding infinite loops (target value 0). For futher explanation of these diagnostic criteria, see the Stan Manual (Team, 2017).

After the model was fit to the data, 100 datasets were simulated from the posterior predictive 318 distribution of the model. These simulations were used to test for adequacy of model fit as described below.

Survival analysis is complicated by censored observations where the ultimate time of extinction 321 for some taxa could not be fully observed during the study window. Importantly, posterior

predictive simulations for these observations must be similarly censored. To accomplish this, posterior predictive simulated durations for right-censored observations were the minimum of
324 its final observed duration and the simulated duration. For left-censored individuals, their simulated duration was pegged at a minimum of one stage with simulated values less than one stage set to one.

327 Model adequacy was evaluated using a series of posterior predictive checks. Posterior predictive checks are a means for understanding model fit or adequacy. The concept of model adequacy is that if our model is an adequate descriptor of the observed data, then data simulated from the
330 posterior predictive distribution should be similar to the observed given the same covariates, etc. (Gelman et al., 2013). Posterior predictive checks can take many forms but the basic idea is to compare some property of the empirical data to that property estimated from each of the
333 simulated datasets. Additionally, for structured datasets like the one analyzed here, the fit of the model to different parts of the data can be assessed, which in turn can reveal a great deal if the model has good fit to some aspects of data but not others; it is in these scenarios when knowledge about the biology, geology, and paleoenvironment becomes important in order to explain
336 what unmodeled processes might lead to these discrepancies between our data and the model (Gelman et al., 2013).

339 The types of posterior predictive tests used in this analysis fall into two categories: comparison of observed mean and median genus duration to a distribution of mean and median genus duration estimates from the posterior simulations, comparison of a non-parametric estimate of
342 the survival function from the observed data to estimates of that same survival function from the simulations.

The survival function describes the probability of a taxon persisting given that it has survived
345 up to time t ; this is expressed $P(T \geq t)$ because T is the true extinction time of the species and t is some arbitrary time of observation and we are estimating that probability that t is less than T . It is important to note, however, that the survival function does not reflect density of observations
348 unlike e.g. histograms. Instead, this posterior predictive check reflects the model's ability to

predict genus survival.

These posterior predictive tests were done for the entire data and for each of the origination
351 cohorts.

Results

I first present the results of the multiple posterior predictive checks for the whole dataset as
354 well as each of the origination cohorts. I next present the parameter posterior estimates and their interpretations. Importantly, the adequacy of model fit associated with each cohort-specific interpretation is presented to demonstrate which results for which I have the greatest confidence.

357 Comparisons between the observed distribution of durations to the distributions of 100 simulated datasets reveals the relatively good but heterogeneous fit of the model to the data (Fig. 1). The two major aspects of possible misfit that are observable are at at durations of 2-3 stages. The
360 model slightly under-estimates the number of observations with duration of 2 or 3 stages. The goal of this model is estimating the expected duration of a genus given its covariate information. While the model estimates are not exact, it is possible that our model fits the bulk of our data
363 well but does poorly towards the tails.

Comparisons between the survival functions estimated from the empirical data and from 100 simulated datasets further expands the picture of model adequacy (Fig. 2). The survival curves of
366 the 100 simulated datasets are very similar to the survival function estimated from the empirical data. The major points of potential misfit between the model and the data are underestimated percentage of taxa with duration 1 stage, and an over-estimate of probability of species surviving
369 at least 10-13 stages. Importantly, the major divergence between the observed and estimated applies to taxa with a less than 15% probability of continuing to surviving. Keep in mind, also, that the survival curve as presented does not depict density of observations as in Fig. 1.

372 In addition to distributional comparisons, model adequacy at the total data level was assessed through comparison of the mean and median of the observed data to those from simulated data

sets. While the previous posterior predictive checks have focused on the relatively good but
375 heterogeneous fit of the model to the entire distribution of the data, the fitted model's ability
to predict the mean and median of the observed data appears adequate (Fig. 3a, 3b). Because
the principle goal of this model is to obtain adequate prediction of how a taxon's expected
378 duration for a given set of ecological covariates, the seemingly adequate fit of our model to mean
taxon duration is reassuring (Fig. 3a). Additionally, given the skewness of the observed taxon
durations (Fig. 1, the ability for the model to closely recapitulates the median observed taxon
381 duration points to the overall good fit of the model to the data.

When considered together, all of the above posterior predictive checks indicate approximately
adequate model fit for key questions such as expected taxon duration (Fig. 3a). However, there is
384 obviously heterogeneity in model fit because, while the model can recapitulate some aspects of
the observed data (Fig. 3a, 3b), there are obvious discrepancies between the model and the data
(Fig. 1, 2). By performing the same posterior predictive tests for each of the origination cohorts,
387 it may be possible to get a better picture of the sources of model misfit.

When the posterior predictive tests are visualized for each of the origination cohorts, a com-
plex picture of model fit emerges. Comparison between the empirical survival functions es-
390 timated for each cohort to those estimated from the simulated datasets reveals the degree of
heterogeneity in model fit (Fig. 4, as some origination cohorts appear to be very well fit by the
model (e.g. Tremadoc, Darriwilian Wenlock, Ludlow, Lochkovian, etc.) while others are more
393 poorly fit by the model (e.g. Tournaisian, Visean, Bashirian, Moscovian, Stephanian, Asselian,
etc.). The poverty of model fit to some origination cohorts may indicate that these cohorts are
undergoing a different extinction process whose aspects are unmodeled in this analysis. How-
396 ever, for those cohorts where the model recapitulates the empirical survival function it is likely
that the model may be capturing some of the processes underlying taxon extinction.

For nearly every origination cohort, the model is able to approximately recapitulate the ob-
399 served mean duration (Fig. 5). In comparison, the model has a much more heterogeneous fit to
each origination cohort's median taxon duration (Fig. 6). The skewness of the distribution un-

derlying (Fig. 1) means that for some origination cohorts, median duration might be pegged at
402 1 stage; this means that the posterior predictive distributions for some cohorts can be extremely skewed. The cohorts with notably inadequate poor predictions are the Hirnantian, Priodoli, Em-
405 sian, Eifelian, Givetian, Asselian, Artinskian, and Roadian. The remaining cohorts, however, have approximately adequate fit. These results indicate that our model is very good at recapitulate mean taxon duration (Fig. 3a, 5), and it is capable of estimating overall median duration and median duration of most origination cohorts (Fig. 3b, 6).

408 A larger than average geographic range is expected to have a positive effect on taxon survival (Table 1). The cohort-level estimate of the effect of geographic range size indicates that as a taxon's geographic range increases, that taxon's duration is expected to increase (Table 1). Given
411 the estimates of μ^r and τ^r , there is an approximately 3.7% ($\pm 4.3\%$ SD) probability that this relationships would be reversed ($\text{Pr}(\mathcal{N}(\mu^r, \tau^r) > 0)$).

Body size measured as valve length is estimated to, on average, have no effect on duration
414 (Table 1).

The group-level estimate of the effect of environmental preference is estimated from μ^v and μ^{v^2} . The estimate of μ^v indicates that taxa which slightly prefer epicontinental environments
417 to open-ocean environments are expected to have a greater duration than open-ocean favoring taxa (Table 1). Additionally, given the estimate of between-cohort variance τ^v , there is approximately 18.1% ($\pm 7.5\%$ SD) probability that, for any given cohort, taxa which favor open-ocean environments would have a greater expected duration than taxa which favor epicontinental environments ($\text{Pr}(\mathcal{N}(\mu^v, \tau^v) > 0)$). The estimate of μ^{v^2} indicates that the overall relationship between environmental preference and $\log(\sigma)$ is concave down (Fig. 7), with only a 2.5% ($\pm 2.9\%$ SD)
420 probability that any given cohort is convex up ($\text{Pr}(\mathcal{N}(\mu^{v^2}, \tau^{v^2}) < 0)$).

423 The cohort-specific estimates of all the regression coefficients demonstrate a lot of between cohort variance, with no obvious long-term trends (Fig. 8). While most cohort-specific estimates are very similar to the overall cohort-level estimate, there are a few notable cohorts for which two or more individual-level parameter estimates diverge greatly from the group-level averages (Fig. 8).

What's even more interesting is that for many cohort's for which two or more covariate effect
429 estimates are different from the overall group-level mean are well fit by the model (Fig. 4, 5, 6).

In chronological order, the Wenlock (433.4-427.4 Mya) is the first origination cohort for which
at least two effect estimates diverge from their group-level averages: the effect of the linear
432 aspect of environmental preference β^v increases (shifting the parabola left-ward) while the effect
of average body size β^m decreases meaning that greater than average size is associated with a
longer duration than taxa with less than average body sizes (Fig. 8). Additionally, this cohort is
435 well fit by our model (Fig. 4, 5, 6) which allows us to have greater confidence in these results.
This cohort is one of the few for which the estimated effect of body size is different from the
group-level average.

438 The effects of the linear and quadratic aspects of environmental preference, β^v and β^{v^2} , for
taxa originating in the Frasnian are divergent from the overall group-level mean. For this cohort,
 β^v is estimated to be less than expected while β^{v^2} is estimated to be greater than expected. This
441 result means that the curvature of the relationship increased while the apex was right-shifted
from average. Additionally, this origination cohort is adequately fit by the model (Fig. 4, 5, 6)
which increases confidence in interpreting these results.

