

The macroecology behind macroevolution: North American  
mammal functional diversity and its relation to environmental  
change

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## Abstract

The set of species in a region changes over time as new species enter through speciation or immigration and as species leave the system through extinction and extirpation. How a regional species pool changes over time is the product of many processes acting at multiple levels of organization. Changes in the functional composition of a regional species pool are changes that occur across all local communities drawn from that species pool. While a species' presence in a local community is due to the availability of the necessary biotic-biotic or biotic-abiotic interactions that enable coexistence, a species' presence in a regional species pool just requires that at least one local community has that set of necessary interactions. The goal of this analysis is to understand when, and possibly for what reasons, mammal ecotypes are enriched or depleted relative to their average diversity. Here, I analyze the diversity history of North American mammals ecotypes for most of the Cenozoic (the last 65 million years). This analysis frames mammal diversity in terms of both their means of interacting with the biotic and abiotic environment (i.e. functional group or ecotype) as well as their regional and global environmental context. Using two hierarchical Bayesian hidden Markov models of diversity, I find that changes to mammal diversity are driven more by the influx of new species than by selective extinction. I also find that the only ecotypes which experience a near constant increase in diversity over time are digitigrade and unguligrade herbivores, while arboreal ecotypes become increasingly rare and in many cases disappear entirely from the species pool over the Cenozoic. Additionally, I find that global temperature is only associated with the origination of some mammal ecotypes but, in almost all cases, does not affect the extinction of mammal ecotypes.

## Introduction

Changes to species diversity are the result of evolutionary and ecological processes acting in concert and continually over time. Local communities are shaped by dispersal and local ecological processes such as resource competition and predator-prey relationships. The constituent species of these communities are drawn from a regional species pool, or the set of all species that are present in at least one community within a region (Harrison and Cornell, 2008; Mittelbach and Schemske, 2015; Urban et al., 2008). Species dispersal from the regional species pool to the local communities is a

sorting process shaped by biotic and abiotic environmental filters which are mediated by those  
30 species' traits (Cottenie, 2005; Elith and Leathwick, 2009; Harrison and Cornell, 2008; Loeuille and  
Leibold, 2008; Shipley et al., 2006; Urban et al., 2008). Regional species pools are shaped by  
32 speciation, extinction, migration, and extirpation. The gain or loss of regional diversity is the result  
of macroevolutionary dynamics which, in turn, shape the downstream macroecological dynamics of  
34 the regional species pool and its constituent local communities (Harrison and Cornell, 2008;  
Mittelbach and Schemske, 2015; Urban et al., 2008). In turn, the distribution of species within  
36 regional species pool represents the expected distribution of local communities under a purely  
diffusive process of community assembly as would be expected neutral theory of biodiversity  
38 CITATION.

Fundamentally, all species respond differently to climate and environmental change (Blois and  
40 Hadly, 2009). Those species with similar ecological roles within a regional species pool can be  
described as belonging to a guild or functional group (Bambach, 1977; Brown and Maurer, 1989;  
42 Simberloff and Dayan, 1991; Valentine, 1969; Wilson, 1999). Species within the same functional  
group are expected to have more similar macroecological dynamics to each other than to species of  
44 a different functional group. By focusing on the relative diversity of functional groups, changes to  
diversity are interpretable as changes to the set of ways species within a species pool could interact  
46 with the biotic and abiotic environment.

A key question when comparing communities or regional species pools based on their functional  
48 composition is whether specific functional groups are enriched or depleted and why; what are the  
processes that led to a species pool having the functional composition it does (Blois and Hadly,  
50 2009; Brown and Maurer, 1989; McGill et al., 2006; Smith et al., 2008; Weber et al., 2017)?

Comparisons of contemporaneous regional species pools can only determine if a functional group is  
52 enriched or depleted in one species pool relative to the other species pools CITATION. These types  
of comparison do not take into account if a functional group is enriched or depleted relative to its  
54 diversity over time (Blois and Hadly, 2009). While a species pool may be depleted of a functional  
group relative to other contemporaneous species pools, that same functional group may be actually  
56 be enriched in that species pool relative to its historical diversity. Because the processes which

shape regional species pool diversity (e.g. origination, extinction) operate on much longer time scales than is possible for studies of the Recent, paleontological data provides a unique opportunity to observe and estimate the changes to functional diversity and how species functional traits and environmental context can shape the enrichment or depletion of functional groups within a regional species pool (Blois and Hadly, 2009; Smith et al., 2008). Being able to identify if the diversity of a functional group is depleted relative to their long term average diversity in the species pool is particularly useful in conservation settings; species in depleted groups are most likely more at risk of extinction than species in enriched groups, even if those enriched groups are relatively rare when compared to the functional composition of other contemporaneous species pools.

The paleontological record of North American mammals for the Cenozoic ( $\sim$  66 million years ago to the present) provides one of the best opportunities for understanding how regional species pool functional diversity changes over time. The North American mammal record is a relatively complete temporal sequence for the entire Cenozoic which is primarily, but not exclusively, based on fossil localities from the Western Interior of North America (Alroy, 1996, 2009; Alroy et al., 2000). Additionally, mammal fossils preserve a lot of important physiological information, such as teeth, so that functional traits like the dietary/trophic category of species are easy to estimate (Eronen et al., 2010; Polly et al., 2011, 2015).

The goals of this study are to understand when are unique functional groups enriched or depleted in the North American mammal regional species pool and to estimate the relationship between these changes to regional ecotypic diversity and changes to their environmental context. My contribution is to develop a joint model of observation, origination, survival, as well as the effects of species traits and environmental factors on these processes.

## Background

The history of standing diversity for all mammals along with that some individual clades of North American mammals for the Cenozoic has been the focus of considerable study (Alroy, 1996, 2009; Alroy et al., 2000; Badgley and Finarelli, 2013; Blois and Hadly, 2009; Figueirido et al., 2012;

Fraser et al., 2015; Janis, 1993; Janis and Wilhelm, 1993; Pires et al., 2015; Quental and Marshall, 84 2013; Silvestro et al., 2015; Slater, 2015; Smits, 2015). Previous approaches to understanding mammal diversity, both in North America and elsewhere, fall into a number of overlapping 86 categories: total diversity (Alroy, 1996; Alroy et al., 2000; Figueirido et al., 2012; Liow et al., 2008), with/between guild comparisons (Janis et al., 2004; Janis, 2008; Janis et al., 2000; Janis and 88 Wilhelm, 1993; Jernvall and Fortelius, 2004; Pires et al., 2015), within/between clade comparisons (Cantalapiedra et al., 2017; Fraser et al., 2015; Quental and Marshall, 2013; Silvestro et al., 2015; 90 Slater, 2015), and estimating the impact of environmental process on total diversity (Alroy et al., 2000; Badgley and Finarelli, 2013; Badgley et al., 2017; Blois and Hadly, 2009; Eronen et al., 2015; 92 Fraser et al., 2015; Janis, 1993; Janis and Wilhelm, 1993). Each of these studies provide a limited perspective on the macroevolutionary and macroecological processes shaping diversity and 94 diversification. Integration across perspectives is necessary for producing a holistic and internally consistent picture of how the North American mammal species pool has changed through time. One 96 of the goals of this study is to present a framework for approaching hypotheses about diversity and diversification through multiple lenses simultaneously through a joint model so that any inferences 98 are better constrained and the relative importance of species' ecological function, taxonomic affinities, and environmental context may be better elucidated.

100 The narrative of the diversification of North American mammals over the Cenozoic is one of gradual change. There is little convincing evidence that there have been any sudden 102 cross-functional or cross-taxonomic group turnover events in mammal diversity at any point in the Cenozoic record of North America (Alroy, 1996, 2009; Alroy et al., 2000; Eronen et al., 2015; Janis, 104 1993). Instead of being concentrated at specific time intervals, species turnover has been found to be distributed through time. It is then expected then that, for this analysis, turnover events or 106 periods of rapid diversification or depletion should not occur simultaneously for all functional groups under study. Additionally, changes to mammal diversification seem to be primarily driven by 108 changes to origination rate and not to extinction (Alroy, 1996, 2009; Alroy et al., 2000). An unresolved aspect of the general history of mammal diversification is whether that diversity is 110 limited or self-regulating; namely, to what extent is mammal diversification diversity-dependent

(Alroy, 2009; Harmon and Harrison, 2015; Rabosky, 2013; Rabosky and Hurlbert, 2015). Similarity,  
112 this question can also be asked of specific functional groups (Jernvall and Fortelius, 2004; Quental  
and Marshall, 2013; Silvestro et al., 2015; Van Valkenburgh, 1999).

114 Within the overall narrative of mammal diversity, the histories of some functional and taxonomic  
groups are better understood than others. These groups include ungulate herbivores and Neogene  
116 carnivores which have particularly good fossil records and have been the focus of previous analyses.

The diversity history of ungulate herbivores has been characterized by more recently originating  
118 taxa having longer legs, higher crowned teeth, and a shift from graze-dominated to  
browse-dominated diets than their earlier originating counterparts (Cantalapiedra et al., 2017;  
120 Fraser et al., 2015; Janis et al., 2004; Janis, 1993, 2008; Janis et al., 2000). The mechanisms which  
drive this pattern are theorized to be some combination of tectonic activity driving environmental  
122 change such as the drying of the western interior of North America due mountain building and  
global temperature and environmental change such as the formation of polar icecaps (Badgley et al.,  
124 2017; Blois and Hadly, 2009; Eronen et al., 2015; Janis, 2008).

In contrast, the origination of modern cursorial carnivore forms was not until later in the Cenozoic;  
126 this is not to say that carnivore diversity only grew in the late Cenozoic, but that those forms were  
late entrants (Janis and Wilhelm, 1993). Instead, the diversity history of carnivores is reflective of  
128 density-dependence or some other form of self-regulation (Silvestro et al., 2015; Slater, 2015; Van  
Valkenburgh, 1999). Specifically, it has been proposed that different canid clades have replaced each  
130 other as the dominate members of their functional group within the species pool (Silvestro et al.,  
2015; Van Valkenburgh, 1999). It is then expected that, for this analysis, the diversity of digitigrade  
132 and plantigrade carnivores (i.e. the “carnivore” guild of Van Valkenburgh (1999)) should be  
relatively constant for the Cenozoic or at least have plateaued by the Neogene.

134 In a relevant study, Smits (2015) found that functional traits such as a species dietary or locomotor  
category structure differences in mammal extinction risk. In particular, arboreal taxa were found to  
136 have a shorter duration on average than species from other locomotor categories (Smits, 2015). Two  
possible scenarios that could yield this pattern were proposed: the extinction risk faced by arboreal

138 species is constant and high for the entire Cenozoic or the Paleogene and Neogene represent  
139 different regimes and extinction risk increased in the Neogene, thus driving up the Cenozoic average  
140 extinction risk. These two possible explanations have clear and testable predictions with respect to  
141 the diversity history of arboreal taxa: 1) if arboreal taxa always have an elevated extinction risk  
142 when compared to other taxa, then the diversity history of arboreal taxa is expected to be constant  
143 with time, albeit possibly at low diversity; and 2) if the Paleogene and Neogene represent difference  
144 selective regimes with the former being associated with lower extinction risk than the latter, then  
145 the diversity history of arboreal taxa are expected to be present in the Paleogene but depleted or  
146 absent from the species pool during the Neogene.

There is a lack of consensus as to the effect of species body size on mammal diversity and aspects of  
148 the diversification processes, specifically extinction (Liow et al., 2008, 2009; Smits, 2015; Tomiya,  
149 2013). Species body size is frequently framed as an important biological descriptor because of its  
150 correlation with other important and relevant ecological traits such as metabolic rate and home  
151 range size (Brown, 1995). It is also relatively easy to estimate for extinct species using proxy  
152 measures and regression equations, as was done in this study (see below). However, body size is  
153 normally analyzed without simultaneous reference to other relevant species traits (Huang et al.,  
154 2017; Liow et al., 2008; Raia et al., 2012; Smith et al., 2004), but see (Smits, 2015); this combined  
155 with the high amount of correlation between life history traits and body size limits process-based  
156 inference, because the actual causal mechanisms underlying an observed pattern are obscured or  
157 missing.

158 The climate history of the Cenozoic can be broadly described as a gradual cooling trend, with polar  
159 ice-caps forming in the Neogene (Cramer et al., 2011; Zachos et al., 2008, 2001). There are of course  
160 exceptions to this pattern such as the Eocene climatic optimum, the mid-Miocene climatic  
161 optimum, and the sudden drop in temperature at the Eocene/Oligocene boundary (Zachos et al.,  
162 2008, 2001). In terms of the North American biotic environment, the Cenozoic is additionally  
163 characterized by major transition from having closed, partially forested biomes being common in  
164 the Paleogene to the landscape being dominated by savannah and grasslands biomes by the  
Neogene (Blois and Hadly, 2009; Janis, 1993; Janis et al., 2000; Strömberg, 2005). Additionally, the

<sup>166</sup> landscape structure and topology of North America changed substantially over the Cenozoic with  
<sup>167</sup> mountain uplift and other tectonic actives in Western North America (Badgley and Finarelli, 2013;  
<sup>168</sup> Blois and Hadly, 2009; Eronen et al., 2015; Janis, 2008). This type of geological activity affects  
<sup>169</sup> both local climates as well as continental weather patterns while also mobilizing increased grit into  
<sup>170</sup> the environment, something which may be responsible for increasing trend of hyposodony (high  
<sup>171</sup> crowned teeth) among ungulate and rodent herbivores (Damuth and Janis, 2011; Janis, 1993;  
<sup>172</sup> Jardine et al., 2012; Jernvall and Fortelius, 2002) Badgley CITATION.

The Eocene-Oligocene transition has been observed to be associated with extinction of many  
<sup>174</sup> ungulate taxa (Janis, 2008). This boundary also marks the transition from the Paleogene to the  
Neogene and from herbivores being browsing dominated to grazing dominated, though not  
<sup>176</sup> concurrently (Janis, 1993; Strömberg, 2005). Additionally, the Paleogene-Neogene boundary marks  
the approximate start of Antarctic ice sheets, which were previously absent (Zachos et al., 2008).  
<sup>178</sup> There is an observed stability in estimates of global temperature from the E/O transition till the  
end of the Miocene called the Mid-Miocene climatic optimum (Zachos et al., 2008, 2001). The  
<sup>180</sup> Mid-Miocene climatic optimum is bookended by periods of temperature decline. We would then  
expect that, for the Miocene, turnover and other diversification events would most likely be due to  
<sup>182</sup> biological interactions or immigration and not biotic-abiotic interactions because of the constancy  
of the climate, and that those groups that are driven primarily by environmental factors, the  
<sup>184</sup> Miocene would be a period of marked by an absence of major changes to diversity or the  
diversification process.

<sup>186</sup> The effect of climate on mammal diversity and its accompanying diversification process has been  
the focus of considerable research with a slight consensus favoring mammal diversification being  
<sup>188</sup> more biologically-mediated than climate-mediated when considering the entire Cenozoic (Alroy  
et al., 2000; Clyde and Gingerich, 1998; Figueirido et al., 2012). However, differences in temporal  
<sup>190</sup> and geographic scale seem to underly the contrast between these two perspectives. For example  
when the mammal fossil record analyzed at small temporal and geographic scales a correlation  
<sup>192</sup> between diversity and climate is observable (Clyde and Gingerich, 1998). However, when the record  
is analyzed at the scale of the continent and most of the Cenozoic this correlation disappears (Alroy

<sup>194</sup> et al., 2000). This result, however, does not go against the idea that there may be short periods of correlation between diversity and climate and that this relationship can change or even reverse  
<sup>196</sup> direction over time; this type result means that there is no single direction or longterm correlation between diversity and climate (Figueirido et al., 2012).

<sup>198</sup> In the case of a fluctuating correlation between diversity and climate it is hard to make the argument for an actual causal link between the two without modeling the underlying ecological  
<sup>200</sup> differences between species; after all, species respond differently based on their individual ecologies (Blois and Hadly, 2009). When analysis is based on diversity or taxonomy alone no mechanisms are  
<sup>202</sup> possible to infer. Taxonomy, like body size, stands in for many important species traits to the point that mechanistic or process based inference is impossible. While emergent patterns might  
<sup>204</sup> correspond to taxonomic grouping, this itself is an emergent phenomenon. Instead, by framing hypotheses in terms of species traits and their environmental context, these emergent phenomena  
<sup>206</sup> can be observed and analyzed rather than assumed.

## Foreground

<sup>208</sup> The fourth-corner problem is conceptual and statistical framework to explaining the patterns of either species abundance or presence/absence in a community as a product of species traits,  
<sup>210</sup> environmental factors, and the interaction between traits and environment (Brown et al., 2014;  
Jamil et al., 2013; Pollock et al., 2012; Warton et al., 2015); effectively uniting climate-based species  
<sup>212</sup> distribution modeling (SDMs) with trait-based community assembly models (CATS, MaxEnt). The fourth-corner problem is normally phrased in modern ecological studies as understanding how traits  
<sup>214</sup> and environment interact to predict the occurrence of species at localities distributed across a region (Jamil et al., 2013; Pollock et al., 2012).