444 Taxa originating during the Famennian (372.2-358.9 Mya) were estimated to have a lower
than average expected duration than the group-level average (i.e. greater than average β^0) as
well as lower than average estimate of β^v (i.e. right-shifted) (Fig. 8). Finally, this cohort has only
447 moderate quality of fit as the model is able to estimate average cohort duration (Fig. 5) but has
difficulty reproducing the survival function and median duration (Fig. 4, 6), meaning that these
excursions from the group-level mean may be driven by the difference in processes underlying
450 extinction of taxa in this origination cohort.

Two of the effect estimates for the Sakmarian origination cohort (295.5-290.1 Mya) are di-
vergent from the group-level averages (Fig. 8). Specifically, β^v has an above average estimate
453 indicating a left-shifted relationship between environmental preference and duration, and finally
 β^m was estimated to be below the group-level average which means that taxa with greater than

average body sizes are expected to have greater durations than taxa originating in that cohort
456 with below average body size. The model has a moderate fit to the data, reproducing the mean duration (Fig. 5) while slightly under estimating median durations and not fully recapitulating the survival pattern of the observed data (Fig. 4, 6).

459 The cohort-specific relationships between environmental preference and $\log(\sigma)$ were calculated from the estimates of β^0 , β^v , and β^{v^2} (Fig. 9) and reflect how these three parameters act in concert and not just individually (Fig. 8). Because of the relationship between β^v and β^{v^2} , it is
462 important to consider them together when drawing conclusions from the model. In many cases, the cohort-specific estimated relationship between environmental preference and duration is approximately equal to the group-level average, but 14 of the 33 analyzed origination cohorts have
465 at least one of these three parameters being noticeably different from the group-level average.

The Wenlock, Asseilian, and Sakmarian cohorts all have estimates of the linear aspect of environmental preference, β^v , that are greater than the group-level average. Additionally, this is
468 the only aspect of the relationship between environmental preference and expected taxon duration for these cohorts than is divergent from the group-level means (Fig. 8). These estimates mean that the relationship between environmental preference and duration is right-shifted such
471 that taxa which prefer epicontinental environments over open-ocean are expected to have greater durations than average. Specifically, this means that taxa that can tolerate open-ocean and epicontinental environments but preferentially occur in epicontinental environments are expected
474 to have greater durations than those that occur equally in these two environments (Fig. 9).

The Tremadocian, Frasnian, and Famennian origination cohorts are all estimated to have lower than average estimates of the linear aspect of environmental preference (β^v) (Fig. 8). This
477 change to β^v manifests as a left-shifted relationship between environmental preference and duration such that the apex of the relationship is closer to 0 which means that there is no “advantage” for favoring either an epicontinental and open-ocean environment; this is slightly different from
480 the group-level average relationship which has an approximate 64% probability of the apex being right-shifted so that taxa which slightly favor epicontinental environments are expected to

have a greater duration than those that favor open-ocean environments (Fig. 7). Keep in mind,
483 however, there is an approximately 2.5% probability that any cohort would have a concave down
relationship between environmental preference and duration which means that taxa which favor
purely open-ocean or epicontinental environments are expected to have shorter durations than
486 taxa which can exist in either environment (Fig. 9).

488 Frasnian, Visean, Kungurian origination cohorts are all estimated to have greater than aver-
age estimates of the quadratic aspect of the relationship between environmental preference and
duration β^v ² (Fig. 8). This relationship means that the relationship between taxon environmental
preference is more peaked than expected from the group-level average (Fig. 9), where taxa of
intermediate preference are expected to have an even greater duration than those taxa which
492 exclusively prefer a single environment than would be expected on average.

494 In contrast, the Givetian and Roadian origination cohorts are estimated to have lower than
average estimates of the quadratic aspect of the relationship between environmental preference
and duration β^v ² (Fig. 8). This result means that the relationship between taxon environmental
preference has almost entirely linear as opposed to the peaked relationship expected from the
group-level average (Fig. 9).

498 There is an approximately 90.4% probability that cohort estimates of β^0 and β^r are negatively
correlated, with median estimate of correlation being -0.35. This result means that for any cohort,
we would expect that if extinction intensity increases (β^0 increases), the effect of geographic range
501 on duration increases (β^r decreases). This result is strong evidence for a relationship between
intensity and selectivity with respect to geographic range size.

503 There is an approximate 97.9% probability that the cohort-specific estimates of β^0 and β^v
are negatively correlated with median correlation -0.49. This result means that as extinction
intensity increases it is expected that epicontinental taxa become more favored over open-ocean
environments (i.e. as β^0 increases, β^v decreases). This result is strong evidence for a relationship
507 between intensity and selectivity with respect to the linear aspect of environmental preference.

Correlations between the non-intercept estimates reflect potential similarities in selective pres-

sures between cohorts, however there is only weak evidence of any potential cross-correlations
510 in cohort-specific covariate effects. There is an approximate 31.2% probability that β^r and β^v are
positively correlated. This lack of cross-correlation may be due in part to the higher between-
513 cohort variance of the effect of environmental preference τ^v than the very small between-cohort
variance in the effect of geographic range τ^r (Table 1); the effect of geographic range might simply
not vary enough relative to the much noisier environmental preference.

Conversely, There is a 74.6% probability that estimates of the effect of geographic range (β^r)
516 and the quadratic aspect of environmental preference (β^v^2) are positively correlated; this is weak
evidence of a relationship between the effects of these covariates. Thus, as the effect of geographic
range increases, we might expect with weak evidence that the peakedness of relationship between
519 environmental preference and duration to increase. However, because there is only a 74.6% prob-
ability of a positive correlation, this result cannot interpreted with authority. Instead, this result
is an opportunity for future research to understand a potential relationship between geographic
522 range, environmental preferece, and species duration.

Sampling was found to have a negative effect (positive δ) on duration: greater sampling,
shorter duration (Table 1). While potentially counter intuitive, this result is most likely due to
525 some long lived taxa only be sampled in the stages of the first and last appearance. Also, longer
lived taxa have more opportunities to not be sampled than shorter lived taxa. These two factors
will lead to this result.

528 The Weibull shape parameter α was found to be approximately 1.41 (± 0.05 SD) with a
100% probability of being greater than 1. This result is not consistent with the Law of Con-
stant Extinction (Van Valen, 1973) and is instead consistent with accelerating extinction risk with
531 taxon age. This result is consistent with recent empirical results and may be caused by newly
originating species have a fundamentally lower risk of extinction compared to species which
have already originated (Quental and Marshall, 2013; Smits, 2015; Wagner and Estabrook, 2014).
534 This result is also consistent with a recently proposed nearly-neutral evolution where compe-
tition/selection/evolution drives whole communities to increase in average fitness over time

while still maintaining constant relative fitness across the community, thus older species are
537 more likely to go extinct because of having a fundamentally lower average fitness than newly
originating species (Rosindell et al., 2015). This results, however, is not consistent with other
empirical results from the marine fossil record (Crampton et al., 2016; Finnegan et al., 2008) and
540 could potentially be caused by the minimum resolution of the fossil record (Sepkoski, 1975). It
is thus unclear if a strong biological inference can be made from this result, which means that
further work is necessary on the effect of taxon age on extinction risk.

543

Discussion

The generating observation behind this study was that for bivalves at the end Cretaceous mass
extinction event, the only biological trait that was found the affect extinction risk was geographic
546 range while traits that had previously been associated with difference in duration had no effect
(Jablonski, 1986). This observation raises two linked questions: how does the effect of geographic
range change with changing extinction intensity, and how does the effect of other biological traits
549 change with changing extinction intensity?

I find that as intensity increases (β^0 increases), the magnitude of the effect of geographic range
increases (β^r decreases). I also find that as intensity increases, the difference in survival for taxa
552 favoring epicontinental environments over open-ocean environments is expected to decrease;
this is consistent with the results of Miller and Foote (2009). Finally, there is no evidence for
a correlation between the effects of geographic range and environmental preference on taxon
555 duration.

I find consistent support for the “survival of the unspecialized,” with respect to epicontinen-
tal versus open-ocean environmental preference, as a time-invariant generalization of brachiopod
558 survival (Simpson, 1944). Taxa with intermediate environmental preferences are expected to have
lower extinction risk than taxa specializing in either epicontinental or open-ocean environments
(Fig. 7), though the curvature of the relationship varies from rather shallow to very peaked

561 (Fig. 9). However, this relationship is not symmetric about 0, as taxa favoring epicontinental
environments are expected with approximately 75% probability to have a greater duration than taxa
favoring open-ocean environments. This description of environment preference only describes
564 one major aspect of a taxon's environmental context, with factors such as bathymetry and tem-
perature being further descriptors of a taxon's adaptive zone (Harnik, 2011; Harnik et al., 2012;
Heim and Peters, 2011; Nürnberg and Aberhan, 2013); inclusion of these factors in future analy-
567 ses would potentially improve our understanding the extent and complexity of the "survival of
the unspecialized" hypothesis as it applies to all dimensions of an adaptive zone.

570 Hopkins et al. (2014), in their analysis of niche conservatism and substrate lithological pref-
erence in marine invertebrates, found that brachiopods were among the least "conservative"
groups; taxa were found to easily change substrate preference on short time scales. While sub-
strate preference is not the same as environmental preference (as defined here), a question does
573 arise: are there three classes of environmental preference instead of two? These classes would
be taxa with broad tolerance ("true" generalists), inflexible specialists ("true" specialists), and
flexible but with a narrow tolerance. A flexible taxon is one with a narrow habitat preference at
576 one time, but with preference that changes over time with changing environmental availability.
My analysis assumes that traits are constant over the duration of the taxon meaning that this
scenario is not detectable; taxa with broad tolerances and flexible taxa with narrow per-stage
579 preference end up being treated the same way. Future work should explore how environmental
preference changes over lineage duration in relation to environmental availability to estimate if
the generalists–specialists continuum is actually ternary relationship.