<sup>216</sup> This conceptual framework can be extended to include time when considering occurrence as a three-dimensional: species at localities in space over time. This extension changes the goal of  
<sup>218</sup> predicting just occurrence to one of predicting species gain and loss at localities. However, the temporal limitations of modern ecological studies limit studying species over their entire durations,

220 where speciation and extinction govern the occurrence of species. By considering the patterns of  
fossil occurrences in the geological record the macroevolutionary processes governing species'  
222 (macro)ecology can be better understood. One limitation of the fossil record, however, is a lack of  
spatial resolution for most taxonomic groups and periods of time. As such, paleontological data  
224 "looks" at a different side of the three-dimensional occurrence matrix of the extended fourth-corner  
problem than modern ecological data.

226 In this study, the fourth-corner problem is phrased as understanding how mammal functional  
groups respond to environmental change in order to predict the origination and survival of species  
228 over time (Fig. 1). Additionally, I also consider the incompleteness of the fossil record and the static  
effect of other species descriptors not related to functional group on origination and survival.

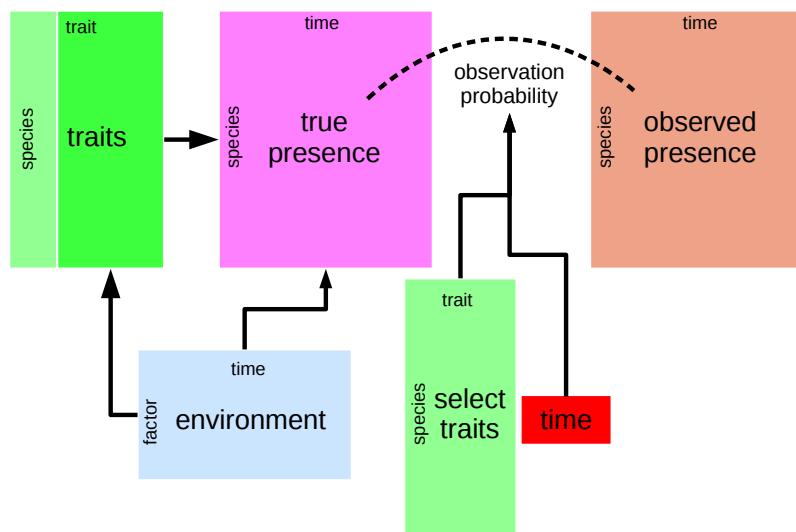


Figure 1: Conceptual diagram of the analysis at the center of this study. The observed presence matrix (orange) is the empirical presence/absence pattern for all species for all time points; this matrix is an incomplete observation of the "true" presence/absence pattern (purple). This observation process is modeled as a function of both time (red) and a selection of species traits (green). The estimated true presence matrix is modeled as a function of both environmental factors over time (blue) and multiple species traits (green). Additionally, the effects of environmental factors on some of those species traits are also modeled, as traits are expected to mediate the effects of a species environmental context. This diagram is based partially on material presented in Brown et al. (2014) and Warton et al. (2015).

230 My approach to delimiting and assigning mammal functional groups is inspired on the ecocube  
heuristic used to classify marine invertebrate species by three functional traits (Bambach et al.,  
232 2007; Bush and Bambach, 2011; Bush et al., 2007; Bush and Novack-Gottshall, 2012;  
Novack-Gottshall, 2007; Villéger et al., 2011). In this study, the two functional traits used to define  
234 a species' functional group are dietary (e.g. herbivore, carnivore, etc.) and locomotor category (e.g.  
arboreal, unguligrade, etc.). Species body mass was also included as a species trait in this analysis,  
236 but not as a trait for defining a functional group; instead, its inclusion is principally to control for  
differences in species dynamics that driven by mass and not functional group.

238 The environmental covariates included in this study are estimates of global temperature as well as  
which of three high-level North American plant taxonomic phases corresponds to that temporal  
240 unit (Cramer et al., 2011; Graham, 2011). These covariates were chosen because they provide a  
characterizations of the environmental context of the entire North American regional species pool  
242 for most of the Cenozoic. Importantly, the effects of a species functional group on diversity are  
themselves modeled as functions of environmental factors (Fig. 1) allowing for inference as to how a  
244 species ecology can mediate selective pressures do to its environmental context.

All observations, paleontological or modern, are made with uncertainty. With presence/absence  
246 data this uncertainty comes from not knowing if an absence is a “true” absence or just a failure to  
observe (Foote, 2001; Foote and Sepkoski, 1999; Lloyd et al., 2011; Royle and Dorazio, 2008; Royle  
248 et al., 2005; Wang and Marshall, 2016). For paleontological data, the incomplete preservation and  
sampling of species means that the true times of origination or extinction may not be observed  
250 (Foote, 2001; Foote and Sepkoski, 1999; Wang et al., 2016; Wang and Marshall, 2016). The model  
used in this analysis is a translation of the conceptual framework described above (Fig. 1) into a  
252 statistical model in order to estimate the relative diversity of mammal functional groups over time  
and how those functional groups respond to changes to environmental context while taking into  
254 account the fundamental incompleteness of the fossil record.

Ultimately, the goals of this analysis are to understand when are different functional groups  
256 enriched or depleted in the North American mammal regional species pool and how these changes

in functional diversity are related to changes in species' environmental context. In the analysis  
258 performed here, I consider multiple covariates which describe a species' macroecology and  
environmental context. In order to analyze this complex, multi-level question and accompanying  
260 highly-structured data set, I developed a hierachal Bayesian model combing the fourth-corner  
modeling approach with a model of an observation-occurrence or observation-originatation-extinction  
262 process.

## Materials and Methods

### 264 Taxon occurrences and species-level information

All fossil occurrence information used in this analysis was downloaded from the Paleobiology  
266 Database (PBDB). The initial download restricted occurrences to Mammalia observed in North  
America between the Maastrichtian (72-66 Mya) and Gelasian (2.58-1.8 Mya) stages (Cohen et al.,  
268 2015). Taxonomic, stratigraphic, and ecological metadata for each occurrence and species was also  
downloaded. A new download for a raw, unfiltered PBDB datafile following the same criterion used  
270 here is available at <http://goo.gl/2s1geU>. The raw datafile used as a part of this study, along  
with all code for filtering and manipulating this download is available at  
272 <http://github.com/psmits/copings>.

After being downloaded, the raw occurrence data was then sorted, cleaned, and manipulated  
274 programmatically before analysis. Occurrences were restricted to those occurring between 64 and 2  
million years ago (Mya); this age restriction was to insure that observation time series lines up with  
276 the temperature time series (Cramer et al., 2011). All taxa whose life habit was classified as either  
volant (i.e. Chiroptera) or aquatic (e.g. Cetacea) were excluded from this analysis because of their  
278 lack of direct applicability to the study of terrestrial species pools.

Many species taxonomic assignments as present in the raw PBDB data were updated for accuracy  
280 and consistency. Species present in the PBDB have some taxonomic information, including possible  
Family and Order assignments. In order to increase consistency between species and reflect more

recent taxonomic assignments, each species taxonomic assignments updated as follows: 1) species family and order assignemnts as present in the Encyclopedia of life (<http://eol.org>) was downloaded using the *taxize* package for R; 2) for species not present in the EoL or not assigned order, their taxonomic inforation was further updated based on whatever family information was recorded in the PBDB or EoL; 3) for species still missing order assignemnts, their genus information was used to assign either an order or family, which was then used to assign an order.

This procedure is similar to that used in Smits (2015) and is detailed in the code repository associated with this study.

Species functional group is defined as the combination of locomotor and diet categories; the goal is to classify species based on the manner with which they interact with their environment. Mammal species records in the PBDB have life habit (i.e. locomotor category) and dietary category assignments. In order to simplify interpretation, analysis, and per-functional group sample size these classifications were coarsened in a similar manner to Smits (2015) (Table 1). Ground dwelling species locomotor categories were then reassigned based on the ankle posture associated with their taxonomic group, as described in Table 2 (Carrano, 1999). Ankle posture was assumed uniform for all species within a taxonomic group except for those species assigned a non-ground dwelling locomotor category in the PBDB, which retained their non-ground dwelling assignment. All species for which it was possible to assign a locomotor category had one assigned, including species for which post-cranaia are unknown but for which a taxonomic grouping is known. Ground dwelling species which were unable to be reassigned based on ankle posture were excluded from analysis.

Finally, ecotype categories with less than 10 total species were excluded, yielding a total of 18 observed ecotypes out of a possible 24.

Table 2: Ankle posture assignment as based on taxonomy. Assignments are based on (Carrano, 1999). Taxonomic groups are presented alphabetically and without reference for their relatedness.

Family	Stance
Ailuridae	plantigrade
Allomyidae	plantigrade

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**Table 2 – continued from previous page**

Family	Stance
Amphicyonidae	plantigrade
Amphilemuridae	plantigrade
Anthracotheriidae	digitigrade
Antilocapridae	unguligrade
Apheliscidae	plantigrade
Aplodontidae	plantigrade
Apternodontidae	scansorial
Arctocyonidae	unguligrade
Barbourofelidae	digitigrade
Barylambdidae	plantigrade
Bovidae	unguligrade
Camelidae	unguligrade
Canidae	digitigrade
Cervidae	unguligrade
Cimolodontidae	scansorial
Coryphodontidae	plantigrade
Cricetidae	plantigrade
Cylindrodontidae	plantigrade
Cyriacotheriidae	plantigrade
Dichobunidae	unguligrade
Dinocerata	unguligrade
Dipodidae	digitigrade
Elephantidae	digitigrade
Entelodontidae	unguligrade
Eomyidae	plantigrade

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**Table 2 – continued from previous page**

Family	Stance
Erethizontidae	plantigrade
Erinaceidae	plantigrade
Esthonychidae	plantigrade
Eutypomyidae	plantigrade
Felidae	digitigrade
Florentiamyidae	plantigrade
Gelocidae	unguligrade
Geolabididae	plantigrade
Glyptodontidae	plantigrade
Gomphotheriidae	unguligrade
Hapalodectidae	plantigrade
Heteromyidae	digitigrade
Hyaenidae	digitigrade
Hyaenodontidae	digitigrade
Hypertragulidae	unguligrade
Ischyromyidae	plantigrade
Jimomyidae	plantigrade
Lagomorpha	digitigrade
Leptictidae	plantigrade
Leptochoeridae	unguligrade
Leptomerycidae	unguligrade
Mammutidae	unguligrade
Megalonychidae	plantigrade
Megatheriidae	plantigrade
Mephitidae	plantigrade

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**Table 2 – continued from previous page**

Family	Stance
Merycoidodontidae	digitigrade
Mesonychia	unguligrade
Mesonychidae	digitigrade
Micropternodontidae	plantigrade
Mixodectidae	plantigrade
Moschidae	unguligrade
Muridae	plantigrade
Mustelidae	plantigrade
Mylagaulidae	fossorial
Mylodontidae	plantigrade
Nimravidae	digitigrade
Nothrotheriidae	plantigrade
Notoungulata	unguligrade
Oromerycidae	unguligrade
Oxyaenidae	digitigrade
Palaeomerycidae	unguligrade
Palaeoryctidae	plantigrade
Pampatheriidae	plantigrade
Pantolambdidae	plantigrade
Peritychidae	digitigrade
Perissodactyla	unguligrade
Phenacodontidae	unguligrade
Primates	plantigrade
Procyonidae	plantigrade
Proscalopidae	plantigrade

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**Table 2 – continued from previous page**

Family	Stance
Protoceratidae	unguligrade
Reithroparamyidae	plantigrade
Sciuravidae	plantigrade
Sciuridae	plantigrade
Simimyidae	plantigrade
Soricidae	plantigrade
Suidae	digitigrade
Talpidae	fossorial
Tayassuidae	unguligrade
Tenrecidae	plantigrade
Titanoideidae	plantigrade
Ursidae	plantigrade
Viverravidae	plantigrade
Zapodidae	plantigrade

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Estimates of species mass used in this study were sourced from multiple databases and papers,  
306 especially those focusing on similar macroevolutionary or macroecological questions (Brook and  
Bowman, 2004; Freudenthal and Martín-Suárez, 2013; McKenna, 2011; Raia et al., 2012; Smith  
308 et al., 2004; Tomiya, 2013); this is similar to Smits (2015). When a species' mass was not available,  
proxy measures were used to estimate their mass. For example, given a measurement of a mammal  
310 tooth size, it is possible and routine to estimate its mass given some regression equation. The  
PBDB has one or more body part measures for many species. These were used as body size proxies  
312 for many species, as was the case in Smits (2015). Mass was log-transformed and then rescaled by  
first subtracting mean log-mass from all mass estimates, then dividing by two-times its standard  
314 deviation; this insures that the magnitude of effects for both continuous and discrete covariates are

Table 1: Species trait assignments in this study are a coarser version of the information available in the PBDB. Information was coarsened to improve per category sample size.

This study		PBDB categories
Diet	Carnivore	Carnivore
	Herbivore	Browser, folivore, granivore, grazer, herbivore.
	Insectivore	Insectivore.
	Omnivore	Frugivore, omnivore.
Locomotor	Arboreal	Arboreal.
	Ground dwelling	Fossorial, ground dwelling, semifossorial, saltatorial.
	Scansorial	Scansorial.

directly comparable (Gelman, 2008; Gelman and Hill, 2007).

- 316 In total, 1400 mammal species occurrence histories were included in this study after applying all of the restrictions above.

Table 3: Regression equations used in this study for estimating body size. Equations are presented with reference to taxonomic grouping, part name, and reference.

Group	Equation	log(Measurement)	Source
General	$\log(m) = 1.827x + 1.81$	lower m1 area	Legendre (1986)
General	$\log(m) = 2.9677x - 5.6712$	mandible length	Foster (2009)
General	$\log(m) = 3.68x - 3.83$	skull length	Luo et al. (2001)
Carnivores	$\log(m) = 2.97x + 1.681$	lower m1 length	Van Valkenburgh (1990)
Insectivores	$\log(m) = 1.628x + 1.726$	lower m1 area	Bloch et al. (1998)
Insectivores	$\log(m) = 1.714x + 0.886$	upper M1 area	Bloch et al. (1998)
Lagomorph	$\log(m) = 2.671x - 2.671$	lower toothrow area	Tomiya (2013)
Lagomorph	$\log(m) = 4.468x - 3.002$	lower m1 length	Tomiya (2013)
Marsupials	$\log(m) = 3.284x + 1.83$	upper M1 length	Gordon (2003)
Marsupials	$\log(m) = 1.733x + 1.571$	upper M1 area	Gordon (2003)
Rodentia	$\log(m) = 1.767x + 2.172$	lower m1 area	Legendre (1986)
Ungulates	$\log(m) = 1.516x + 3.757$	lower m1 area	Mendoza et al. (2006)
Ungulates	$\log(m) = 3.076x + 2.366$	lower m2 length	Mendoza et al. (2006)
Ungulates	$\log(m) = 1.518x + 2.792$	lower m2 area	Mendoza et al. (2006)
Ungulates	$\log(m) = 3.113x - 1.374$	lower toothrow length	Mendoza et al. (2006)

- 318 All fossil occurrences from 64 to 2 million years ago (Mya) were binned into the 19 North American Land Mammal Ages (NALMA) covered by this interval CITATION. The choice of binning by  
 319 NALMA reflects the belief that these represent distinct communities or periods of mammal evolution, something that is central to this study. Additionally, because of the inherently discrete  
 320 nature of the fossil record it can be hard to re-bin fossils by temporal interval because of the

Table 4: Definitions of the start and stop times of the three plant phases used this study as defined by Graham (2011).

Plant phase	Phase code	Start	Stop
Paleocene-Eocene	Pa-Eo	66	50
Eocene-Miocene	Eo-Mi	50	16
Miocene-Pleistocene	Mi-Pl	16	2

inherent uncertainty in their ages CITATION.

### 324 Environmental and temporal covariates

The environmental covariates used in this study are collectively referred to as group-level covariates  
 326 because they predict the response of a “group” of individual-level observations (i.e. species  
 occurrences of an ecotype). Additionally, these covariates are defined for temporal bins and not the  
 328 species themselves; as such they predict the individual parts of each species occurrence history. The  
 group-level covariates in this study are two global temperature estimates and the Cenozoic “plant  
 330 phases” defined by Graham (2011).

Global temperature across most of the Cenozoic was calculated from Mg/Ca isotope record from  
 332 deep sea carbonates (Cramer et al., 2011). Mg/Ca based temperature estimates are preferable to  
 the frequently used  $\delta^{18}\text{O}$  temperature proxy (Alroy et al., 2000; Figueirido et al., 2012; Zachos  
 334 et al., 2008, 2001) because Mg/Ca estimates do not conflate temperature with ice sheet volume and  
 depth/stratification changes. The former is particularly important to this analysis as the current  
 336 polar ice-caps appeared and grew during the second half of the Cenozoic. These properties make  
 Mg/Ca based temperature estimates preferable for macroevolutionary and macroecological studies  
 338 (Ezard et al., 2016). Temperature was calculated as the mean of all respective estimates for each of  
 the NALMA units. The distributions of temperature was then rescaled by subtracting its mean  
 340 from all values and then dividing by twice its standard deviation.

The second set of environmental factors included in this study are the Cenozoic plant phases  
 342 defined in Graham (2011). Graham’s plant phases are holistic descriptors of the taxonomic  
 composition of 12 ecosystem types, which plants are present at a given time, and the relative

		State at $t + 1$		
		$0_{never}$	1	$0_{extinct}$
State at $t$	$0_{never}$	$1 - \pi$	$\pi$	0
	1	0	$\phi$	$1 - \phi$
	$0_{extinct}$	0	0	1

Table 5: Transition matrix for the birth-death model (Eq. 1). Note that while there are only two state “codes” (0, 1), there are in fact three states: never having originated  $0_{never}$ , present 1, extinct  $0_{extinct}$  (Allen, 2011). The two modeled transition probabilities are origination  $\pi$  and survival  $\phi$ .

344 modernity of those plant groups with younger phases representing increasingly modern taxa  
 (Graham, 2011). Graham (2011) defines four intervals from the Cretaceous to the Pliocene, though  
 346 only three of these intervals take place during the time frame being analyzed. Graham’s plant  
 phases was included as a series of “dummy variables” encoding the three phases included in this  
 348 analysis (Gelman and Hill, 2007); this means that the Miocene-Pleistocene phase is synonymous  
 with the intercept and other phases are defined by their differences from this baseline. The  
 350 temporal boundaries of these plant phases, their durations, and abbreviations are defined in Table 4.

## Modelling species occurrence

352 At the core of the model used in this study is hidden Markov process where the latent process has  
 an absorbing state; also refered to as a discrete-time birth-death model (Allen, 2011) or a  
 354 capture-mark-recapture model CITATION. While there are only two state “codes” in a  
 presence-absence matrix (i.e. 0/1), there are in fact three states in a birth-death model: not having  
 356 originated yet, extant, and extinct. The last of these is the absorbing state, as once a species has  
 gone extinct it cannot re-originate (Allen, 2011). Thus, in the transition matrices the probability of  
 358 an extinct species changing states is 0 (Table 5). See below for parameter explanations (Tables 6, 7,  
 and 8).

360 **Basic model**

I will begin defining the model used in this study by focusing on the basic machinery of the hidden  
 362 Markov process at the model’s core. This basic model is similar to the Jolly-Seber

Table 6: Parameters associated with the hidden Markov Model at core of this model (Eq. 1).  $N$  is the number of species tracked in this study, and  $T$  is the number of time units (NALMAs) covered by this study.

Parameter	dimensions	explanation
$y$	$N \times T$	observed species presence/absence
$z$	$N \times T$	“true” species presence/absence
$p$	$N \times T$	probability of observing a species at time $t$ if it is present
$\phi$	$N \times T$	probability of species originating from time $t$ to $t + 1$ if it is not present
$\pi$	$N \times (T - 1)$	probability of species surviving at time $t$ , given that it is already originated

capture-mark-recapture model CITATION which has three characteristic probabilities: probability  
 364  $p$  of observing a species given that it is present, probability  $\pi$  of a species surviving from one time  
 to another, and probability  $\phi$  of a species first appearing (Royle and Dorazio, 2008) (Table 6). In  
 366 this formulation, the probability of a species becoming extinct is  $1 - \pi$ . The inclusion of species and  
 temporal information means that all three of these probabilities are defined for every species at  
 368 every time point (Table 6); how this is accomplished is described below. Importantly, only  
 origination can occur during the first time step as nothing is already present to survive.

$$\begin{aligned}
 y_{i,t} &\sim \text{Bernoulli}(p_{i,t} z_{i,t}) \\
 z_{i,1} &\sim \text{Bernoulli}(\phi_{i,1}) \\
 z_{i,t} &\sim \text{Bernoulli} \left( z_{i,t-1} \pi_{i,t} + \sum_{x=1}^t (1 - z_{i,x}) \phi_{i,t} \right)
 \end{aligned} \tag{1}$$

370 The parameters associated with Equation 1 are described in Table 6; this formulation is identical to  
 that described in Royle and Dorazio (2008). The product term that appears when calculating  
 372 values of  $z$  not at  $t = 1$  ensures that once a species goes extinct it does not re-originate. The basic  
 model described here (Eq. 1) does not include the additional, necessary prior information which is  
 374 described below.

### Expanding on the basics

376 Expanding on the basic model involves modeling the observation, origination and survival  
 probability as independent multi-level logistic regressions. Origination and survival probabilities

378 share the same covariates and model structure, but observation probability is modeled as a function  
of a smaller selection of covariates.

380 The probability of observing a species given that it is present  $p$  is modeled as a logistic regression  
with a time-varying intercept with an additional zero-centered varying effect for species' functional  
382 group, respectively. The effect of species mass was also included through a slope term  $\beta^p$ .

The log-odds of a species originating (logit  $\pi$ ) or surviving (logit  $\phi$ ) are modeled independently but  
384 take the same form: a regression with an intercept that varies by both time and functional group,  
an additional taxonomic order varying-intercept term, and the slope term for species mass.

386 Importantly, the time and functional group varying-intercept is itself modeled such that the  
intercept for each functional group is a time series with group-level covariates (described below).

388 The expanded model incorporating these regression models is written as

$$\begin{aligned} y_{i,t} &\sim \text{Bernoulli}(p_{i,t} z_{i,t}) \\ p_{i,t} &= \text{logit}^{-1}(u_t + e_{j[i]} + \beta^p m_i) \\ z_{i,1} &\sim \text{Bernoulli}(\phi_{i,1}) \\ z_{i,t} &\sim \text{Bernoulli}\left(z_{i,t-1} \pi_{i,t} + \sum_{x=1}^t (1 - z_{i,x}) \phi_{i,t}\right) \\ \phi_{i,t} &= \text{logit}^{-1}(f_{j[i],t}^\phi + o_{k[i]}^\phi + \beta^\phi m_i). \\ \pi_{i,t} &= \text{logit}^{-1}(f_{j[i],t}^\pi + o_{k[i]}^\pi + \beta^\pi m_i) \end{aligned} \tag{2}$$

How the priors for the varying-effects and coefficients in this expanded model are described below  
390 along with the complete model.

### Complete model

392 The expanded model (Eq. 2) is still incomplete as it is missing the group-level covariates of interest  
such as global temperature, and it is missing all of the necessary priors.

394 Here I describe how the effects of mammal functional group on origination and survival are

Table 7: Parameters for the first expansions

Parameter	dimensions	explanation
$u$	$T$	time-varying intercept
$e$	$J$	effect of functional group on observation
$f^\phi$	$J \times T - 1$	intercept of log-odds $\phi$ , varies by time and functional group
$f^\pi$	$J \times T$	intercept of log-odds $\pi$ , varies by time and functional group
$o^\phi$	$K$	effect of species' order on log-odds of $\phi$
$o^\pi$	$K$	effect of species' order on log-odds of $\pi$
$\beta^\phi$	1	effect of species' mass on log-odds of $\phi$
$\beta^\pi$	1	effect of species' mass on log-odds of $\pi$

modeled.  $f^\phi$  and  $f^\pi$  are modeled as the responses from a multivariate normal distribution, where  
 396 each functional group's time series is modeled as a regression. The time-series structure of these  
 regressions is represented as a random-walk prior for the varying intercept of the group-level  
 398 regressions. The effects of these group-level covariates on origination and survival are included for  
 each functional group as a vector regression coefficients. The expansion to include this group-level  
 400 regression is described in Equation 3, the parameters of which are described in Table 8.

$$\begin{aligned}
 f^\phi &\sim \text{MVN}(\mu^\phi, \Sigma^\phi) \\
 f^\pi &\sim \text{MVN}(\mu^\pi, \Sigma^\pi) \\
 \mu_{j,t}^\phi &= \alpha_{j,t}^\phi + U * \gamma_j^\phi \\
 \mu_{j,t}^\pi &= \alpha_{j,t}^\pi + U * \gamma_j^\pi \\
 \alpha_{j,t}^\phi &\sim \begin{cases} \mathcal{N}(0, 1) & \text{if } t = 1 \\ \mathcal{N}(\alpha_{j,t-1}^\phi, \sigma_j^\phi) & \text{if } t > 1 \end{cases} \\
 \alpha_{j,t}^\pi &\sim \begin{cases} \mathcal{N}(0, 1) & \text{if } t = 1 \\ \mathcal{N}(\alpha_{j,t-1}^\pi, \sigma_j^\pi) & \text{if } t > 1 \end{cases}
 \end{aligned} \tag{3}$$

In hierarchical models like the one described here (Eq. 2, 3) it can be hard to distinguish between  
 402 the likelihood and prior as data can enter the model through many different parameters CITATION.  
 For example, in Equation 2 the model of  $z$  can be considered a prior and statements in Equation 3

Table 8: Parameters for the group-level regressions.  $J$  is the number of functional groups, and  $D$  is the number of group-level covariates.

Parameter	dimensions	explanation
$\mu^\phi$	$J \times T$	time-series of the mean log-odds of $\phi$ for each functional group
$\mu^\pi$	$J \times T$	time-series of the mean log-odds of $\pi$ for each functional group
$\Sigma^\phi$	$J \times J$	covariance matrix between functional groups for $\phi$
$\Sigma^\pi$	$J \times J$	covariance matrix between functional groups for $\phi$
$\alpha^\phi$	$J \times T$	time-varying intercept of $\mu^\phi$
$\alpha^\pi$	$J \times T$	time-varying intercept of $\mu^\pi$
$\sigma^\phi$	$J$	scale of random-walk prior for $\alpha^\phi$
$\sigma^\pi$	$J$	scale of random-walk prior for $\alpha^\pi$
$\gamma^\phi$	$D$	group-level regression coefficients for $\mu^\phi$
$\gamma^\pi$	$D$	group-level regression coefficients for $\mu^\pi$

404 can be considered priors for the parameters which predict  $\phi$  and  $\pi$ . The remaining priors necessary  
 to this model, however, are not based on parameter expansion but are prior estimates for the  
 406 remaining unmodeled parameters and are sampling statements where no new data enters the model.  
 These prior choices are expressed in Equation 4 and are explained below.

408 For the regression coefficients, such as  $\beta^\phi$  and  $\gamma^\phi$ , the chosen priors are considered weakly  
 informative as they concentrate most of the probability density between -2 and 2. Similarly, the  
 410 scale parameters, such as  $\tau^\phi$  and  $\sigma^\phi$ , are also given weakly informative half-Normal priors which  
 concentrate most of the probability density between 0 and -2. The covariance matrices, such as  $\Sigma^\phi$ ,  
 412 are decomposed into a vector of scale terms (e.g.  $\tau^\phi$ ) and correlation matrices (e.g.  $\Omega^\phi$ ) which were  
 then given weakly informative priors. This approach and choice of LKJ priors for the correlation  
 414 matrices follows the Stan User Manual CITATION. For parameter vectors which are presented with

only a single prior (e.g.  $\beta^\phi$ ), that prior statement is for each of the elements of that vector.

$$\begin{aligned}
e &\sim \mathcal{N}(0, \sigma^e) \\
\sigma^e &\sim \mathcal{N}^+(1) \\
\beta^p &\sim \mathcal{N}(0, 1) \\
o^\phi &\sim \mathcal{N}(0, v^\phi) \\
o^\pi &\sim \mathcal{N}(0, v^\pi) \\
v^\phi &\sim \mathcal{N}^+(1) \\
v^\pi &\sim \mathcal{N}^+(1) \\
\beta^\phi &\sim \mathcal{N}(0, 1) \\
\beta^\pi &\sim \mathcal{N}(0, 1) \\
\Sigma^\phi &= \text{diag}(\tau^\phi) \Omega^\phi \text{diag}(\tau^\phi) \\
\Sigma^\pi &= \text{diag}(\tau^\pi) \Omega^\pi \text{diag}(\tau^\pi) \\
\tau^\phi &\sim \mathcal{N}^+(1) \\
\tau^\pi &\sim \mathcal{N}^+(1) \\
\Omega^\phi &\sim \text{LKJ}(2) \\
\Omega^\pi &\sim \text{LKJ}(2) \\
\sigma^\phi &\sim \mathcal{N}^+(1) \\
\sigma^\pi &\sim \mathcal{N}^+(1) \\
\gamma^\phi &\sim \mathcal{N}(0, 1) \\
\gamma^\pi &\sim \mathcal{N}(0, 1)
\end{aligned} \tag{4}$$

- <sup>416</sup> The model used in this study is the complete sampling statement expressed through the combination of equations 2, 3, and 4. These statements taken together form a complete generative  
<sup>418</sup> model from which posterior inference of parameter values is possible.

## Posterior inference and model adequacy

420 A computer program that implements joint posterior inference the model described above (Eqs. 2,  
421 3, and 4) was written in the probabilistic programming language Stan (Stan Development Team,  
422 2016). All methods for posterior inference implemented in Stan are derivative-based; this causes  
complications for actually implementing the above models, because integers do not have derivatives.  
424 In order to infer the values of the matrix of latent discrete parameters  $z$  (Tables 6) the log posterior  
probabilities of all possible states of the unknown values of  $z$  were calculated and summed (i.e.  
426 marginalized) (Stan Development Team, 2016).

Species durations at minimum range through from a species first appearance to their last  
428 appearance in the fossil record, but the incompleteness of all observations means that the actual  
times of origination and extinction are unknown. The marginalization approach used here means  
430 that the (log) probabilities of all possible histories for a species are calculated, from the end  
members of the species having existed for the entire study interval and the species having only  
432 existed between the directly observed first and last appearances to all possible intermediaries (Fig  
2) (Stan Development Team, 2016). Marginalization is identical, language-wise, to assuming  
434 range-through and then estimating the (log) probability of all possible range extension due to  
incomplete sampling.

436 The combined size of the dataset and large number of parameters (Eqs. 2, 3, and 4), in specific the  
total number of latent parameters that are the matrix  $z$ , means that MCMC based posterior  
438 inference is computationally slow. Instead, an approximate Bayesian approach was used: variational  
inference. A recently developed automatic variational inference algorithm called “automatic  
440 differentiation variational inference” (ADVI) is implemented in Stan and is used here (Kucukelbir  
et al., 2015; Stan Development Team, 2016). ADVI assumes that the posterior is Gaussian but still  
442 yields a true Bayesian posterior; this assumption is similar to quadratic approximation of the  
likelihood function commonly used in maximum likelihood based inference (McElreath, 2016). The  
444 principal limitation of assuming the joint posterior is Gaussian is that the true topology of the  
log-posterior isn’t estimated; this is a particular burden for scale parameters which are bounded to

	Time Bin							
	1	2	3	4	5	6	7	8
Observed	0	0	0	1	0	1	1	0
-----	-----	-----	-----	-----	-----	-----	-----	-----
Certain	?	?	?	1	1	1	1	?
.....	.....	.....	.....	.....	.....	.....	.....	.....
Potential	0	0	0	1	1	1	1	0
Potential	0	0	1	1	1	1	1	0
Potential	0	1	1	1	1	1	1	0
Potential	1	1	1	1	1	1	1	0
Potential	0	0	0	1	1	1	1	1
Potential	0	0	1	1	1	1	1	1
Potential	0	1	1	1	1	1	1	1
Potential	1	1	1	1	1	1	1	1

Figure 2: Conceptual figure of all possible occurrence histories for an observed species. The first row represents the observed presence/absence pattern for a single species at eight time points. The second row corresponds to the known aspects of the “true” occurrence history of that species. The remaining rows correspond to all possible occurrence histories that are consistent with the observed data. By marginalizing over all possible occurrence histories, the probability of each potential history is estimated. The process of parameter marginalization is described in the text.

446 be positive (e.g. standard deviation).