582 This analysis treats genus duration as a continuous-time survival process, but duration in
paleontological data can also be treated as a discrete-time survival process, something that is
equally common in the literature CITATION. For example, a populat class of disctrete-time sur-
585 vival models that takes into account imperfect observation than the method used here is the
Cormack-Jolly-Seber (CJS) model (Liow et al., 2008; Liow and Nichols, 2010; Royle and Dorazio,
2008; Tomiya, 2013). This model is a type of hidden Markov model with an absorbing state (i.e.

extinction). In this model, survival is defined as the probability of surviving from time t to time $t + 1$. Additionally, the effect of preservation and sighting is estimated as probability of observing a taxon that is present; this can extend the duration of a taxon beyond its last occurrence.

This approach is a fundamentally different from the method used in my analysis: I am estimating the biasing effect of sampling probability on taxon duration to then compare with effects of other covariates, while the CJS model estimates the pre-sampling fossil record and then estimates per-time unit survival probability.

The use of genera as the unit of the study and how to exactly interpret the effects of the biological traits is an important question. For example, if any of the traits analyzed here are associated with increases in speciation rates, this might increase the duration of genera through self-renewal (Raup, 1991, 1994), which would be an example of the difference in biological pattern between species and genera (Jablonski, 1987, 2007, 2008). This could lead to a trait appearing to decrease generic level extinction risk by that trait increasing species level origination rate instead of decreasing species level extinction risk.

The model used here could be improved through either increasing the number of analyzed traits, expanding the hierarchical structure of the model to include other major taxonomic groups of interest, and the inclusion of explicit phylogenetic relationships between the taxa in the model as an additional hierarchical effect. An example trait that may be of particular interest is the affixing strategy or method of interaction with the substrate of the taxon, which has been found to be related to brachiopod survival where, for cosmopolitan taxa, taxa that are attached to the substrate are expected to have a greater duration than those that are not (Alexander, 1977).

It is theoretically possible to expand this model to allow for comparisons within and between major taxonomic groups which would better constrain the brachiopod estimates while also allowing for estimation of similarities and differences in cross-taxonomic patterns. The major issue surrounding this particular expansion involves finding a similarly well sampled taxonomic group that is present during the Paleozoic. Potential groups include Crinoidea, Ostracoda, and other members of the “Paleozoic fauna” (Sepkoski, 1981).

615 With significant updates, it would also be possible to compare the brachiopod record with
with Modern groups such as bivalves or gastropods (Sepkoski, 1981), though remembering that
the groups may not necessarily share all cohorts with the brachiopods. This particular model
618 expansion would act as a test of any universal cross-taxonomic patterns in the effects of emergent
traits on extinction such as has been proposed for geographic range (Payne and Finnegan, 2007).
Additionally, this expanded model would also act as a test of the distinctness of the Sepkoski
621 (1981) three-fauna hypothesis in terms of trait-dependent extinction.

Traits like environmental preference or geographic range (Hunt et al., 2005; Jablonski, 1987)
are most likely heritable. Without phylogenetic context, this analysis assumes that differences
624 in extinction risk between taxa are independent of the shared evolutionary history of those taxa
(Felsenstein, 1985). In contrast, the origination cohorts only capture shared temporal context. For
example, if taxon duration is phylogenetically heritable, then closely related taxa may have more
627 similar durations as well as more similar biological traits. Without taking into account phylogenetic
similarity the effects of these biological traits would be inflated solely due to inheritance.
The inclusion of phylogenetic context as an additional individual-level hierarchical effect, inde-
630 pendent of origination cohort, would allow for determining how much of the observed variability
is due to shared evolutionary history versus shared temporal context versus actual differences
associated with biological traits (Smits, 2015).

633 The combination and integration of the phylogenetic comparative and paleontological ap-
proaches requires both sources of data, something which is not possible for this analysis because
there is no phylogenetic hypothesis for all Paleozoic taxa, something that is frequently the case
636 for marine invertebrates with a good fossil record. When both data sources are available has been
possible, however, the analysis can more fully address the questions of interest in macroevolu-
tion (Fritz et al., 2013; Harnik et al., 2014; Raia et al., 2012, 2013; Simpson et al., 2011; Slater, 2013,
639 2015; Slater et al., 2012; Smits, 2015; Tomiya, 2013).

Conclusion

In summary, patterns of Paleozoic brachiopod survival were analyzed using a fully Bayesian hierarchical survival modelling approach while also eschewing the traditional separation between background and mass extinction. I find that cohort extinction intensity is negatively correlated with the cohort-specific effects of geographic range and environmental preference. These results imply that as extinction intensity increases (β^0) increases, it is expected that these effects will increase in magnitude. Taken together, these results point to a potential macroevolutionary mechanism behind differences in trait-based survival during and away from mass extinctions due to correlations between intensity and selectivity. Additionally, I find support for greater survival in environmental generalists over specialists in all origination cohorts analyzed; this is consistent with the long standing “survival of the unspecialized” hypothesis (Baumiller, 1993; Liow, 2004, 2007; Nürnberg and Aberhan, 2013, 2015; Simpson, 1944, 1953; Smits, 2015). The results of this analysis support the conclusion that for Paleozoic brachiopods, as extinction intensity increases overall extinction selectivity is expected to increase as well.

654

Acknowledgments

I would like to thank K. Angielczyk, M. Foote, P. D. Polly, R. Ree, and G. Slater for helpful discussion during the conception of this study. I'd also like to thank D. Bapst, N. Pierrehumbert and M. Villarosa Garcia for additional comments. An additional thank you to A. Miller for the epicontinental versus open-ocean assignments. Finally, thank you to P. Harnik, L. L. Hsiang, G. Simpson, and the other anonymous reviewers for their comments at various points during this manuscripts life that improved this manuscript. This entire study would not have been possible without the Herculean effort of the many contributors to the Paleobiology Database. In particular, I would like to thank J. Alroy, M. Aberhan, D. Bottjer, M. Clapham, F. Fürsich, N. Heim, A. Hendy, S. Holland, L. Ivany, W. Kiessling, B. Kröger, A. McGowan, T. Olszewski, P.

Novack-Gottshall, M. Patzkowsky, M. Uhen, L. Villier, and P. Wager. This work was supported by a NASA Exobiology grant (NNX10AQ446) to A. Miller and M. Foote. I declare no conflicts
666 of interest. This is Paleobiology Database publication XXX. The code necessary for reproducing these results is available as a Zenodo archive DOI 10.5281/zenodo.46928.

Literature Cited

- 669 Alexander, R. R. 1977. Generic longevity of articulate brachiopods in relation to the mode of
stabilization on the substrate. *Palaeogeography, Palaeoclimatology, Palaeoecology* 21:209–226.
- Alroy, J. 2010. The Shifting Balance of Diversity Among Major Marine Animal Groups. *Science*
672 329:1191–1194.
- . 2014. A simple Bayesian method of inferring extinction. *Paleobiology* 40:584–607.
- Baumiller, T. K. 1993. Survivorship analysis of Paleozoic Crinoidea: effect of filter morphology
675 on evolutionary rates. *Paleobiology* 19:304–321.
- Chao, A., T. C. Hsieh, R. L. Chazdon, R. K. Colwell, N. J. Gotelli, and B. D. Inouye. 2015. Unveiling
the species-rank abundance distribution by generalizing the Good-Turing sample coverage
678 theory. *Ecology* 96:1189–1201.
- Cooper, W. S. 1984. Expected time to extinction and the concept of fundamental fitness. *Journal
of Theoretical Biology* 107:603–629.
- 681 Crampton, J. S., R. A. Cooper, P. M. Sadler, and M. Foote. 2016. Greenhouse–icehouse transition
in the Late Ordovician marks a step change in extinction regime in the marine plankton.
Proceedings of the National Academy of Sciences 113:1498–1503.
- 684 Ezard, T. H. G., P. N. Pearson, T. Aze, and A. Purvis. 2012. The meaning of birth and death (in
macroevolutionary birth-death models). *Biology Letters* 8:139–142.
- Felsenstein, J. 1985. Phylogenies and the comparative method. *The American Naturalist* 125:1–15.
- 687 Finnegan, S., N. A. Heim, S. E. Peters, and W. W. Fischer. 2012. Climate change and the selective
signature of the Late Ordovician mass extinction. *Proceedings of the National Academy of
Sciences* 109:6829–6834.