Of additional concern for posterior inference is the partial identifiability of observation parameters  
 448  $p_{t=1}$  and  $p_{t=T}$  (Royle and Dorazio, 2008). This issue means that the estimates of sampling  
 probabilities at the “edges” of the time series cannot fully be estimated because there are no known  
 450 “gaps” in species occurrence histories that are guaranteed to be filled. Instead, the values of the first  
 and final columns of the “true” presence-absence matrix  $z$  for those observations that do not already  
 452 have presences in the observed presence-absence matrix  $y$  cannot be estimated (Royle and Dorazio,  
 2008). The hierarchical modeling approach used here helps mitigate this problem by pulling the  
 454 values of  $p_{t=1}$  and  $p_{t=T}$  towards the overall mean of  $p$  (Gelman et al., 2013), and in fact this  
 approach might be more analytically sound than the more ad-hoc approaches that are occasionally  
 456 used to overcome this hurdle (Royle and Dorazio, 2008). Additionally, because  $p_{t=1}$  and  $p_{t=T}$  are  
 only partially identifiable, estimates of occurrence  $\theta$  and origination  $\phi$  at  $t = 1$  and estimates of  $\theta$ ,  $\phi$

458 and survival  $\pi$  at  $t = T$  may suffer from similar edge effects. Again, the hierarchical modeling  
460 approach used here may help correct for this reality by drawing these estimates towards the overall  
460 means of those parameters.

462 After obtaining approximate posterior inference using ADVI, model adequacy and quality of fit  
464 were assessed using a posterior predictive check (Gelman et al., 2013). By simulating 100 theoretical  
466 data sets from the posterior estimates of the model parameters and the observed covariate  
468 information the congruence between predictions made by the model and the observed empirical  
470 data can be assessed. These datasets are simulated by starting with the observed states of the  
472 presence-absence matrix at  $t = 1$ ; from there, the time series roll forward as stochastic processes  
with covariate information given from the empirical observations. Importantly, this is fundamentally  
different from observing the posterior estimates of the “true” presence-absence matrix  $z$ . The  
posterior predictive check used in this study is to compare the observed average number of  
observations per species to a distribution of simulated averages; if the empirically observed value  
sits in the middle of the distribution then the model can be considered adequate in reproducing the  
observed number of occurrences per species.

The ADVI assumption of a purely Gaussian posterior limits the utility and accuracy of the  
474 posterior predictive checks because parameter estimates do not reflect the true posterior  
distribution and are instead just an approximation (Gelman et al., 2013). Because of this, posterior  
476 predictive estimates are themselves only approximate checks of model adequacy. The posterior  
predictive check that is used in this study focuses on mean occurrence and not to any scale  
478 parameters that might be most affected by the ADVI assumptions.

Given parameter estimates, diversity and diversification rates are estimated through posterior  
480 predictive simulations. Given the observed presence-absence matrix  $y$ , estimates of the true  
presence-absence matrix  $z$  can be simulated and the distribution of possible occurrence histories  
482 can be analyzed. This is conceptually similar to marginalization where the probability of each  
possible occurrence history is estimated (Fig. 2), but now these occurrence histories are generated  
484 relative to their estimated probabilities.

The posterior distribution of  $z$  gives the estimate of standing diversity  $N_t^{stand}$  for all time points as

$$N_t^{stand} = \sum_{i=1}^M z_{i,t}. \quad (5)$$

486 Total regional standing diversity can also be partitioned into the standing diversity of each of the  
functional groups.

488 **Results**

The results of the analyses described above take one of two forms: direct inspection of posterior  
490 parameter estimates, and downstream estimates of diversity and diversification rates based on  
posterior predictive simulations.

492 **Posterior parameter estimates**

The model used here in this study appears to have approximately adequate fit to the data based on  
494 the results of the posterior predictive check (Fig. 3). Simulated datasets as estimated from the  
models' posterior appears similar in terms of average number of occurrences per species to the  
496 observed number of occurrences in the empirical mammal dataset.

Log-odds of observing a species given that it is present varies greatly with time (Fig. 4) with lowest  
498 log-odds of observation being during the Gerigian and Harrisonian land-mammal ages. It is  
important to note, however, that all land-mammal ages with log-odds of observation greater than 2  
500 have very high probabilities of observation, which means that while there may be large differences  
in log-odds of observation between land-mammal ages this may not translate to substantial  
502 difference in the probability of observation.

There is little variance in the effect of functional group on the log-odds of observing a species that  
504 is present (Fig. 5). The only functional group with substantially less than expected log-odds of  
observation is scansorial insectivores, indicating that the fossil record of this group is the least

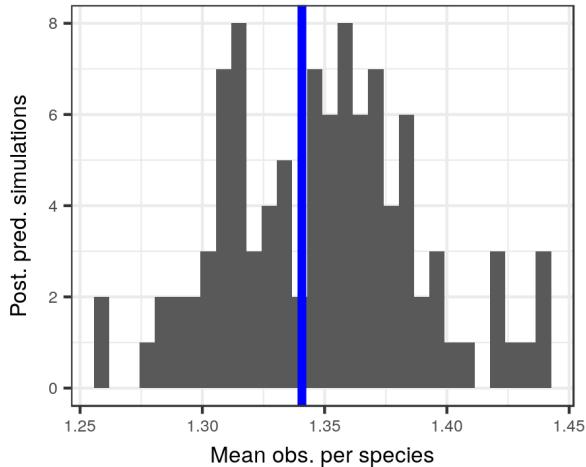


Figure 3: Comparison of the average observed number of occurrences per species (blue line) to the average number of occurrences from 100 posterior predictive datasets using the posterior estimates from the model used in this study. Adequate fit is indicated by the observed value of the test statistic being in the middle of the distribution of those calculated from the simulations.

506 complete of all the functional groups studied. Few functional groups have marginally better than  
 expected log-odds of observation, the other insectivorous functional groups have marginally greater  
 508 than average log-odds of observation; this is also the case for plantigrade omnivores. These results  
 indicate that the observation histories of these functional groups are expected to be complete than  
 510 most other functional groups. However, it is important to note that for many functional groups,  
 their estimated log-odds of observation are poorly constrained with great uncertainty indicating  
 512 little structure in how log-odds of observation varies between functional groups (Fig. 5).

Species mass is found to have a positive effect on probability of observing a species that is present  
 514 (Fig. 6). This result indicates that species with greater than average mass are expected to have  
 more complete observation histories than species with less than average mass. However, this  
 516 estimate does not translate to substantial differences in the estimated probability of observation  
 because observation probability is so high for most of the Cenozoic (Fig. 4). In fact, it is only when  
 518 land-mammal age observation probability is low that the effect of mass is observable. It is  
 important to remember the effect of mass on observation was considered constant over time and  
 520 that all differences observation probability between land-mammal ages is driven by variation over  
 time. When log-odds of observation is high, differences due to covariate effects translate to very

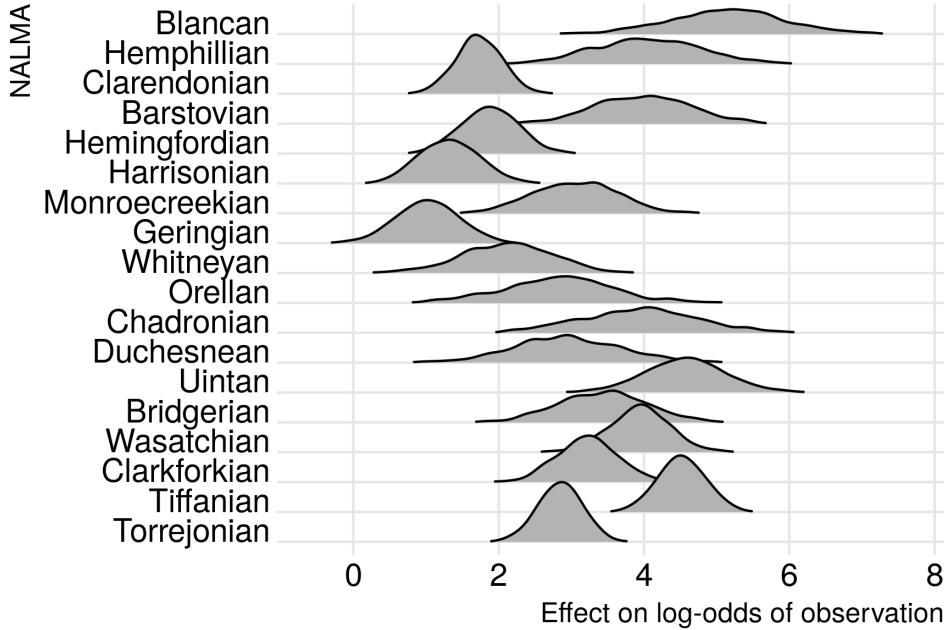


Figure 4: Ridgeline density plots of the estimates for the log-odds of observation from the time-varying intercept term. Each of the named time units are North American land-mammal ages. The oldest land-mammal age is at the bottom of the stack and the youngest is at the top.

522 small differences in actual probability.

Origination probability varies greatly among functional groups with each functional group  
 524 exhibiting a unique time series with a few shared features (Fig. 7). When origination probability is  
 below 0.50 this means that few if any new species of that functional group are entering the species  
 526 pool, and when origination probability is greater than 0.50 new species of that functional group are  
 probably entering the species pool. Finally, if origination probability is approximately 0.50, this  
 528 indicates that it is equally likely that a new species is entering the species pool as that it is not.  
 The slope of origination probability time-series is also very revealing; when the slope of the time  
 530 series is positive then new species are being continually being added to the species pool, and when  
 the slope is negative then the number of new species entering the pool is decreasing with time.

532 Most of the functional groups have peak origination probability at the present (Fig. 7); new species  
 in these functional groups are continually being added to the species pool. In the case of some  
 534 functional groups, such as digitigrade carnivores and fossorial herbivores, this is the culmination of

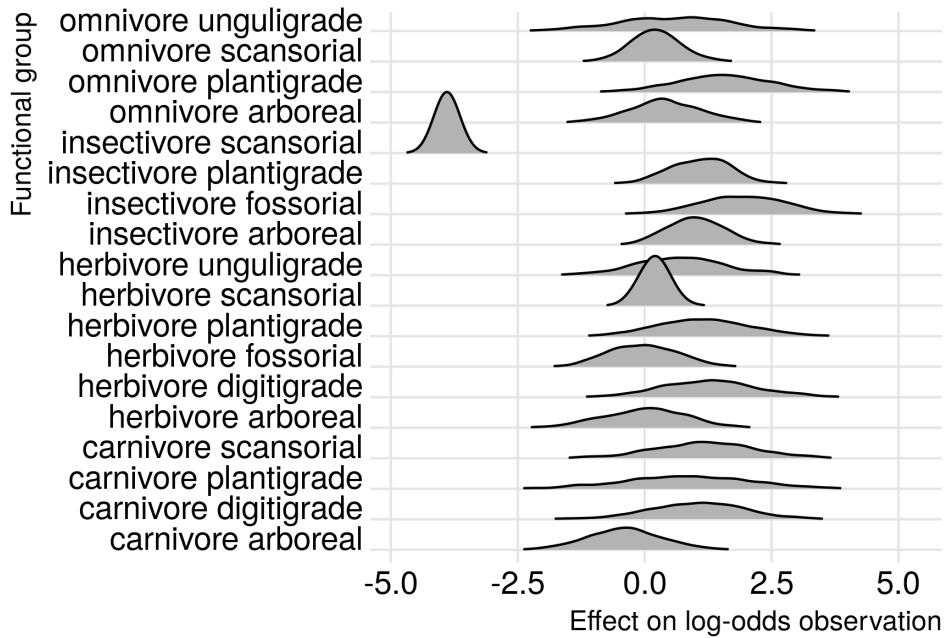


Figure 5: Ridgeline density plots of the estimates of the effect of functional group on log-odds of observation. Each of the rows correspond to a different functional group as indicated by the dietary and locomotor category combination.

those groups continued growth in the species pool. For other functional groups, such as arboreal

536 herbivores, this peak is a reversal from previously relatively low origination probability; this indicates an expansion of these functional groups following a retraction.

538 Five of the functional groups have peak origination probabilities not at the present: arboreal carnivores, arboreal insectivores, plantigrade insectivores, scansorial insectivores, and unguiligrade 540 omnivores. The arboreal functional groups reach peak origination probability in the Paleogene, after which their origination probabilities approach and remain at 0.50, reflecting the loss of these 542 functional groups from the species pool as origination probability never again increases.

Additionally, the uncertainty surrounding in the estimates of origination probability is very large, 544 especially in the Neogene. Large uncertainty in probabilities can reflect complete separation which results from that functional group leaving the species pool and it's (lack of) occurrence is without 546 ambiguity CITATION. The patterns evinced by the other functional groups have similar properties but reach peak origination probability early in the Neogene. Interestingly, origination probability of

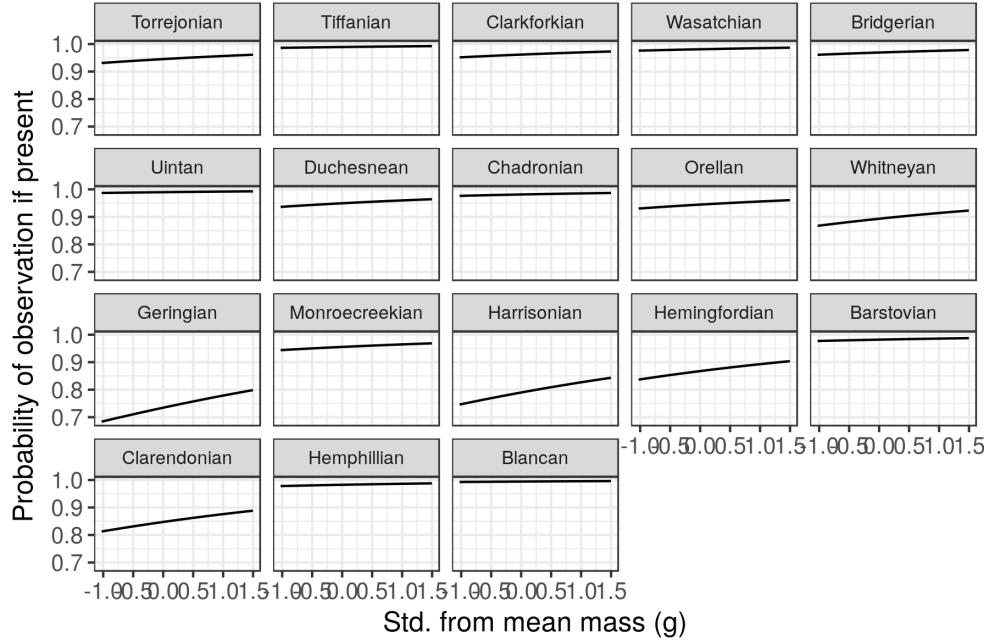


Figure 6: Estimates of the effect of species mass on probability of sampling a present species ( $p$ ). Mass has been log-transformed, centered, and rescaled; this means that a mass of 0 corresponds to the mean of log-mass of all observed species and that mass is in standard deviation units. Probability of observation is presented for each of the NALMAs where the differences in mean probability of observation are due to variation between the time units (Fig. 4).

548 scansorial insectivores has effectively two peaks, once in the late Paleogene and again in the early  
Neogene. Additionally, as will be discussed later in the context of standing diversity, all five of these  
550 functional groups decrease in diversity through the Cenozoic.

Origination probability varies greatly amongst mammal orders (Fig. 8). These estimates reflect  
552 differences origination probability as well as the relative rarity of that order in the fossil record; if  
members of that order appear infrequently, they must have lower probability of origination. Orders  
554 with greater than average log-odds of origination include Multituberculata, Dinocerata,  
Didelphimorphia, Creodonta, Condylarthra, Cimolesta, and Acroodi. These orders are major  
556 components of the Paleogene fossil record. Orders with lower than average log-odds of origination  
include Rodentia, Pilosa, Lagomorpha, Eulipotyphla, Cingulata, Carnivora, and Artiodactyla.  
558 These orders are characterized by small body size or primarily Neogene records. Additionally, the  
variance between orders is very large ranging from -3 to 3 log-odds of origination; this large of

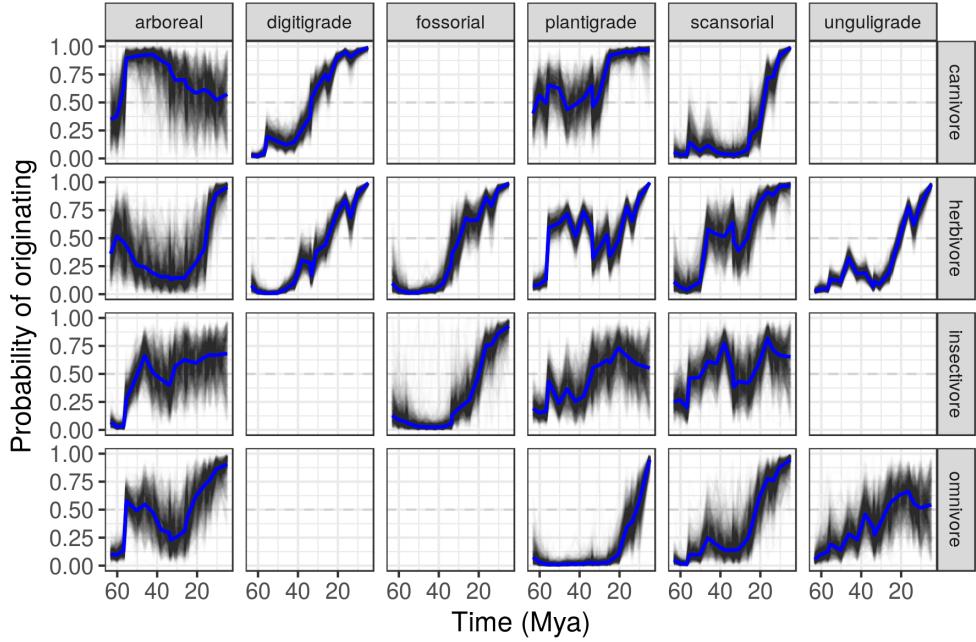


Figure 7: Probability of a mammal functional origination at each time point. Each panel depicts 100 time-series sampled from the model’s posterior. The blue line is the mean origination probability as predicted by the group-level predictors. The columns are by locomotor category and rows by dietary category; their intersections are the observed and analyzed ecotypes.

560 variance reflects how species within these orders have very different patterns of origination independent from their origination based on functional ecology (Fig. 7).

562 Species mass is estimated to have a negative relationship with origination probability (Fig. 9). This result means that species with greater than average mass have a lower probability of originating

564 than species with a below average mass. This result is sensible given the left-skewed distribution of

566 mammal species body sizes where large body sizes form the right-hand tail. There are fewer large

568 body-sized mammals which have originated than small body sized mammals. Interestingly, many of

570 the orders with small body sizes (e.g. Rodentia, Lagomorpha) have below average probabilities of

572 originating (Fig. 8); while not completely kosher, when this result is considered together with the effect of mass on origination these effects could be counteracting each other. These results continue

574 to add to the understanding of the heterogeneity and nuance associated with species origination

576 dynamics.

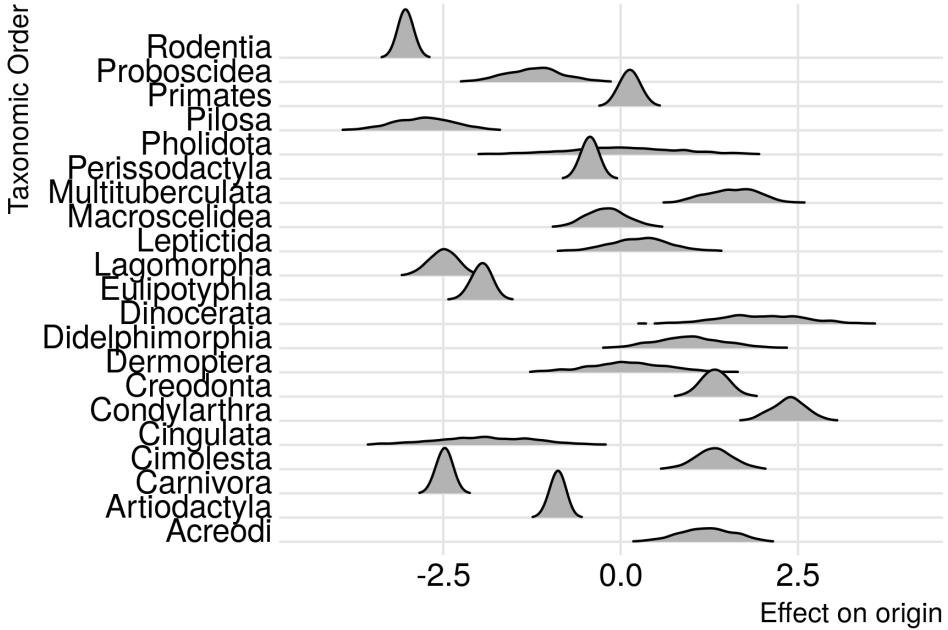


Figure 8: Differences in log-odds of origination based on mammal orders. Positive values correspond to greater log-odds origination than average, while negative values correspond to lower log-odds of origination than average. These estimates reflect the rarity of that order in the fossil record as well as differences in origination.

572 The survival probability time-series vary greatly between each of the functional groups with each  
 573 exhibiting unique patterns (Fig. 12). Interestingly, unlike origination probability (Fig. 7), survival  
 574 probability is frequently estimated with considerable uncertainty. When survival  
 575 probability is below 0.50 then a species that is present is unlikely to survive from one time unit to  
 576 the next, while when survival probability is greater than 0.50 species can be expected to survive to  
 577 the next time unit. Finally, when survival probability is approximately 0.50 then survival and  
 578 extinction are equally likely. Overall, survival probability is rarely estimated to be greater than 0.50  
 579 with any certainty. This result is consistent with the average occurrence being <1.35 time unit per  
 580 species which means that a plurality of species have only a single temporal occurrence (Fig. 3).

The survival probability of many functional groups is frequently approximately 0.50, indicating  
 581 extinction is frequently random with respect to functional group (Fig. 12). For example, the  
 582 survival probability scansorial canivores is approximately 0.50 for the entire time series which  
 583 indicates that there is no best or worst time for this functional groups survival. Similar patterns can

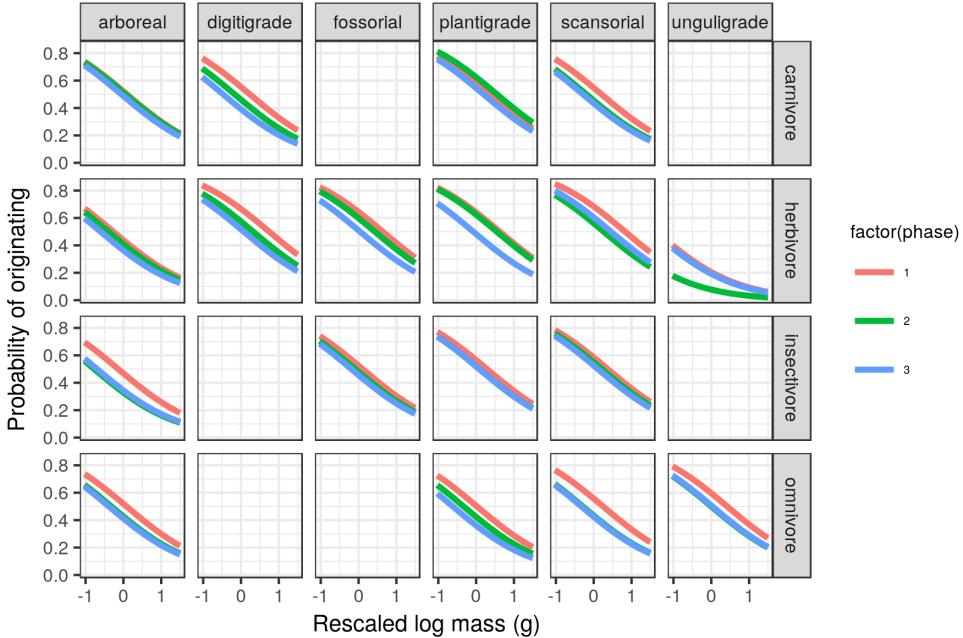


Figure 9: Mean estimate of the effect of species mass on the probability of a species originating for each of the three plant phases. The effect of mass is considered constant over time and that the only aspect of the model that changes with plant phase is the intercept of the relationship between mass and origination. The three plant phases are indicated by the color of the line. Mass has been log-transformed, centered, and rescaled; this means that a mass of 0 corresponds to the mean of log-mass of all observed species and that mass is in standard deviation units. For clarity, only the mean estimates of the effects of mass and plant phase are plotted.

be observed for mean survival probability of arboreal omnivores, fossorial insectivores, and

586 plantigrade omnivores though all three of these groups have sudden drops in survival probability in  
approximately the last 10Mya.

588 Arboreal herbivores are the only functional group for which survival probability is approximately  
above 0.50 for the entire Cenozoic (Fig. 12). This result indicates that when an arboreal herbivore  
590 species is present it is expected to survive from one time unit to the next. However, it is important  
to note that arboreal herbivores are estimated to have an origination probability below 0.50 for  
592 most of the Cenozoic. Together, these results mean that arboreal herbivore species are rare but are  
expected to survive from one time point to the next.

594 A common feature of multiple functional group's survival probability time-series is a peak in  
survival during the Neogene (Fig. 12). In most cases, these peaks are estimated with little

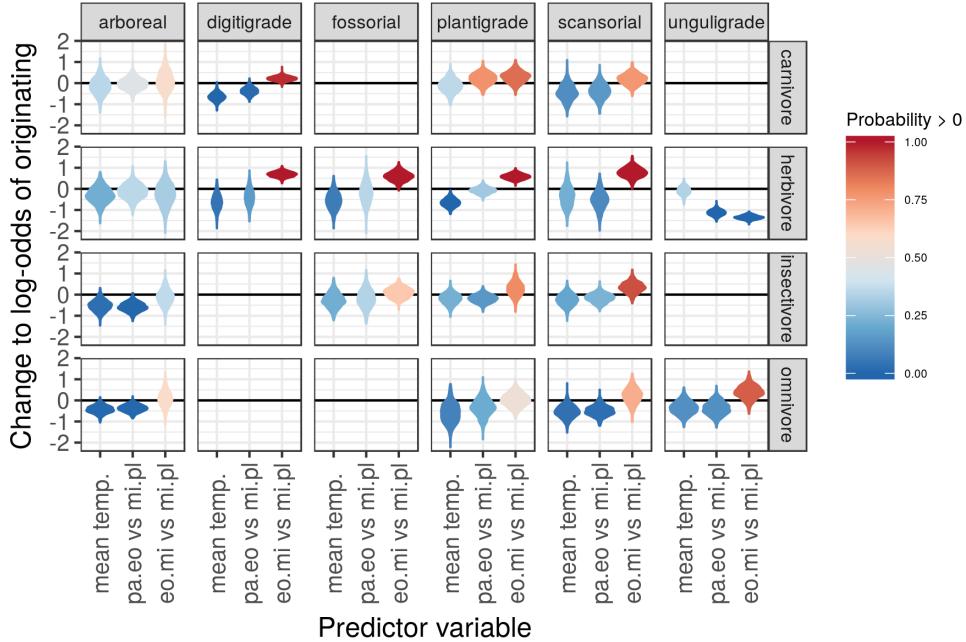


Figure 10: Estimated effects of the group-level covariates describing environmental context on log-odds of species origination. These estimates are from the birth-death model. What is plotted is a violin of the distribution of 1000 samples from the approximate posterior. The effect of plant phase graphed here is calculated as Phase 1=  $\gamma_{phase\ 1}$ , Phase 2=  $\gamma_{phase\ 1} + \gamma_{phase\ 2}$ , and so on.

596 uncertainty which indicates how apparent this event is. Digitigrade carnivores, digitigrade  
 597 herbivores, plantigrade herbivores, scansorial insectivores, unguiligrade herbivores, and unguiligrade  
 598 omnivores all peak in survival probability at approximately 25Mya. This peak in survival means  
 599 that species of these functional groups which are unlikely to go extinct at this point, potentially  
 600 indicating favorable environmental conditions for these groups at the Paleogene-Neogene transition.  
 Additionally, this peak does not coincide with the movement from one plant phase to another  
 602 (Table 4).

The effect of order on survival probability has much lower variance (Fig. 13) than the effect of order  
 604 on origination probability (Fig. 8. Primates, Multituberculata, Eulipotyphla, Dermoptera,  
 Creodonta, Condylarthra, Carnivora, and Artiodactyla are estimated to have a lower than average  
 606 survival probability which implies that species of these orders are expected to be present for a  
 single time unit. Of these orders, Primates and Multituberculata are expected to have the lowest  
 608 survival probability of all orders. The orders expected to have greater than average survival

Table 9: Posterior probability of the differences in the log-odds of an ecotype originating based on plant phase.

	P(Eo.Mi > 0)	P(Pa.Eo > 0)	P(Eo.Mi > Pa.Eo)
arboreal carnivore	0.575	0.447	0.598
digitigrade carnivore	0.976	0.017	0.998
plantigrade carnivore	0.857	0.780	0.578
scansorial carnivore	0.768	0.154	0.889
arboreal herbivore	0.318	0.357	0.428
digitigrade herbivore	1.000	0.161	0.995
fossilorial herbivore	0.999	0.353	0.926
plantigrade herbivore	1.000	0.304	0.998
scansorial herbivore	0.999	0.108	0.998
unguligrade herbivore	0.000	0.000	0.100
arboreal insectivore	0.364	0.003	0.857
fossilorial insectivore	0.645	0.341	0.708
plantigrade insectivore	0.794	0.148	0.881
scansorial insectivore	0.916	0.235	0.940
arboreal omnivore	0.590	0.006	0.882
plantigrade omnivore	0.524	0.209	0.762
scansorial omnivore	0.713	0.027	0.938
unguligrade omnivore	0.888	0.127	0.960

probability are Rodentia, Lagomorpha, and Didelphimorphia.

610 Species mass is estimated to have no relationship or at best a weakly positive relationship with  
 survival probability (Fig. 14). This result means that differences in mass do not lead to differences  
 612 in species survival. This result is consistent with previous studies of North American species and  
 genus survival dynamics CITATION SMITS TOMIYA, and implies that other ecological factors  
 614 have greater importance on survival than mass alone. GET PROBABILITY ESTIMATE

Functional group survival probability is rarely associated with differences between the three plant  
 616 phases (Table 11) with only five pair-wise comparisons having greater than 89% probability of  
 differences in survival between phases. Unuligrade herbivores have an approximately 89%  
 618 probability of having lower survival probability during the Paleocene-Eocene than the  
 Miocene-Pleistocene. For digitgrade herbivores, and unuligrade omnivores, the Eocene-Miocene  
 620 phase have an approximately 90% probability of having greater survival probability than during the  
 Miocene-Pleistocene phase. In contrast, unuligrade herbivores are estimated to have lower

Table 10: Posterior probability that the effects of the two temperature covariates on the log-odds of an ecotype origination are greater than 0. What is estimated is the probability that these estimates are greater than 0; high or low probabilities indicate the “strength” of the covariate in that direction (positive and negative, respectively). These estimates are from the birth-death model.

	$P(\gamma_{temp\ mean} > 0)$
arboreal carnivore	0.355
digitigrade carnivore	0.001
plantigrade carnivore	0.358
scansorial carnivore	0.121
arboreal herbivore	0.219
digitigrade herbivore	0.045
fossorial herbivore	0.067
plantigrade herbivore	0.000
scansorial herbivore	0.221
unguligrade herbivore	0.339
arboreal insectivore	0.027
fossorial insectivore	0.219
plantigrade insectivore	0.224
scansorial insectivore	0.192
arboreal omnivore	0.009
plantigrade omnivore	0.087
scansorial omnivore	0.035
unguligrade omnivore	0.129

survival probability in the Eocene-Miocene phase than the Miocene-Pleistocene phase. Finally, unculigrade herbivores have an approximately 99% probability of having a lower survival probability during the Paleocene-Eocene than the Eocene-Miocene.

Temperature is estimated to have no effect on functional group survival probability (Table 12).

## Analysis of diversity

All of the analyses of diversification and macroevolutionary rates has been done using only the birth-death model because of the model’s better posterior predictive check performance (Fig. 3).

The general pattern of the estimated North American total mammal diversity for the Cenozoic is “stable” in that diversity fluctuates around a constant mean standing diversity, does not fluctuate wildly and rapidly over the Cenozoic, and demonstrates no sustained directional trends (Fig. 17a).

Table 11: Posterior probability of the differences in the log-odds of an ecotype surviving based on plant phase.

	P(Eo.Mi > 0)	P(Pa.Eo > 0)	P(Eo.Mi > Pa.Eo)
arboreal carnivore	0.297	0.560	0.328
digitigrade carnivore	0.786	0.367	0.743
plantigrade carnivore	0.411	0.744	0.273
scansorial carnivore	0.428	0.445	0.486
arboreal herbivore	0.256	0.768	0.174
digitigrade herbivore	1.000	0.400	0.942
fossorial herbivore	0.696	0.563	0.565
plantigrade herbivore	0.659	0.508	0.596
scansorial herbivore	0.616	0.539	0.531
unguligrade herbivore	0.000	0.102	0.012
arboreal insectivore	0.289	0.483	0.368
fossorial insectivore	0.532	0.420	0.592
plantigrade insectivore	0.499	0.361	0.605
scansorial insectivore	0.443	0.252	0.634
arboreal omnivore	0.651	0.597	0.591
plantigrade omnivore	0.417	0.549	0.393
scansorial omnivore	0.486	0.525	0.487
unguligrade omnivore	0.929	0.521	0.844

- 632 In broad strokes, the first 15 or so million years of the Cenozoic are characterized by first an  
 increase and then a decline in standing diversity at approximately 45-50 Mya (early-middle Eocene).  
 634 Following this decline, standing diversity is broadly constant from 45 to 18 Mya (early Miocene).  
 After this, there is a rapid spike in diversity followed by a slight decline in diversity up to the  
 636 Recent.