- 690 Finnegan, S., J. L. Payne, and S. C. Wang. 2008. The Red Queen revisited: reevaluating the age selectivity of Phanerozoic marine genus extinctions. *Paleobiology* 34:318–341.
- Fitzjohn, R. G. 2010. Quantitative Traits and Diversification. *Systematic Biology* 59:619–633.
- 693 Foote, M. 1988. Survivorship analysis of Cambrian and Ordovician Trilobites. *Paleobiology* 14:258–271.
- . 2000a. Origination and extinction components of taxonomic diversity: general problems. 696 *Paleobiology* 26:74–102.
- . 2000b. Origination and extinction components of taxonomic diversity: Paleozoic and post-Paleozoic dynamics. *Paleobiology* 26:578–605.
- 699 ———. 2014. Environmental controls on geographic range size in marine animal genera. *Paleobiology* 40:440–458.
- Foote, M., and A. I. Miller. 2013. Determinants of early survival in marine animal genera. *Paleobiology* 702 39:171–192.
- Foote, M., and D. M. Raup. 1996. Fossil preservation and the stratigraphic ranges of taxa. *Paleobiology* 22:121–140.
- 705 Fritz, S. A., J. Schnitzler, J. T. Eronen, C. Hof, K. Böhning-Gaese, and C. H. Graham. 2013. Diversity in time and space: wanted dead and alive. *Trends in Ecology & Evolution* 28:509–516.
- Gelman, A., J. B. Carlin, H. S. Stern, D. B. Dunson, A. Vehtari, and D. B. Rubin. 2013. Bayesian 708 data analysis. 3rd ed. Chapman and Hall, Boca Raton, FL.
- Gelman, A., and J. Hill. 2007. Data Analysis using Regression and Multilevel/Hierarchical Models. Cambridge University Press, New York, NY.
- 711 Goldberg, E. E., L. T. Lancaster, and R. H. Ree. 2011. Phylogenetic inference of reciprocal effects between geographic range evolution and diversification. *Systematic Biology* 60:451–465.

- Goldberg, E. E., K. Roy, R. Lande, and D. Jablonski. 2005. Diversity, endemism, and age distributions in macroevolutionary sources and sinks. *The American Naturalist* 165:623–633.
- Harnik, P. G. 2011. Direct and indirect effects of biological factors on extinction risk in fossil bivalves. *Proceedings of the National Academy of Sciences* 108:13594–13599.
- Harnik, P. G., P. C. Fitzgerald, J. L. Payne, and S. J. Carlson. 2014. Phylogenetic signal in extinction selectivity in Devonian terebratulide brachiopods. *Paleobiology* 40:675–692.
- Harnik, P. G., C. Simpson, and J. L. Payne. 2012. Long-term differences in extinction risk among the seven forms of rarity. *Proceedings of the Royal Society B: Biological Sciences* 279:4969–4976.
- Heim, N. A., and S. E. Peters. 2011. Regional environmental breadth predicts geographic range and longevity in fossil marine genera. *PloS one* 6:e18946.
- Hijmans, R. J. 2015. raster: Geographic data analysis and modeling. R package version 2.3-24.
- Hoehn, K. B., P. G. Harnik, and V. L. Roth. 2015. A framework for detecting natural selection on traits above the species level. *Methods in Ecology and Evolution* pages doi: 10.1111/2041—210X.12461.
- Hoffman, M. D., and A. Gelman. 2014. The No-U-Turn Sampler: Adaptively Setting Path Lengths in Hamiltonian Monte Carlo. *Journal of Machine Learning Research* 15:1351–1381.
- Hopkins, M. J., C. Simpson, and W. Kiessling. 2014. Differential niche dynamics among major marine invertebrate clades. *Ecology Letters* 17:314–323.
- Hunt, G., and D. L. Rabosky. 2014. Phenotypic Evolution in Fossil Species: Pattern and Process. Annual Review of Earth and Planetary Sciences 42:421–441.
- Hunt, G., K. Roy, and D. Jablonski. 2005. Species-level heritability reaffirmed: a comment on "On the heritability of geographic range sizes". *The American Naturalist* 166:129–135.

- 735 Jablonski, D. 1986. Background and mass extincitons: the alternation of macroevolutionary regimes. *Science* 231:129–133.
- 738 ———. 1987. Heritability at the species level: analysis of geographic ranges of cretaceous mollusks. *Science* 238:360–363.
- 741 ———. 2007. Scale and hierarchy in macroevolution. *Palaeontology* 50:87–109.
- . 2008. Species Selection: Theory and Data. *Annual Review of Ecology, Evolution, and Systematics* 39:501–524.
- Jablonski, D., and K. Roy. 2003. Geographical range and speciation in fossil and living molluscs. *Proceedings of the Royal Society B: Biological Sciences* 270:401–406.
- 744 Johnson, J. G. 1974. Extinction of Perched Faunas. *Geology* 2:479–482.
- Kiessling, W., and M. Aberhan. 2007. Environmental determinants of marine benthic biodiversity dynamics through Triassic – Jurassic time. *Paleobiology* 33:414–434.
- 747 Klein, J. P., and M. L. Moeschberger. 2003. *Survival Analysis: Techniques for Censored and Truncated Data*. 2nd ed. Springer, New York.
- Kleinbaum, D. G., and M. Klein. 2005. *Survival analysis: a self-learning text*. 2nd ed. Springer, 750 New York, NY.
- Lewandowski, D., D. Kurowicka, and H. Joe. 2009. Generating random correlation matrices based on vines and extended onion method. *Journal of Multivariate Analysis* 100:1989–2001.
- 753 Liow, L. H. 2004. A test of Simpson's "rule of the survival of the relatively unspecialized" using fossil crinoids. *The American Naturalist* 164:431–443.
- 756 ———. 2007. Does versatility as measured by geographic range, bathymetric range and morphological variability contribute to taxon longevity? *Global Ecology and Biogeography* 16:117–128.

- Liow, L. H., M. Fortelius, E. Bingham, K. Lintulaakso, H. Mannila, L. Flynn, and N. C. Stenseth.
2008. Higher origination and extinction rates in larger mammals. *Proceedings of the National
Academy of Sciences* 105:6097–6102.
- 759
- Liow, L. H., and J. D. Nichols. 2010. Estimating rates and probabilities of origination and ex-
tinction using taxonomic occurrence data: Capture-mark-recapture (CMR) approaches. Pages
762 81–94 in J. Alroy and G. Hunt, eds. *Quantitative Methods in Paleobiology*. The Paleontological
Society.
- Liow, L. H., T. B. Quental, and C. R. Marshall. 2010. When can decreasing diversification rates be
765 detected with molecular phylogenies and the fossil record? *Systematic biology* 59:646–659.
- Maddison, W. P., P. E. Midford, and S. P. Otto. 2007. Estimating a binary character's effect on
speciation and extinction. *Systematic Biology* 56:701.
- 768 Miller, A. I., and M. Foote. 2009. Epicontinental seas versus open-ocean settings: the kinetics of
mass extinction and origination. *Science* 326:1106–1109.
- Nürnberg, S., and M. Aberhan. 2013. Habitat breadth and geographic range predict diversity
771 dynamics in marine Mesozoic bivalves. *Paleobiology* 39:360–372.
- . 2015. Interdependence of specialization and biodiversity in Phanerozoic marine inverte-
brates. *Nature Communications* 6:6602.
- 774 Palmer, M. E., and M. W. Feldman. 2012. Survivability is more fundamental than evolvability.
PLoS one 7:e38025.
- Payne, J. L., A. M. Bush, E. T. Chang, N. A. Heim, M. L. Knope, and S. B. Pruss. 2016. Extinc-
777 tion intensity, selectivity and their combined macroevolutionary influence in the fossil record.
Biology Letters 12:20160202.
- Payne, J. L., and S. Finnegan. 2007. The effect of geographic range on extinction risk during

780 background and mass extinction. *Proceedings of the National Academy of Sciences* 104:10506–
10511.

Payne, J. L., N. A. Heim, M. L. Knope, and C. R. McClain. 2014. Metabolic dominance of bivalves
783 predates brachiopod diversity decline by more than 150 million years. *Proceedings of the Royal
Society B: Biological Sciences* 281:20133122.

Peters, S. E. 2007. The problem with the Paleozoic. *Paleobiology* 33:165–181.

786 ———. 2008. Environmental determinants of extinction selectivity in the fossil record. *Nature*
454:626–629.

Quental, T. B., and C. R. Marshall. 2009. Extinction during evolutionary radiations: reconciling
789 the fossil record with molecular phylogenies. *Evolution* 63:3158–3167.

———. 2013. How the Red Queen Drives Terrestrial Mammals to Extinction. *Science* 341:290–292.

Rabosky, D. L. 2010. Extinction rates should not be estimated from molecular phylogenies. *Evo-
792 lution* 64:1816–1824.

Rabosky, D. L., and A. R. McCune. 2010. Reinventing species selection with molecular phylogenies. *Trends in Ecology & Evolution* 25:68–74.

795 Rabosky, D. L., F. Santini, J. Eastman, S. a. Smith, B. Sidlauskas, J. Chang, and M. E. Alfaro. 2013.
Rates of speciation and morphological evolution are correlated across the largest vertebrate
radiation. *Nature Communications* 4:1–8.

798 Raia, P., F. Carotenuto, F. Passaro, D. Fulgione, and M. Fortelius. 2012. Ecological specialization
in fossil mammals explains Cope’s rule. *The American Naturalist* 179:328–337.

Raia, P., F. Carotenuto, F. Passaro, P. Piras, D. Fulgione, L. Werdelin, J. Saarinen, and M. Fortelius.
801 2013. Rapid action in the Palaeogene, the relationship between phenotypic and taxonomic
diversification in Coenozoic mammals. *Proceedings of the Royal Society B: Biological Sciences*
280:20122244.