The pattern exhibited by the diversity history estimated in this study (Fig. 17a) has some major  
 638 similarities with previous mammal diversity curves (Alroy, 2009): both curves begin with an  
 increase in diversity most of the major increases in diversity are retained including the large  
 640 diversity spike during the Miocene. Unlike subsampling based approaches to estimating diversity  
 (Alroy, 2010), I'm able to interpolate over unsampled/poorly sampled time periods because of how  
 642 the hierarchical model can share information across the different units Gelman et al. (2013); for  
 cases like unsampled temporal bins, this may lead to estimates with high uncertainty, but that is  
 644 preferable to no estimate at all. Finally, the Bayesian framework here gives a distribution of

Table 12: Posterior probability that the effects of the two temperature covariates on the log-odds of an ecotype survival are greater than 0. What is estimated is the probability that these estimates are greater than 0; high or low probabilities indicate the “strength” of the covariate in that direction (positive and negative, respectively). These estimates are from the birth-death model.

	$P(\gamma_{temp\ mean} > 0)$
arboreal carnivore	0.665
digitigrade carnivore	0.453
plantigrade carnivore	0.618
scansorial carnivore	0.380
arboreal herbivore	0.761
digitigrade herbivore	0.395
fossorial herbivore	0.429
plantigrade herbivore	0.279
scansorial herbivore	0.345
unguligrade herbivore	0.818
arboreal insectivore	0.489
fossorial insectivore	0.452
plantigrade insectivore	0.435
scansorial insectivore	0.384
arboreal omnivore	0.600
plantigrade omnivore	0.639
scansorial omnivore	0.512
unguligrade omnivore	0.396

possible estimates of diversity allowing for direct inspection of the uncertainty of our inferences,  
 something that is preferable to both traditional and resampling based confidence interval estimates  
 (Gelman et al., 2013). Note that my time series of estimated diversity begins at a slightly different  
 point than that of Alroy (2009) and that the time intervals used by Alroy (2009) are slightly shorter  
 than those used here, so this may cause some of the minor differences between the curves. Also,

please note that the diversity values are plotted at the “ceiling” of each temporal interval and not  
 at the midpoint (Fig. 17a).

When viewed through the lens of diversification rate, some of the structure behind the estimated  
 diversity history begins to take shape (Fig. 17b). For most of the Cenozoic, the diversification rate  
 hovers around zero, punctuated by both positive and negative spikes. The largest spike in  
 diversification rate is at 16 Mya, which is early Oligocene (Fig. 17b). Other notable increases in  
 diversification rate occur 56, 46, 22, 18, and 6 Mya (Table 13), though the last of these may be due

to edge effects surrounding the partial-identifiability of  $p_{t=T}$ . Notable decreases in diversification  
658 rate occur at 54, 50, 48, 44, 40, 34, 30, 24, 20, 16, 12, and 8 Mya (Table 13), meaning that  
diversification rate has more major decreases than increases. While diversification rates significantly  
660 lower than average are more common than diversification rates greater than average, when  
diversification rate does increase it is with a greater magnitude than most decreases (Fig. 17b).  
662 Given that diversification rate more closely resembles origination rate than extinction rate (Fig.  
17b, ??, ??), these decreases in diversification rate may be indicative of “depletions” (failure to  
664 replace extinct taxa) rather than pulses of extinction.

The estimates from this study of per capita origination and extinction rates for the entire species  
666 pool (Fig. ??, ??) are very different from the origination and extinction rates estimated by Alroy  
(2009). The two most striking difference are the very different estimates of extinction rate between  
668 the two studies and the very different scales of the origination rate estimates. This may be due to  
the fundamentally different way these rates are calculated, and how the diversification process was  
670 modeled. The per capita rates estimated in this study follow straight from the definition of a per  
capita rate (e.g. number of originations between time  $t$  and  $t + 1$  divided by the diversity at time  $t$ )  
672 while the rates calculated in Alroy (2009) are based on log ratios of standing diversity.

The comparison between per capita origination and extinction rate estimates reveals how  
674 diversification rate is formed (Fig. ??, ??). As expected given previous inspection of the ecotype  
specific estimates of origination and survival probabilities from the birth-death model,  
676 diversification rate seems most driven by changes in origination rate as opposed to extinction rate.  
Extinction rate, on the other hand, demonstrates an almost saw-toothed pattern around a constant  
678 mean (Fig. ??). These results are broadly consistent with those from previous analyses of North  
American mammals diversity and diversification (Alroy, 1996, 2009; Alroy et al., 2000).  
680 Diversity partitioned by ecotype reveals a lot of the complexity behind the pattern of mammal  
diversity for the Cenozoic (Fig. 18).  
682 Arboreal ecotypes obtain peak diversity early in the Cenozoic and then decline for the rest of the  
time series, becoming increasingly rare or absent as diversity approaches the Recent (Fig. 18).

Table 13: Posterior probabilities of diversity  $N_t^{stand}$  or diversification rate  $D_t^{rate}$  being greater than average standing diversity  $\bar{N}^{stand}$  or average diversification rate  $\bar{D}^{rate}$  for the whole Cenozoic. The “Time” column corresponds to the top of each of the temporal bins. Diversification rate can not be estimated for the last time point because it is unknown how many more species originated or went extinct following this temporal bin. The estimates are from the birth-death model.

NALMA	$P(N_t^{stand} > \bar{N}^{stand})$	$P(D_t^{rate} > \bar{D}^{rate})$
Torrejonian	0.79	
Tiffanian	0.95	0.67
Clarkforkian	0.50	0.03
Wasatchian	1.00	0.99
Bridgerian	0.69	0.00
Uintan	0.75	0.45
Duchesnean	0.00	0.00
Chadronian	0.01	0.70
Orellan	0.00	0.01
Whitneyan	0.00	0.09
Geringian	0.00	0.57
Monroecreekian	0.01	1.00
Harrisonian	0.11	0.67
Hemingfordian	0.96	0.99
Barstovian	1.00	1.00
Clarendonian	0.93	0.00
Hemphillian	0.63	0.10
Blancan	0.73	0.43

- 684 Arboreal herbivores and omnivores obtain peak diversity at the beginning of the Cenozoic then go  
 685 into decline while remaining a small part of the species pool, while arboreal carnivores and  
 686 insectivores obtain peak diversity 52-50 Mya and then quickly decline and become extremely rare or  
 687 entirely absent from the species pool. This is consistent with increasing extinction risk in the  
 688 Neogene compared to the Paleogene as proposed by Smits (2015).

The diversity of digitigrade and unguligrade herbivores increases over the Cenozoic (Fig. 18). In  
 690 contrast, plantigrade herbivore diversity does not have a single, broad-strokes pattern; instead,  
 691 diversity increases, decreases, and may have then increased till the Recent. In contrast, fossorial and  
 692 scansorial herbivores demonstrate a much flatter history of diversity, with a slight increase in  
 693 diversity that over time is more pronounced among fossorial taxa than scansorial taxa. The  
 694 expansion of digitigrade and unguligrade herbivores over the Cenozoic is consistent with the  
 gradual expansion of grasslands which these ecotypes are better adapted to than closed

696 environments (Blois and Hadly, 2009; Strömberg, 2005).

Digitigrade carnivores have a multi-modal diversity history, with peaks at 54-52 and 12-10 Mya  
698 (Fig.18). Between these two peaks digitigrade carnivore diversity dips below average diversity  
following the first peak and then grows slowly until the second peak. Plantigrade carnivores obtain  
700 peak diversity in the early Cenozoic and then maintain a relatively stable diversity until another  
peak at the end of the Cenozoic. The generally flat diversity history digitigrade carnivores lacks any  
702 sustained temporal trends and seems to reflect previous findings of limited diversity in spite of  
constant turnover and morphological evolution (Silvestro et al., 2015; Slater, 2015; Van  
704 Valkenburgh, 1999)

There are some broad similarities in diversity histories of insectivorous and omnivorous taxa. The  
706 diversity histories of arboreal, plantigrade, and scansorial insectivorous taxa all demonstrate a  
decreasing pattern with time, while fossorial insectivores have a flat diversity history with a peak  
708 approximately 10 Mya (Fig. 18). Arboreal and scansorial omnivores decrease in diversity from their  
initial peaks early in the Cenozoic, and plantigrade omnivores have a generally flat diversity history  
710 with a sudden peak in diversity late in the Cenozoic (Fig. 18). Unguligrade omnivores also  
demonstrate a possible decrease in diversity over the Cenozoic, but not as clearly as arboreal and  
712 scansorial omnivores.

The waxing and waning of the mammal ecotypes is obvious when comparing changes to estimated  
714 relative log-mean of diversity (Fig. 19). While ecotype diversity does appear to change gradually,  
there are definite changes to the relative contributions of the ecotypes to the regional species pool.  
716 All arboreal ecotypes clearly decrease in relative diversity over the Cenozoic. In contrast the the  
digitigrade herbivore, fossorial herbivore, scansorial herbivore, and unguligrade herbivore ecotypes  
718 which increase in relative diversity over the Cenozoic. The digitigrade carnivore ecotype increases in  
relative diversity until approximately the start of the Neogene, after which it maintains a generally  
720 constant relative diversity; this is consistent with previous observations of constant or  
density-dependent diversity of the canid guild for the Neogene (Silvestro et al., 2015; Slater, 2015;  
722 Van Valkenburgh, 1999), a guild that overlaps with the digitigrade carnivore ecotype. Plantigrade

herbivores remain a constant relative contribution to ecotypic diversity. These results support the  
724 hypothesis of a gradual transition from the early Paleogene with a region with more available  
habitat for arboreal taxa and less available habitat for many digitigrade and unguligrade taxa, to an  
726 environment where arboreal taxa are absent from the species pool and digitigrade and unguligrade  
taxa are much more dominant (Fig. 19). It is the relative contributions of digitigrade carnivores,  
728 digitigrade herbivores, and unguligrade herbivores which really shape the regional species pool of  
the Neogene.

730 Many of the estimated ecotype-specific diversity histories share a similar increase in diversity in the  
late Cenozoic, 16-14 Mya (Fig. 18). These increases are either sustained or temporary and are seen  
732 in digitigrade carnivores, plantigrade carnivores, scansorial carnivores, unguligrade herbivores,  
fossiliferous insectivores, and plantigrade omnivores.

## 734 Discussion

Both the composition of a species pool and its environmental context change over time, though not  
736 necessarily at the same rate or concurrently. Local communities, whose species are drawn from the  
regional species pool, have “roles” in their communities defined by their interactions with a host of  
738 biotic and abiotic interactors (i.e. a species’ niche). For higher level ecological characterizations like  
ecotypes and guilds, these roles are broad and not defined by specific interactions but by the genre  
740 of interactions species within that grouping participate in. The diversity of species within an  
ecotype or guild can be stable over millions of years despite constant species turnover (Jernvall and  
742 Fortelius, 2004; Slater, 2015; Van Valkenburgh, 1999). This implies that the size and scope of the  
role of an ecotype or guild in local communities, and the regional species pool as a whole, is  
744 preserved even as the individual interactors change. This also implies that the structure of regional  
species pools can be constant over time despite a constantly changing set of “players.” There is  
746 even evidence that functional groups are at least partially self-organizing and truly emergent  
(Scheffer and van Nes, 2006).

748 Comparison of the results from the posterior predictive checks for the pure-presence and birth-death  
models supports the conclusion that regional species pool dynamics cannot simply be described by  
750 a single occurrence probability and are instead the result of the interplay between the origination  
and extinction processes. Additionally, changes to the ecotypic composition and diversification rate  
752 of the North American regional species pool are driven primarily by variation in origination and not  
extinction (Fig. 17). These aspects of how regional species pool diversity is shaped are not directly  
754 observable in studies of the Recent where time scales are short and macroevolutionary dynamics are  
inferable solely from phylogeny (Fritz et al., 2013; Price and Schmitz, 2016).

756 Extinction rate for the entire regional species pool through time is highly variable and demonstrates  
a saw-toothed pattern with no obvious temporal trends. While a constant mean extinction rate is  
758 consistent with previous observation (Alroy, 1996; Alroy et al., 2000), the degree to which mammal  
extinction rate is actually variable may not have been equally appreciated as it has been for the  
760 marine invertebrate record (Foote, 2000a,b, 2006, 2010). What is most consistent with previous  
observations, however, is that diversity seems to be most structured by changes to origination  
762 rather than changes to extinction (Alroy, 1996; Alroy et al., 2000).

Comparison of the ecotype specific diversity histories adds a considerable degree of nuance to broad  
764 narrative of shifts in functional composition of the North American mammal species pool as being  
gradual (Fig. 18). While most ecotypes do not experience sudden shifts in origination or extinction  
766 rate (Fig. ??, ??). As with the diversification rate of the entire species pool, the diversification of  
individual ecotypes seem principally driven by origination and not extinction. Instead, while species  
768 seem to originate in waves (Fig. ??), they appear to leave the regional species pool in an  
uncoordinated and individual manner (Fig. ??) which could be considered consistent with the  
770 maxim that all species respond differently to environmental change (Blois and Hadly, 2009). Note,  
however, this result characterizes the entire North American mammal regional species pool and  
772 thus may not reflect the dynamics of individual local communities.

The few large-magnitude, but temporary, increases in ecotype-specific origination rate occur in  
774 digitigrade carnivores, digitigrade herbivores, plantigrade herbivores, and unguligrade herbivores.

Importantly, the large peak in diversification and origination rates 16 Mya (Fig. 17) appears driven  
776 almost entirely by a massive increase in the origination rate of unguligrade herbivores (Fig. ??).

Additionally, there is some evidence that the origination probabilities of these ecotypes are  
778 correlated (Fig. 11, ??). While this result does not mean that there are large and sudden  
cross-ecotype changes to the regional species pool, it does suggest that additions to the species pool  
780 do not occur in individual ecotypes idiosyncratically.

Arboreal taxa disappear from the regional species pool over the Cenozoic, with long term decline  
782 over the Paleogene leading to the disappearance by start of Neogene ~22 Mya. This is partially  
consistent with one of the two possible patterns presented here and in Smits (2015) that would  
784 result in arboreal taxa having a greater extinction risk than other ecotypes: the Paleogene and  
Neogene were different selective regimes and, while the earliest Cenozoic may have been neutral  
786 with respect to arboreal taxa, they disappeared quickly over the Cenozoic which may account for  
their higher extinction risk. However, these results add some nuance to this scenario as arboreal taxa  
788 were declining throughout the Paleogene instead of maintaining a flat diversity as hypothesized  
(Smits, 2015). I interpret the decline of arboreal taxa throughout the Paleogene to mean that the  
790 shift from closed to open environments began in the Paleogene and led to increasingly hostile  
environments for arboreal taxa as opposed to being a sudden change in selective regime between  
792 the Paleogene and Neogene. In addition to all arboreal taxa, the diversity of plantigrade and  
scansorial insectivores decreases with time (Fig. 18).

794 Digitigrade carnivores have a relatively stable diversity history through the Cenozoic and can be  
characterized as varying around a constant mean diversity. This ecotype has a large amount of  
796 overlap with the carnivore guild which has been the focus of much research (Janis and Wilhelm,  
1993; Pires et al., 2015; Slater, 2015; Van Valkenburgh, 1999). This result is consistent with some  
798 form of “control” on the diversity of this ecotype, such as diversity-dependent diversification  
(Silvestro et al., 2015; Slater, 2015; Van Valkenburgh, 1999).

800 Both digitigrade and unguligrade herbivores increase in diversity over the Cenozoic. The increase of  
these cursorial forms is consistent with the gradual opening up of the North American landscape

802 (Blois and Hadly, 2009; Graham, 2011; Strömberg, 2005) and may indicate a long-term shift in the  
803 interactors associated with those ecotypes leading to increased contribution to the regional species  
804 pool. This result may be comparable to the increasing percentage of hypsodont (high-crowned  
805 teeth) mammals in the Neogene of Europe being due to an enrichment of hyposodont taxa and not  
806 a depletion of non-hypsodont taxa. Smaller scale increases in fossorial herbivore species, and a lesser  
807 extent plantigrade herbivores, suggests that the increase of interactors may be associated mostly  
808 with the herbivore dietary category with locomotor category tempering that relationship. These  
809 results support the conclusion that the increase in digitigrade and unguligrade herbivores is the  
810 result of an enrichment of these ecotypes as opposed to being caused by the depletion of other  
811 herbivorous ecotypes; this is further supported by the lack of major changes to the number of  
812 extinctions of all herbivore ecotypes (Fig. ??).

An association between plant phase and differences in ecotype occurrence or origination-extinction  
814 probabilities is interpreted to mean that an ecotype enrichment or depletion is due to associations  
815 between that ecotype and whatever plants are dominant at that time. Plant phase clearly  
816 structures the occurrence and origination probability time series (Fig. ??, 7). These differences in  
817 occurrence or origination translate to the estimates of diversity and diversification rate; the largest  
818 spike in diversity, diversification rate, and origination rate all correspond to the onset of the last  
819 plant phase (Fig. 17). The clearest example of the diversity of an ecotype increasing at this  
820 particular transition is in scansorial carnivores (Fig. 18); similar shifts in other ecotypes are much  
821 more subtle, as was previously noted for fossorial insectivores.