- 804 Raup, D. M. 1975. Taxonomic survivorship curves and Van Valen's Law. *Paleobiology* 1:82–96.
- . 1978. Cohort Analysis of generic survivorship. *Paleobiology* 4:1–15.
- . 1991. *Extinction: Bad Genes or Bad Luck?* Norton, New York.
- 807 ———. 1994. The role of extinction in evolution. *Proceedings of the National Academy of Sciences* 91:6758–6763.
- Ritterbush, K. A., and M. Foote. 2017. Association between geographic range and initial survival
810 of Mesozoic marine animal genera: Circumventing the confounding effects of temporal and taxonomic heterogeneity. *Paleobiology* 43:209–223.
- Rosindell, J., L. J. Harmon, and R. S. Etienne. 2015. Unifying ecology and macroevolution with
813 individual-based theory. *Ecology Letters* 18:472–482.
- Royle, J. A., and R. M. Dorazio. 2008. *Hierarchical modeling and inference in ecology: the analysis of data from populations, metapopulations and communities.* Elsevier, London.
- 816 Rubin, D. B. 1996. Multiple imputation after 18+ years. *Journal of the American Statistical
Assocaition* 91:473–489.
- Sepkoski, J. J. 1975. Stratigraphic biases in the analysis of taxonomic survivorship. *Paleobiology*
819 1:343–355.
- . 1981. A factor analytic description of the Phanerozoic marine fossil record. *Paleobiology* 7:36–53.
- 822 Sheehan, P. M. 2001. The late Ordovician mass extinction. *Annual Review of Earth and Planetary
Sciences* 29:331–364.
- Simpson, C. 2006. Levels of selection and large-scale morphological trends. Ph.D. thesis. University
825 of Chicago.

- Simpson, C., and P. G. Harnik. 2009. Assessing the role of abundance in marine bivalve extinction over the post-Paleozoic. *Paleobiology* 35:631–647.
- 828 Simpson, C., W. Kiessling, H. Mewis, R. C. Baron-Szabo, and J. Müller. 2011. Evolutionary diversification of reef corals: a comparison of the molecular and fossil records. *Evolution* 65:3274–3284.
- 831 Simpson, G. G. 1944. *Tempo and Mode in Evolution*. Columbia University Press, New York.
———. 1953. *The Major Features of Evolution*. Columbia University Press, New York.
- Slater, G. J. 2013. Phylogenetic evidence for a shift in the mode of mammalian body size evolution
834 at the Cretaceous-Palaeogene boundary. *Methods in Ecology and Evolution* 4:734–744.
———. 2015. Iterative adaptive radiations of fossil canids show no evidence for diversity-dependent trait evolution. *Proceedings of the National Academy of Sciences* 112:4897–4902.
- 837 Slater, G. J., L. J. Harmon, and M. E. Alfaro. 2012. Integrating fossils with molecular phylogenies improves inference of trait evolution. *Evolution* 66:3931–3944.
- Smithson, M., and J. Verkuilen. 2006. A better lemon squeezer? Maximum-likelihood regression
840 with beta-distributed dependent variables. *Psychological Methods* 11:54–71.
- Smits, P. D. 2015. Expected time-invariant effects of biological traits on mammal species duration. *Proceedings of the National Academy of Sciences* 112:13015–13020.
- 843 Solow, A. R., and W. Smith. 1997. On fossil preservation and the stratigraphic ranges of taxa. *Paleobiology* 23:271–277.
- Stadler, T. 2011. Mammalian phylogeny reveals recent diversification rate shifts. *Proceedings of
846 the National Academy of Sciences* 108:6187–6192.
———. 2013. Recovering speciation and extinction dynamics based on phylogenies. *Journal of Evolutionary Biology* 26:1203–1219.

- 849 Stadler, T., and F. Bokma. 2013. Estimating speciation and extinction rates for phylogenies of higher taxa. *Systematic biology* 62:220–230.
- Stan Development Team. 2014. Stan: A c++ library for probability and sampling, version 2.5.0.
- 852 Stanley, S. M. 1975. A theory of evolution above the species level. *Proceedings of the National Academy of Sciences* 72:646–650.
- . 1979. Macroevolution: pattern and process. W. H. Freeman, San Francisco.
- 855 Team, S. D. 2017. Stan Modeling Language Users Guide and Reference Manual.
- Tomiya, S. 2013. Body Size and Extinction Risk in Terrestrial Mammals Above the Species Level. *The American Naturalist* 182:196–214.
- 858 Van Valen, L. 1973. A new evolutionary law. *Evolutionary Theory* 1:1–30.
- . 1979. Taxonomic survivorship curves. *Evolutionary Theory* 4:129–142.
- Vilhena, D. A., E. B. Harris, C. T. Bergstrom, M. E. Maliska, P. D. Ward, C. A. Sidor, C. A. E. 861 Strömberg, and G. P. Wilson. 2013. Bivalve network reveals latitudinal selectivity gradient at the end-Cretaceous mass extinction. *Scientific Reports* 3:1790.
- Wagner, P. J., and G. F. Estabrook. 2014. Trait-based diversification shifts reflect differential ex- 864 tinction among fossil taxa. *Proceedings of the National Academy of Sciences* 111:16419–16424.
- Wagner, P. J., and J. D. Marcot. 2013. Modelling distributions of fossil sampling rates over time, space and taxa: assessment and implications for macroevolutionary studies. *Methods in Ecology and Evolution* 4:703–713.
- 867 Wang, S. C. 2003. On the continuity of background and mass extinction. *Paleobiology* 29:455–467.
- Wang, S. C., and C. R. Marshall. 2004. Improved confidence intervals for estimating the position 870 of a mass extinction boundary. *Paleobiology* 30:5–18.

Williams, C., C. H. C. Brunton, and S. J. Carlson. 2007. Treatise on invertebrate paleontology. Part H, Brachiopoda. Geological Society of America, Boulder, Colorado.

Tables

Table 1: Estimates of group-level and invariant parameter values for the fitted model analyzed here.

Category	Parameter	Effect of...	Mean	SD	10%	50%	90%
	μ^i	intercept	-3.04	0.19	-3.29	-3.04	-2.80
	μ^r	geographic	-0.98	0.16	-1.17	-0.98	-0.78
Mean		range					
	μ^v	environmental	-0.76	0.18	-0.99	-0.76	-0.53
		preference					
	μ^{v^2}	environmental	3.15	0.35	2.71	3.15	3.59
		preference ²					
	μ^m	body size	-0.02	0.12	-0.17	-0.02	0.14
	τ^i	intercept	0.50	0.11	0.38	0.50	0.65
	τ^r	geographic	0.49	0.16	0.29	0.49	0.70
Standard deviation		range					
	τ^v	environmental	0.83	0.16	0.63	0.82	1.05
		preference					
	τ^{v^2}	environmental	1.49	0.35	1.08	1.46	1.94
		preference ²					
	τ^m	body size	0.47	0.12	0.32	0.46	0.63
Other	δ	sampling	0.90	0.15	0.71	0.89	1.08
	α	ageing	1.36	0.04	1.30	1.36	1.42

Note: These parameters are the group-level estimates of the effects of biological traits on brachiopod generic survival, the standard deviation of the between-cohort effects, as well as the estimates of the effect of sampling δ and the Weibull shape parameter α . The mean, standard deviation (SD), 10th, 50th, and 90th quantiles of the marginal posteriors are presented.

Figure legends

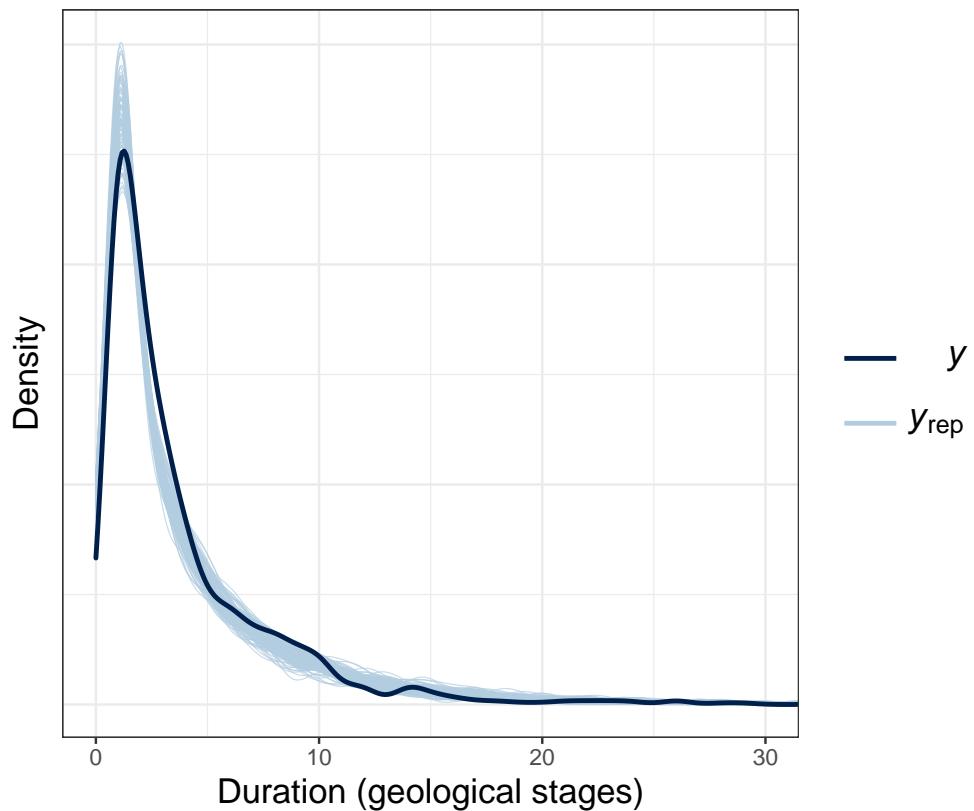


Figure 1: Comparison of the distribution of the observed data (black) to 100 simulated distributions (blue). This is a close-up view of the bulk of the distribution which shows the more subtle aspects of (mis)fit between the data and the model.

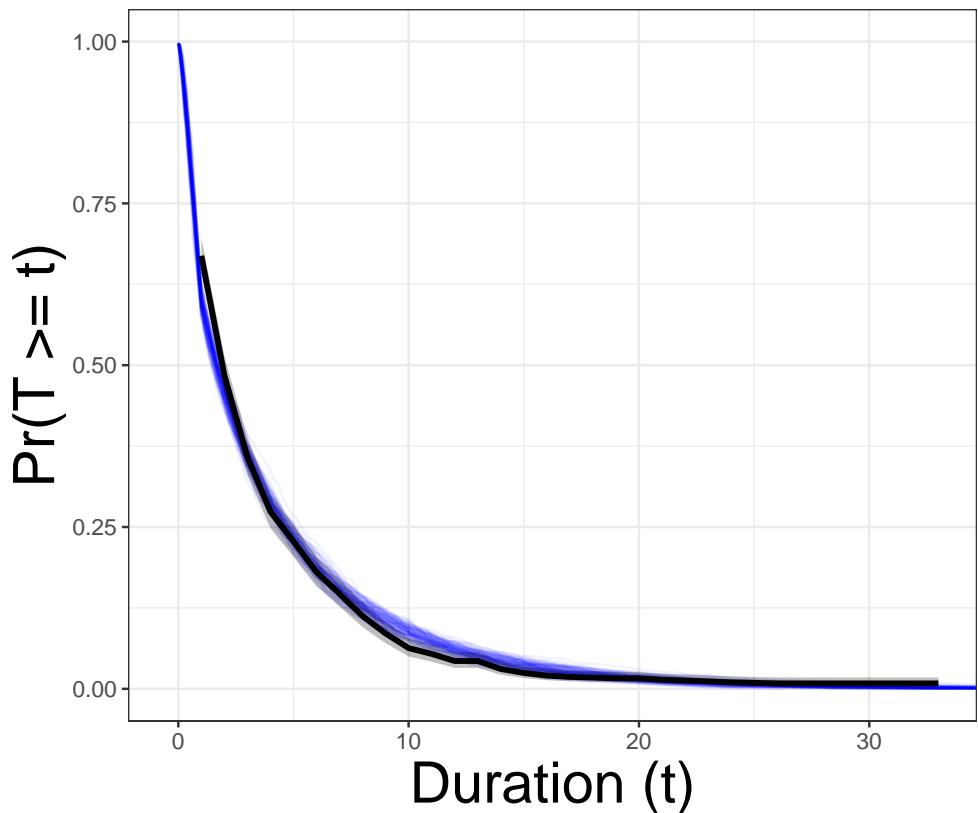


Figure 2: Comparison of the empirical estimate of $S(t)$ (highlighted) versus estimates from 100 posterior predictive data sets (black). $S(t)$ corresponds to the probability that the age of a genus t is less than the genus' ultimate duration T .

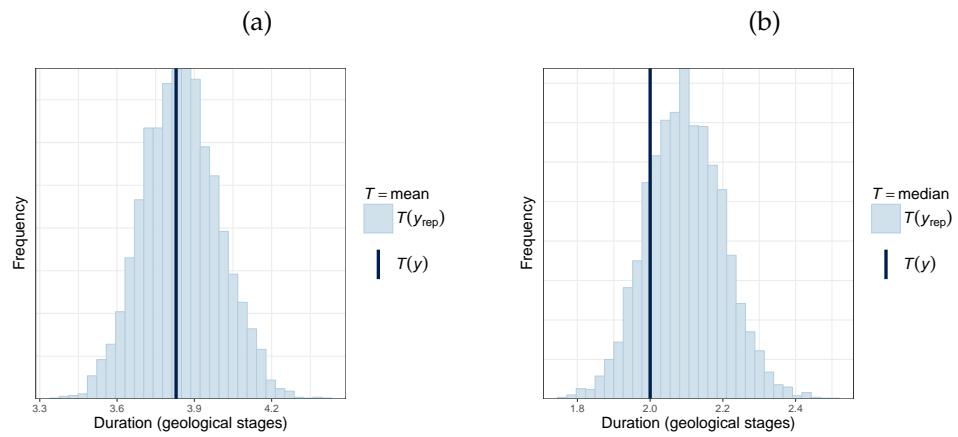


Figure 3: Comparison of the (A) observed mean genus duration (black vertical line) to a distribution of means estimated from 100 simulated datasets (blue), and (B) comparison of the observed median genus duration (black vertical line) to a distribution of medians estimated from 100 simulated datasets (blue). Model fit is evaluated by the similarity between the observed and the estimated, where good fit is demonstrated by the vertical line being “within” the simulated distribution.

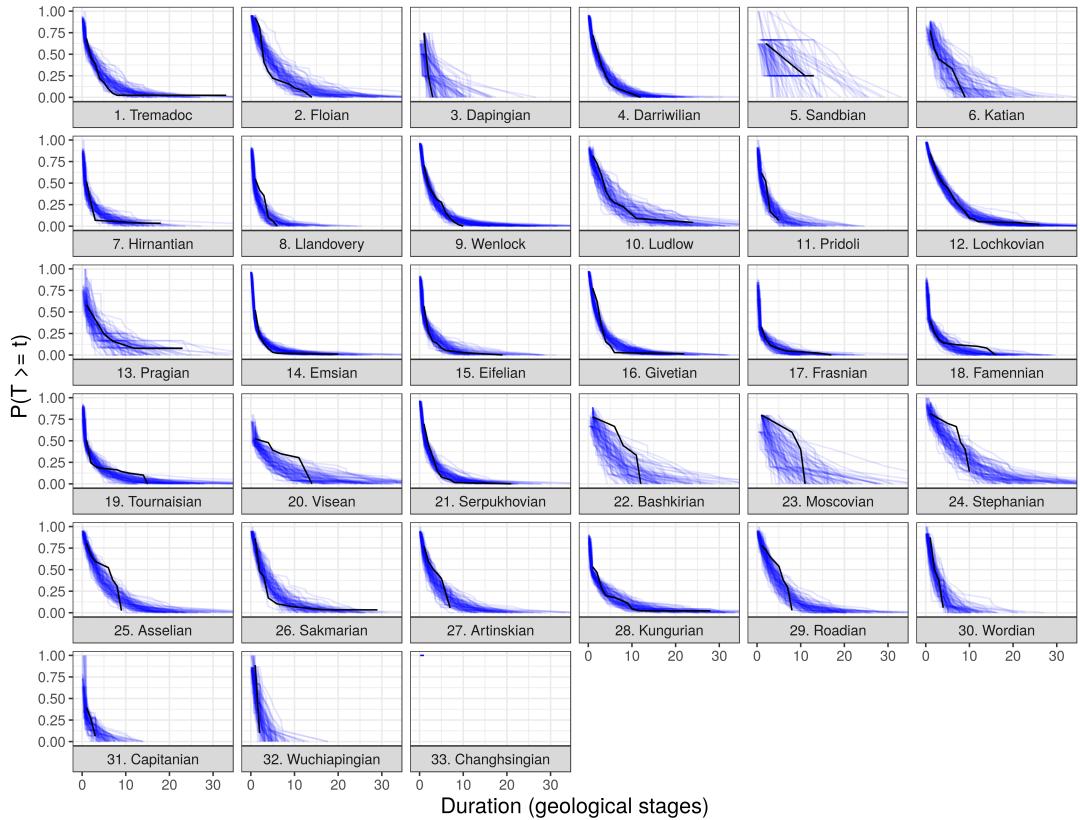


Figure 4: Comparison of the empirical estimate of $S(t)$ (highlighted) versus estimates from 100 posterior predictive data sets (black) for each of the origination cohorts. $S(t)$ corresponds to the probability that the age of a genus t is less than the genus' ultimate duration T . By comparing the fit of the model to the individual cohorts, when and where the model (mis)fits is more observable.