822 Interestingly, for all of the ecotypes with sudden changes in diversity at this transition the change is  
823 an increase, even if only temporarily. There are two interpretations of these results. A biological  
824 interpretation of this result is that, because plant phase associations are only with occurrence or  
825 origination probabilities and not survival, these ecotypes were well suited for the newly available  
826 mammal-plant interactions due to the increased modernization of their floral context (Graham,  
827 2011). Alternatively, the increase in diversity associated with the third plant phase may be caused  
828 by the edge effect in origination probability that is artificially inflating the number of origination  
829 events (Fig. 7). However, the estimated number of origination events does not have a tremendous

830 spike at this transition, nor is a major increase in the number of origination events sustained (Fig. ??).

832 There are fewer, less obvious shifts in diversity surrounding the transition from the first to second  
834 plant phase, with the following ecotypes having apparent shifts in diversity at 50 My: plantigrade  
insectivore peak diversity also occurs 50 Mya, and is then followed by a steep decline in diversity  
836 till 30 Mya when this ecotype is lost from the species pool. Because plant phase has been found to  
structure occurrence/origination (Fig. ??, 7), but not survival (Fig. 12), my interpretation of these  
838 results is that new species were not entering the system because there were fewer available  
mammal-plant interactions available for those ecotypes. Instead, these ecotypes were poorly suited  
840 for the newly available mammal-plant interactions brought upon by the changing environmental  
context (Graham, 2011).

842 The temperature covariates are found to have similar effects on occurrence and origination  
probabilities (Tables ??, 10). Temperature is found to more often affect ecotype occurrence  
844 probabilities than origination probabilities. In most cases, there is a negative association between  
temperature and probability of occurring or first originating; this means that if temperature  
846 decreases, we would then expect an increase in the probability of occurring or first originating. In  
contrast, temperature range is estimated to be a good predictor of survival in only to mammal  
848 ecotypes and only marginally for one of those (Table 12). Additionally, both of these cases have  
positive relationships, meaning that if temperature decreases it is expected that species survival will  
850 also decrease.

The result that temperature does not affect the survival probability of most ecotypes is consistent  
852 with previous analysis of mammal diversity (Alroy et al., 2000). The result that temperature affects  
origination probability, on the other hand, is in strong contrast to the results Alroy et al. (2000).  
854 An important difference between the analyses presented here and that of Alroy et al. (2000) is I am  
considering the effect of temperature on the probability of a species originating, assuming it hasn't  
856 originated yet while Alroy et al. (2000) analyzes the correlation between the first differences of the

origination and extinction rates with an oxygen isotope curve (Zachos et al., 2001). Origination or  
858 extinction rates have very different properties than the origination probabilities estimated here  
brought upon by the difference both in definition and units. Origination probability is the expected  
860 probability that a species that has never been present and is not present at time  $t$  will be present at  
time  $t + 1$ ; origination probability is defined for a single species. In contrast, per capita rates are  
862 defined (for origination) as the expected number of new species to have originated between time  $t$   
and  $t + 1$  given the total number of species present at time  $t$ ; per capita rates are defined for the  
864 standing diversity. It is also important to note that even though there is an edge effect at the last  
time interval that causes an increase in the occurrence and origination probabilities of some  
866 ecotypes (Fig. ??, 7, the corresponding rates and population level birth/death dynamics do not  
share that pattern (Fig. 17, ??, ??). However, it is still possible that the finding that temperature  
868 has an effect on origination may simply be because as time approaches the present the number of  
species which have originated increases and not because of climatic forcing of origination.

870 All environmental factors are found to affect the occurrence and origination probabilities for most,  
but not all, mammal ecotypes (Fig. ??, 10). In contrast, the environmental factors probably do not  
872 affect differences in ecotype survival probability (Fig. 15). The focus in previous research on  
temperature and major climatic or geological events without other measures of environmental  
874 context may have led to confusion in discussions of how the “environment” affects mammal  
diversity and diversification (Alroy et al., 2000; Figueirido et al., 2012). The environment or climate  
876 are more than just global or regional temperature, it is also the set of all possible biotic and abiotic  
interactions that can be experienced by a member of the species pool. By including more  
878 descriptors of species’ environmental context than simple an estimate of global temperature a more  
complete “picture” of the diversification process is inferred.

880 Analysis of relationship between temperature and origination rate is probably better suited for a  
continuous-time birth-death or multilevel stochastic differential equation model instead of a  
882 discrete-time model because the both continuous models estimate rates while discrete time models  
estimate probabilities (Allen, 2011). The PyRate model(s) are based on a continuous-time  
884 birth-death process (Silvestro et al., 2015, 2014). Unfortunately, a continuous-time model may be

unsuited for most paleontological data as the fossil record is naturally discrete; fossils are assigned  
886 to temporal units, such as stages, which have age ranges. Individual fossils are not assigned  
individual numeric ages. This reality was in fact my one of motivations for using discrete-time  
888 birth-death model instead of one in continuous-time. There are of course exceptions to this  
characterization; the fossil record of graptolites from the Ordovician and Silurian (Crampton et al.,  
890 2016) and the fossil record of some mammal orders from Neogene are of high enough resolution that  
the application of continuous-time models is appropriate and less fraught.

892 The effect of species mass on either occurrence or origination and extinction was not allowed to  
vary by ecotype or environmental context. The primary reason for this modeling choice was that  
894 this study focuses on ecotypic based differences in either occurrence, or origination and extinction.  
Allowing the effect of body size to vary by ecotype, time, and environmental factors would increase  
896 the overall complexity of the model beyond the scope of the study. Instead, body size was included  
in order to control for its possible underlying effects (McElreath, 2016). A control means that if  
898 there is variation due to body mass, having a term to “absorb” that effect is better than ignoring it.

The only covariate allowed to affect sampling probability was mass and only as a linear predictor.  
900 Other covariates, such as the environmental factors considered here, could have affected the  
underlying preservation process that limits sampling probability; their exclusion as covariates of  
902 sampling/observation was the product of a few key decisions: model complexity, model  
interpretability, the scope of this study, and a lack of good hypotheses related to these covariates to  
904 warrant their inclusion.

## Conclusions

906 These results add a considerable degree of nuance to the narrative of changes to North American  
diversity being gradual. My results support the conclusions that ecotypic diversity is shaped more  
908 by changes to origination than extinction and that major changes to total diversification rate can  
be attributed to increases in origination of only some ecotypes. There are a number of interesting  
910 estimated ecotype diversity patterns. While arboreal ecotypes are diverse in the Paleogene, by the

Neogene all arboreal ecotypes dramatically decreased in diversity and became either rare or absent  
912 from the regional species pool. The other ecotypes that decrease in diversity over the Cenozoic are  
plantigrade and scansorial insectivores and scansorial omnivores. The only ecotypes that  
914 demonstrate a sustained pattern of increasing diversity are digitigrade and unguligrade herbivores.  
When the environmental covariates analyzed here are inferred to affect the diversification of an  
916 ecotype, this effect is virtually always on origination and not survival. This analysis provides a  
much more complete picture of North American mammal diversity and diversification, specifically  
918 the dynamics of the ecotypic composition of that diversity. By increasing the complexity of analysis  
while precisely translating research questions into a statistical model, the context of the results is  
920 much better understood. Future studies of diversity and diversification should incorporate as much  
information as possible into their analyses in order to better understand or at least contextualize  
922 the complex processes underlying that diversity.

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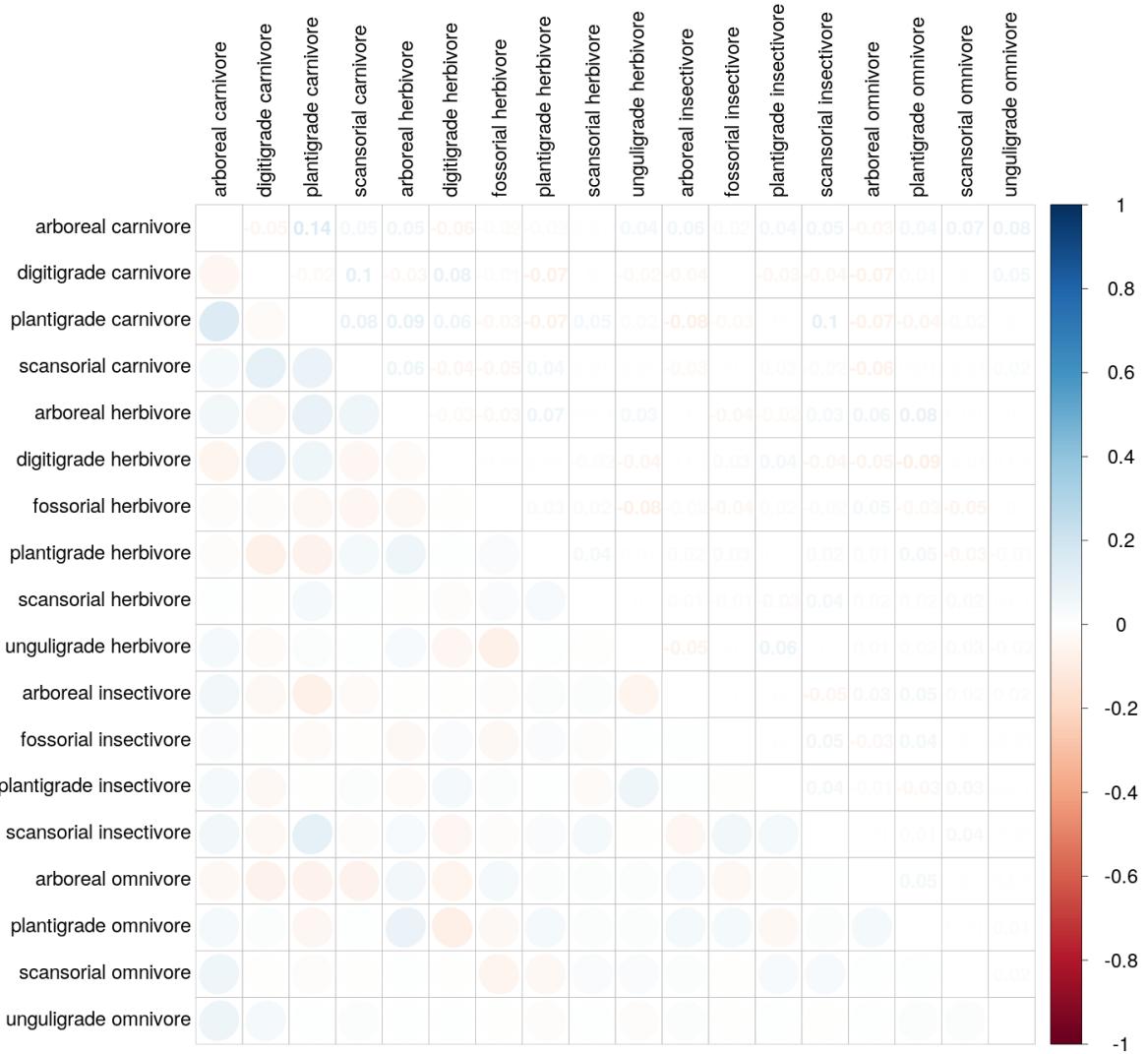


Figure 11: Posterior mean estimates of the correlations in origination probability between the mammal ecotypes. The lower triangle of the matrix is populated with ellipses corresponding to the level of correlation between the two ecotypes, while the upper triangle of the matrix corresponds to the mean estimated correlation between ecotypes. Darker values correspond to a greater magnitude of correlation with blue values corresponding to a positive correlation and red values a negative correlation.

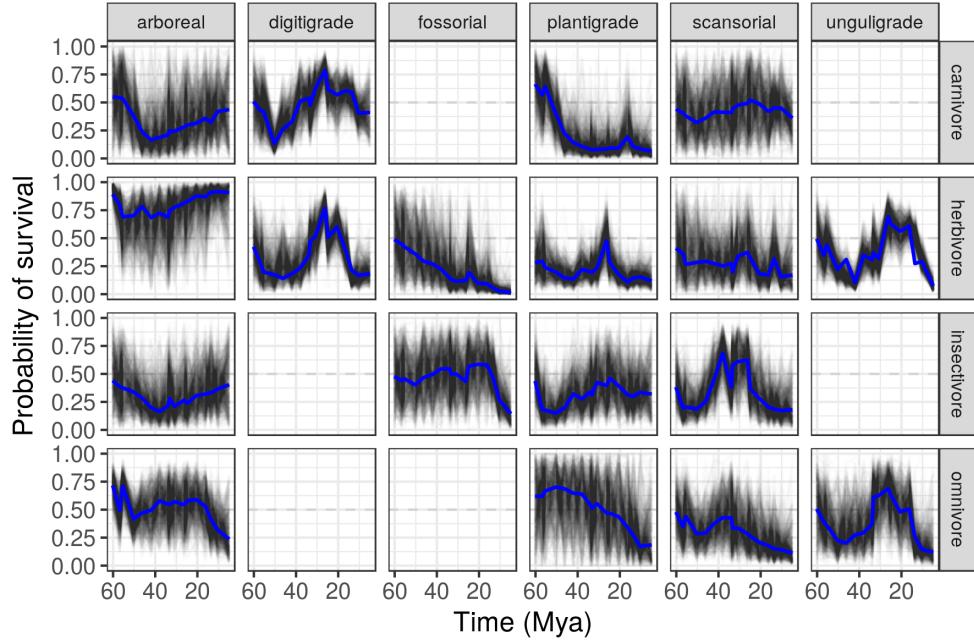


Figure 12: Probability of a mammal ecotype survival probabilities at each time point as estimated from the birth-death model. Each panel depicts 100 random samples from the model’s posterior. The columns are by locomotor category and rows by dietary category; their intersections are the observed and analyzed ecotypes. Panels with no lines are ecotypes not observed in the dataset.

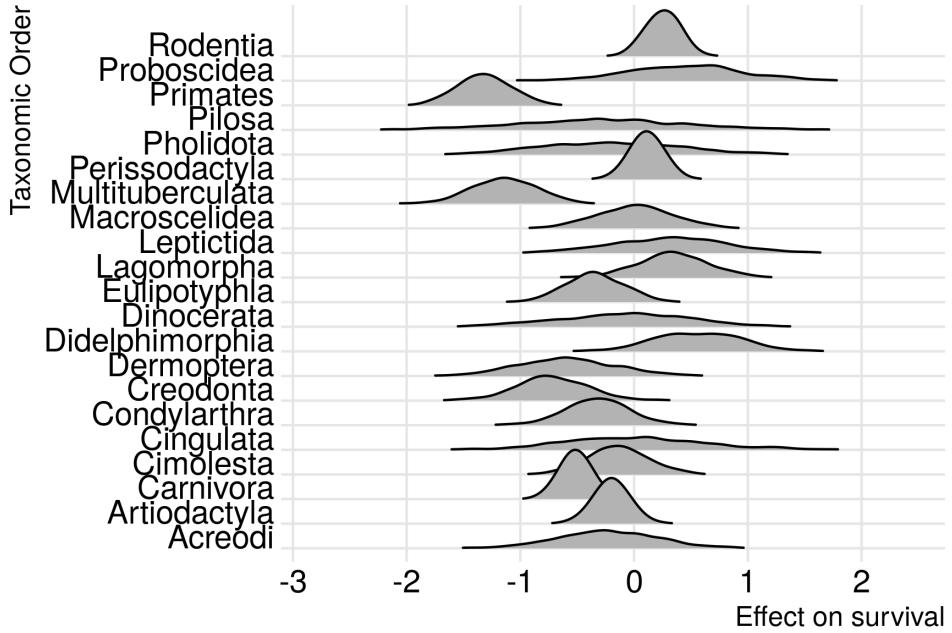


Figure 13: Differences in log-odds of survival based on mammal orders. Positive values correspond to greater log-odds of survival than average, while negative values correspond to lower log-odds of survival than average.