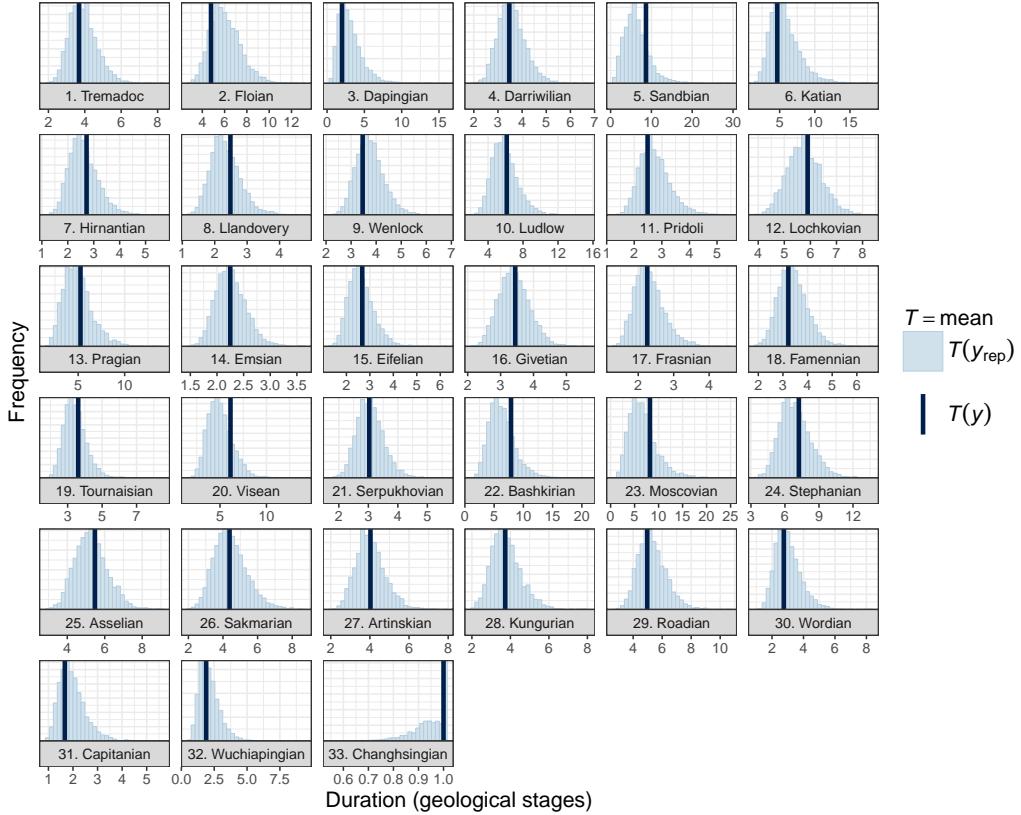


Figure 5: Comparison of the observed mean genus duration (black vertical line) to a distribution of means estimated from 100 simulated datasets (blue) for each of the origination cohorts. Model fit is evaluated by the similarity between the observed and the estimated, where good fit is demonstrated by the vertical line being “within” the simulated distribution.

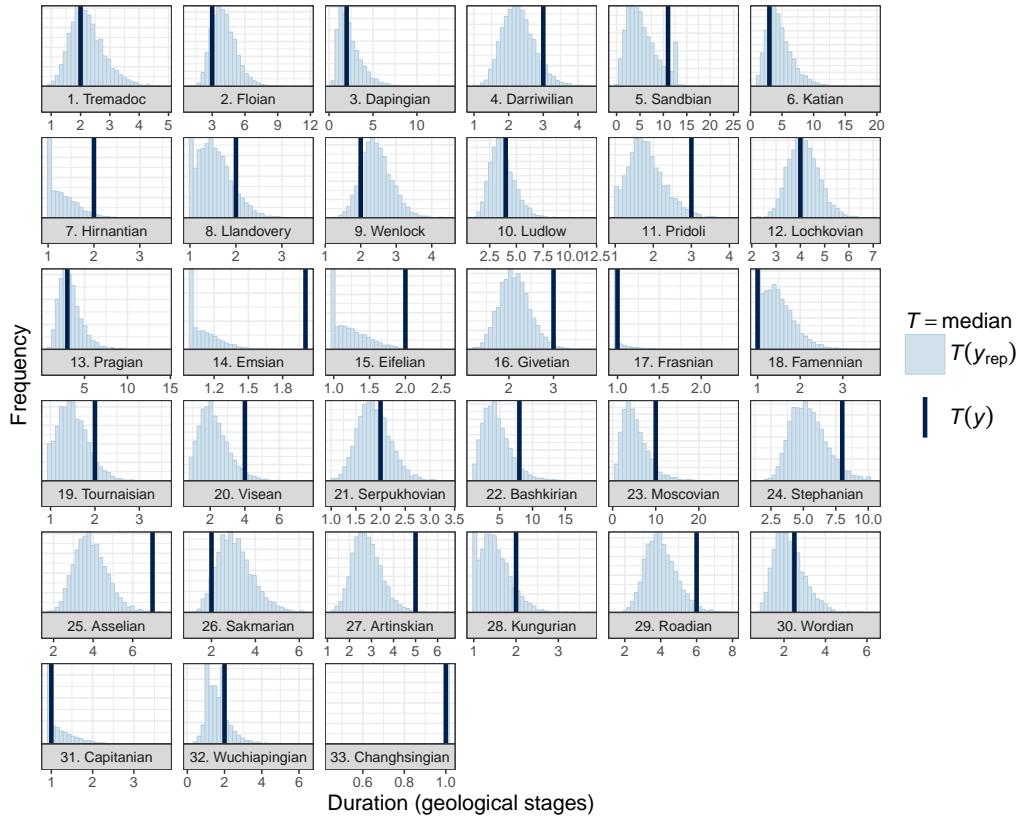


Figure 6: Comparison of the observed median genus duration (black vertical line) to a distribution of medians estimated from 100 simulated datasets (blue) for each of the origination cohorts. Model fit is evaluated by the similarity between the observed and the estimated, where good fit is demonstrated by the vertical line being “within” the simulated distribution.

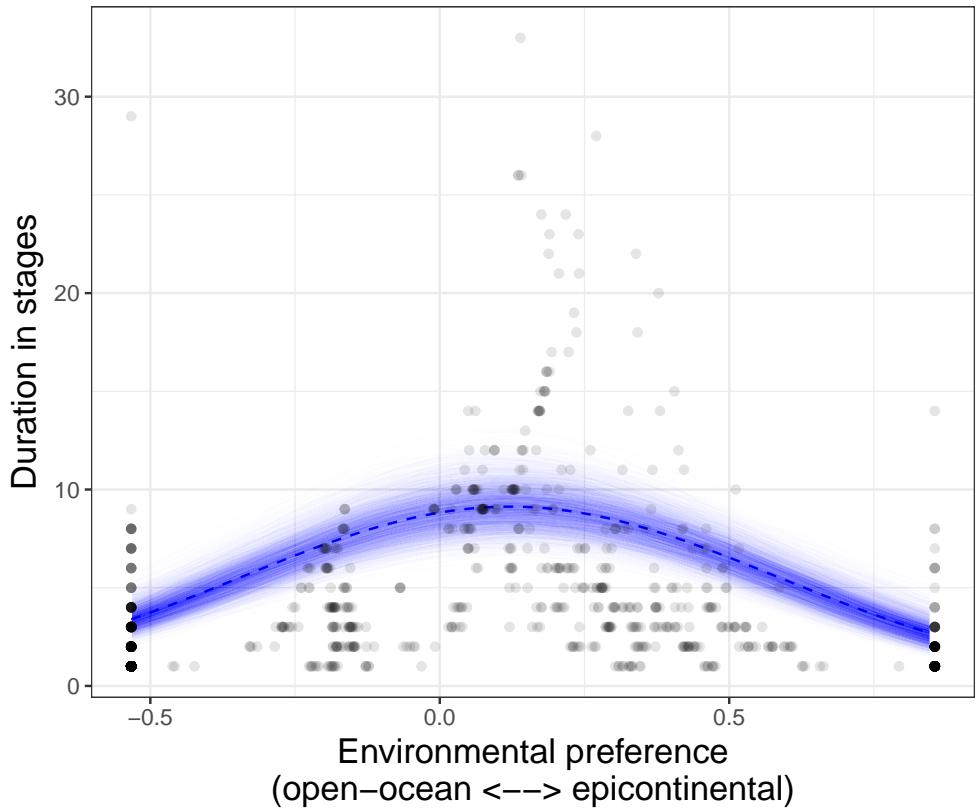


Figure 7: The overall expected relationship between environmental affinity v_i and a $\log(\sigma)$ when $r = 0$ and $m = 0$. The 1000 semi-transparent lines corresponds to a single draw from the posterior predictive distribution, while the highlighted line corresponds to the median of the posterior predictive distribution. The overall relationship is concave down with an optimum greater than 0, which means that taxa favoring epicontinental environments are expected to have longer durations than those favoring open-ocean environments. The tick marks along the bottom of the plot correspond to the (rescaled) observed values of environmental preference.