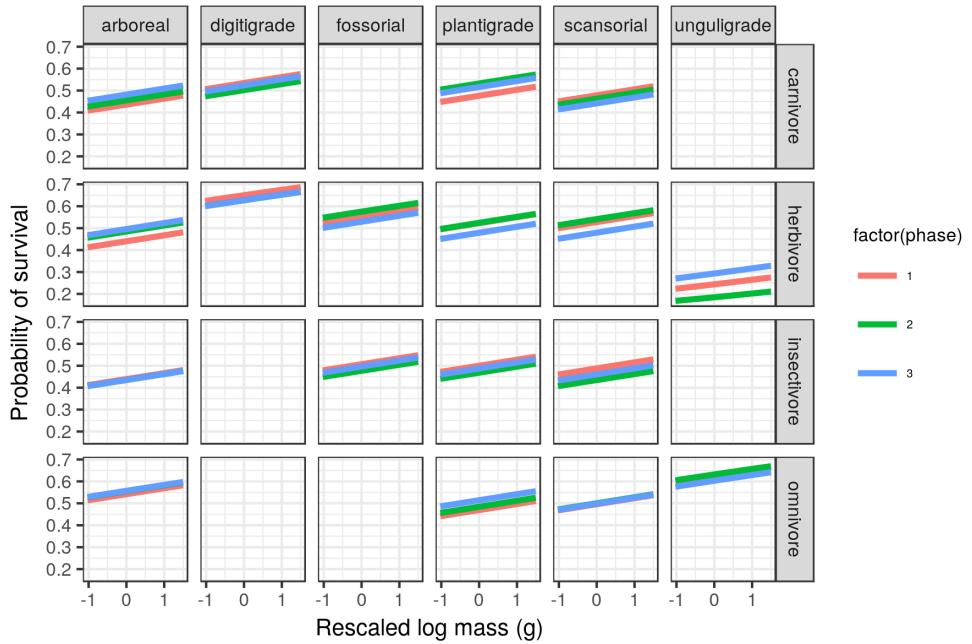


Figure 14: Mean estimate of the effect of species mass on the probability of a species survival for each of the three plant phases. The effect of mass is considered constant over time and that the only aspect of the model that changes with plant phase is the intercept of the relationship between mass and survival. The three plant phases are indicated by the color of the line. Mass has been log-transformed, centered, and rescaled; this means that a mass of 0 corresponds to the mean of log-mass of all observed species and that mass is in standard deviation units. For clarity, only the mean estimates of the effects of mass and plant plant are plotted.

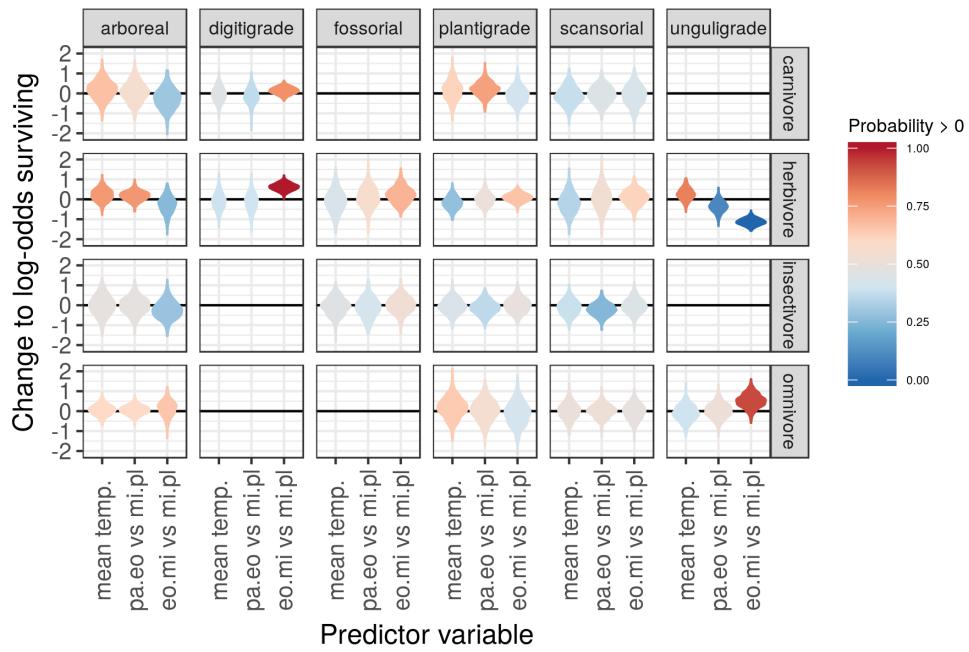


Figure 15: Estimated effects of the group-level covariates describing environmental context on log-odds of species survival. These estimates are from the birth-death model. What is plotted is a violin of the distribution of 1000 samples from the approximate posterior. The effect of plant phase graphed here is calculated as Phase 1 =  $\gamma_{phase\ 1}$ , Phase 2 =  $\gamma_{phase\ 1} + \gamma_{phase\ 2}$ , and so on.

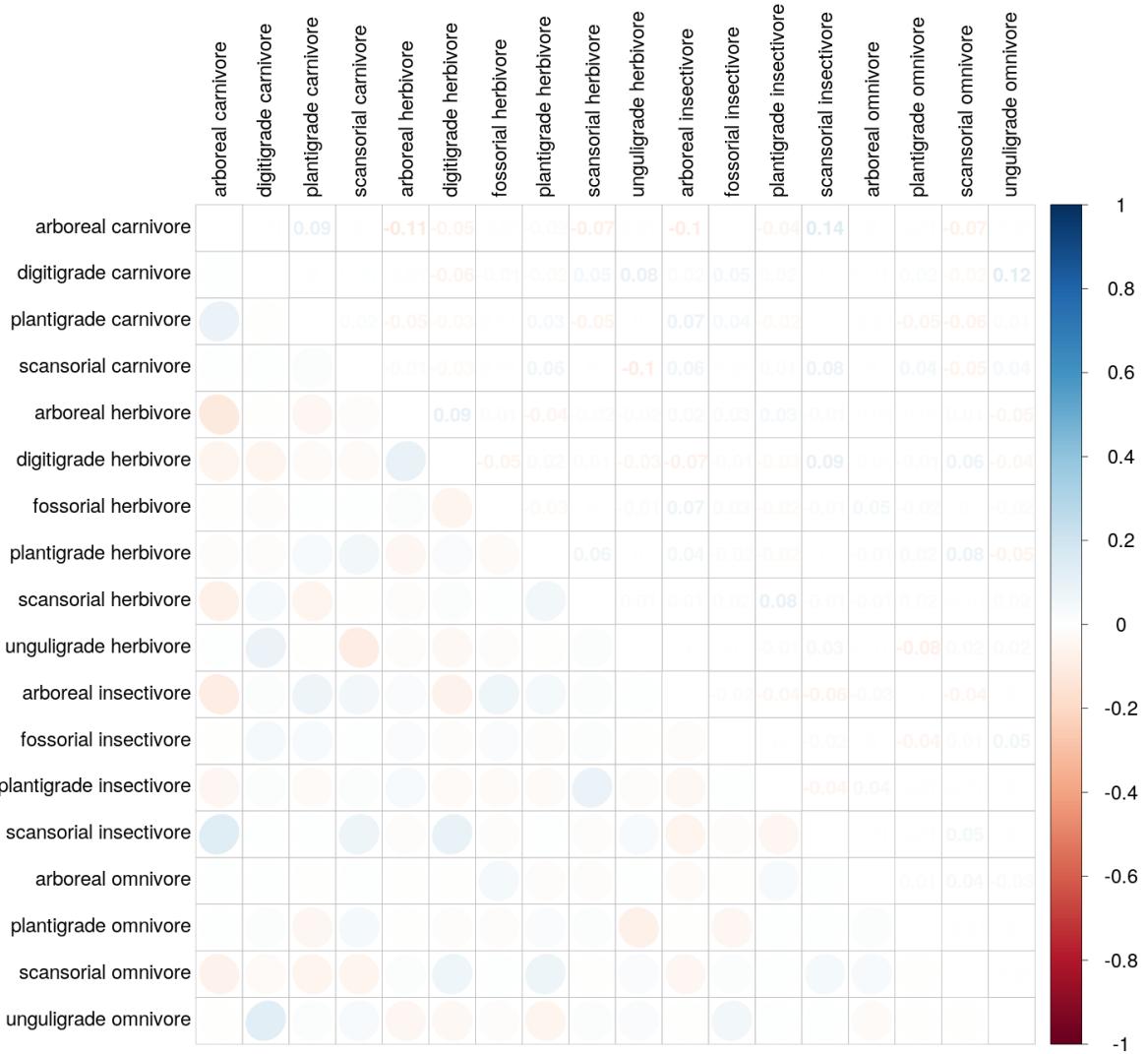


Figure 16: Posterior mean estimates of the correlations in survival probability between the mammal ecotypes. The lower triangle of the matrix is populated with ellipses corresponding to the level of correlation between the two ecotypes, while the upper triangle of the matrix corresponds to the mean estimated correlation between ecotypes. Darker values correspond to a greater magnitude of correlation with blue values corresponding to a positive correlation and red values a negative correlation.

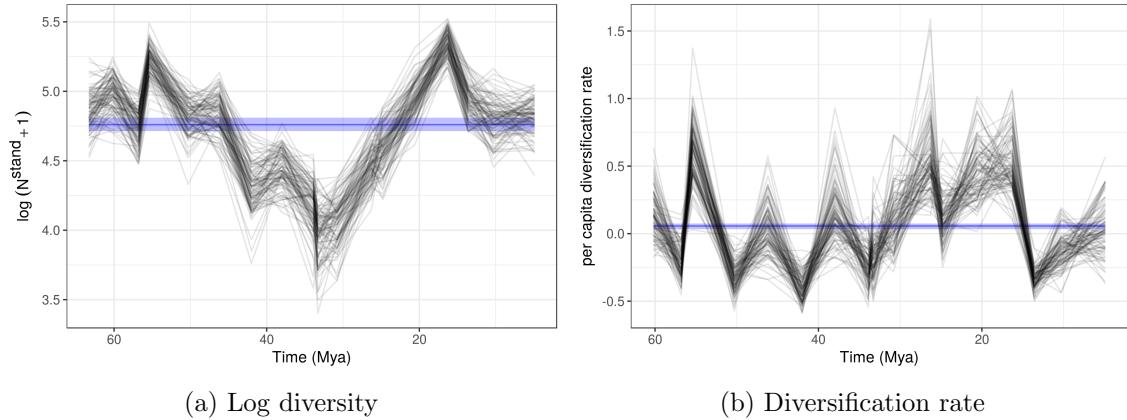


Figure 17: Posterior estimates of the time series of Cenozoic North American mammal diversity and its characteristic macroevolutionary rates; all estimates are from the birth-death model and 100 posterior draws are plotted to indicate the uncertainty in these estimates. The blue horizontal strip corresponds to the 80% credible interval of estimated mean standing diversity, diversification rate, origination rate, and extinction rate respectively; the median estimate is also indicated. What is also plotted is the The dramatic differences between diversity estimates at the first and second time points and the penultimate and last time points in this series are caused by well known edge effects in discrete-time birth-death models caused by  $p_{-,t=1}$  and  $p_{-,t=T}$  being partially unidentifiable (Royle and Dorazio, 2008); the hierarchical modeling strategy used here helps mitigate these effects but they are still present (Gelman et al., 2013; Royle and Dorazio, 2008). Diversification rate is in units of species gained per species present per time unit (2 My), origination rate is in units of species originating per species present per time unit, and extinction rate is in units of species becoming extinct per species present per time unit.

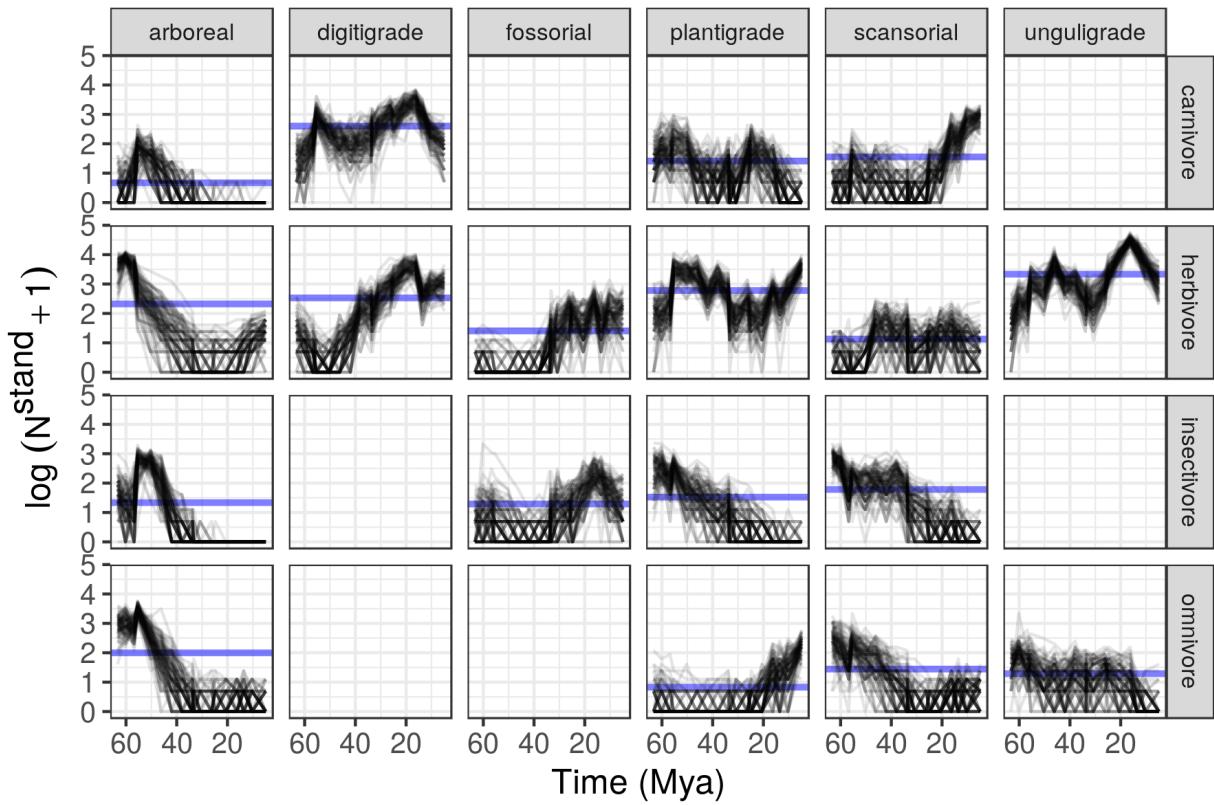


Figure 18: Posterior of standing log-diversity of North American mammals by ecotype for the Cenozoic as estimated from the birth-death model; 100 posterior draws are plotted to indicate the uncertainty in these estimates and what is technically plotted is log of diversity plus 1.

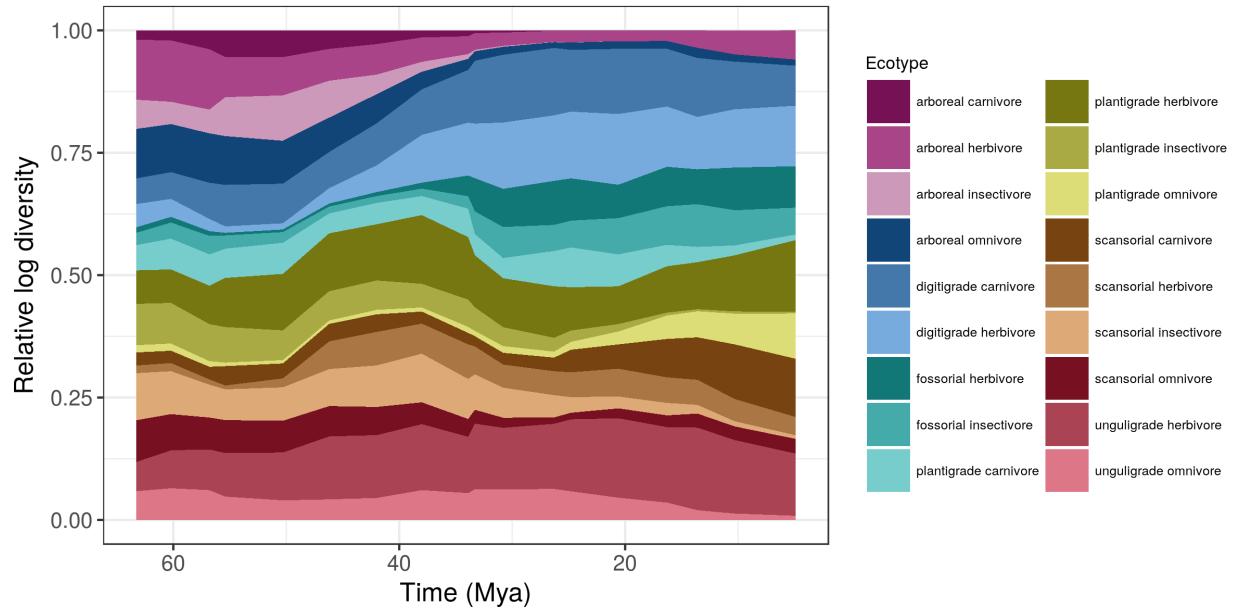


Figure 19: Mean posterior estimate of relative log standing diversity of 18 North American mammal ecotypes for the Cenozoic. These estimates are calculated from 100 posterior estimates of the true occurrence matrix  $z$  as estimated from the birth-death model.