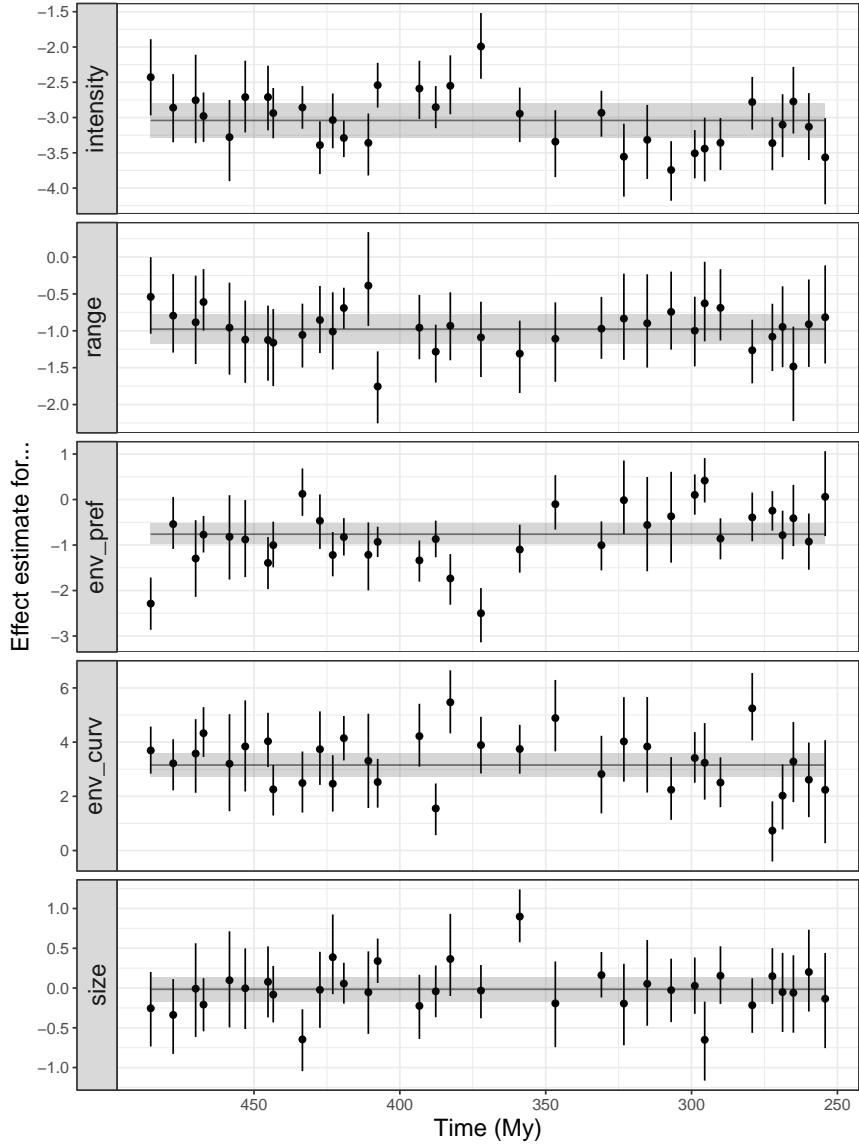


Figure 8: Comparison of cohort-specific estimates of β^0 , the effect of geographic range on extinction risk β^r , the effect of environmental preference β^v and β^{v^2} , and body size β^m . Points correspond to the median of the cohort-specific estimate, along with 80% credible intervals. Points are plotted at the midpoint of the cohorts stage of origination in millions of years before present (My). Black, horizontal lines are the overall estimates of covariate effects along with 80% credible intervals (shaded).

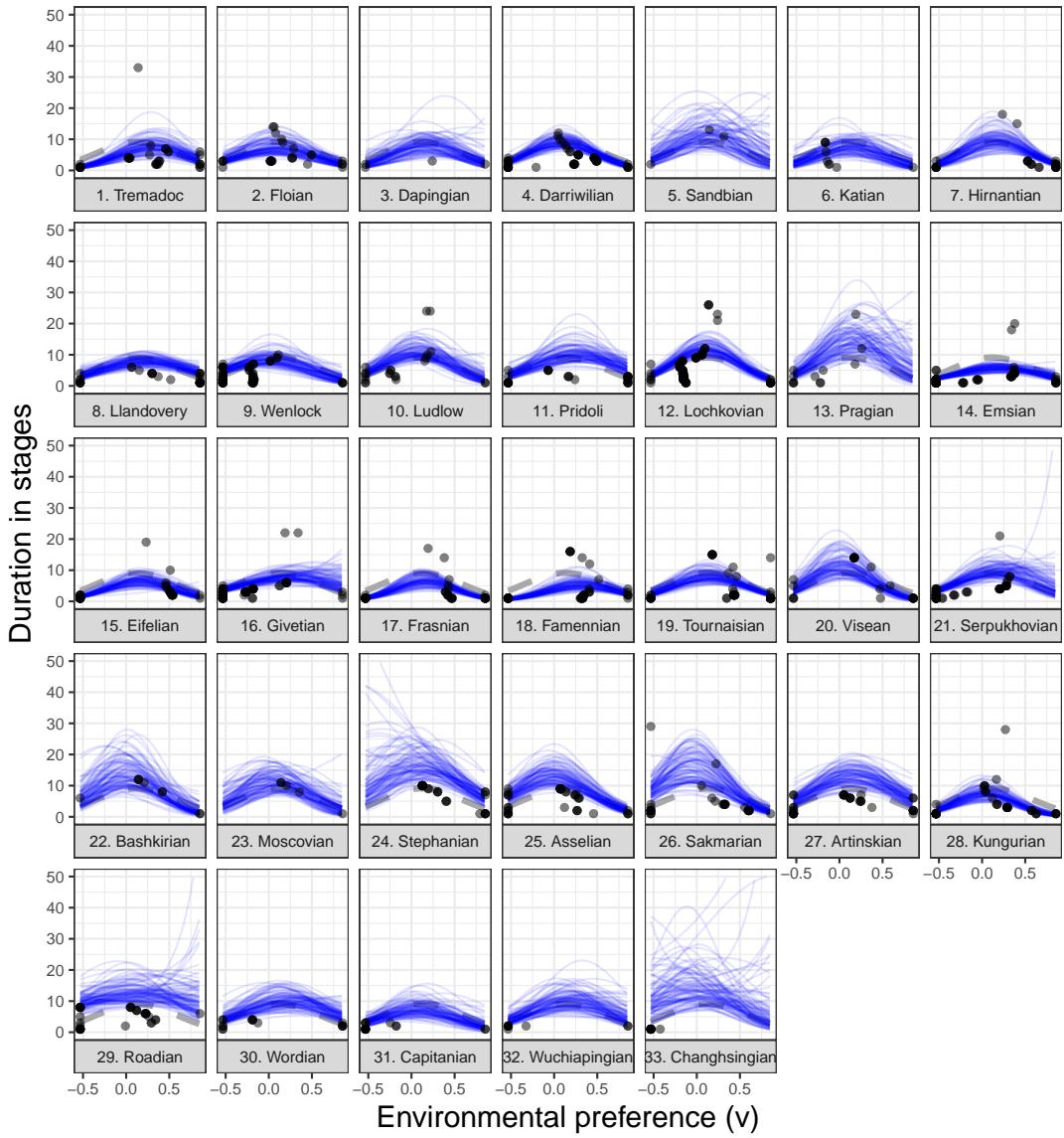


Figure 9: Comparison of origination cohort-specific (posterior predictive) estimates of the effect of environmental preference on $\log(\sigma)$ to the mean overall estimate of the effect of environmental preference. Cohort-specific estimates are from 100 posterior predictive simulations across the range of (transformed and rescaled) observed values of environmental preference. The oldest cohort is in the top-right and younger cohorts proceed left to right, with the youngest cohort being the right-most facet of the last row. Panel names correspond to the name of the stage in which that cohort originated.

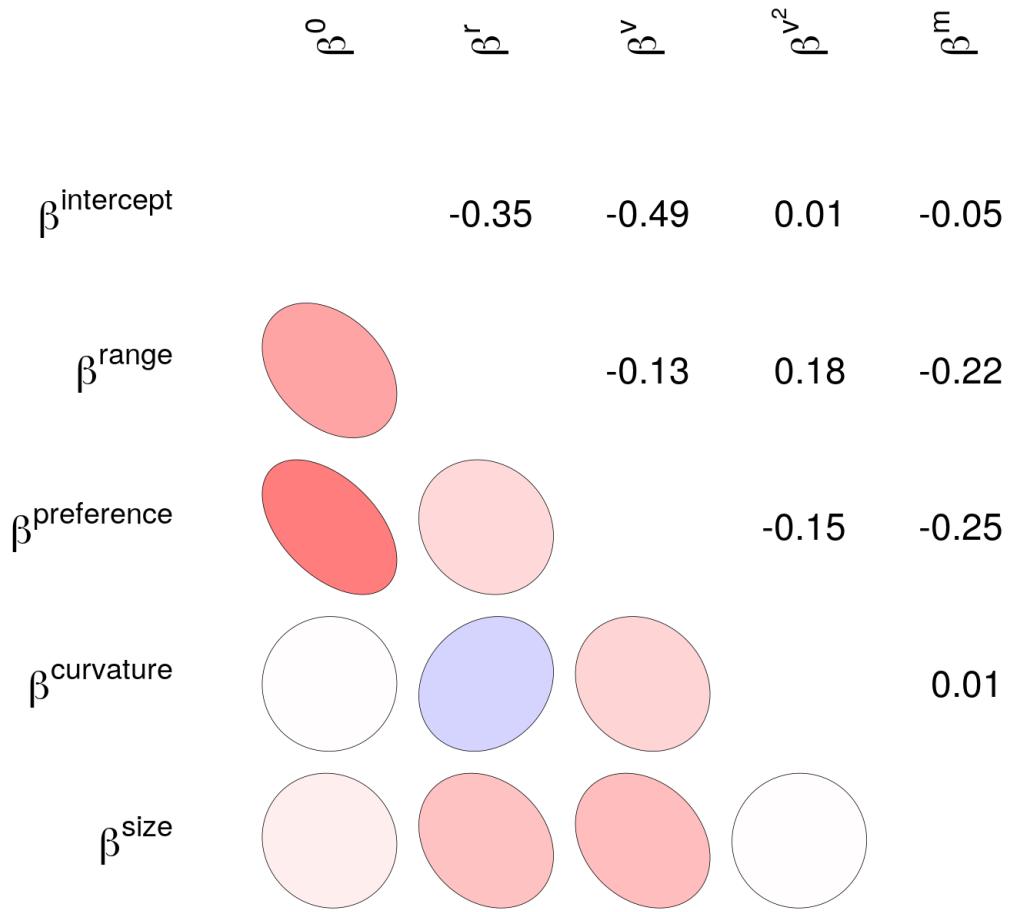


Figure 10: Mixed graphical and numerical representation of the correlation matrix Ω of variation in cohort-specific covariate estimates. These correlations are between the estimates of the cohort-level effects of covariates, along with intercept/baseline extinction risk. The median estimates of the correlations are presented numerically (upper-triangle) and as idealized ellipses representing that much correlation (lower-triangle). The darkness of the ellipse corresponds to the magnitude of the correlation.