

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.

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 processes such as resource competition and predator-prey relationships. The constituent species of these communities are drawn from a regional species pool, the set of species that are present in any 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 species' traits (Cottenie, 2005; Elith and Leathwick, 2009; Harrison and Cornell, 2008; Loeuille and Leibold, 2008; Shipley et al., 2006; Urban et al., 2008). The gain or loss of regional diversity is the result of the macroevolutionary and macroecological processes of speciation, extinction, migration, and extirpation which, in turn, shape the downstream macroecological dynamics of the regional species

28 pool and its constituent local communities (Harrison and Cornell, 2008; Mittelbach and Schemske,
29 2015; Urban et al., 2008). The distribution of species in the regional species pool then represents
30 the expected distribution of local communities under a purely diffusive process of community
assembly such as in the case of the neutral theory of biodiversity CITATION.

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

40 A key question when comparing communities or regional species pools based on their functional
composition is whether specific functional groups are enriched or depleted and why; what are the
42 processes that led to a species pool having the functional composition it does (Blois and Hadly,
2009; Brown and Maurer, 1989; Jernvall and Fortelius, 2004; McGill et al., 2006; Smith et al., 2008;
44 Weber et al., 2017; ?) Comparisons of contemporaneous regional species pools can only determine
if a functional group is enriched or depleted in one species pool relative to the other species pools
46 CITATION. These types of comparison can not take into account if a functional group is enriched
or depleted relative to its diversity over time (Blois and Hadly, 2009). While a species pool may be
48 depleted of a functional group relative to other contemporaneous species pools, that same
functional group may be actually be enriched in that species pool relative to its historical diversity.

50 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 present day ecosystems,
52 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
54 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

56 to their long term average diversity in the species pool is particularly useful in conservation
settings; species in depleted groups are potentially more at risk of extinction than species in
58 enriched groups, even if those enriched groups are relatively rare when compared to the functional
composition of other contemporaneous species pools.

60 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
62 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
64 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
66 that functional traits like the dietary/trophic category of species are easy to estimate (Eronen et al.,
2010; Polly et al., 2011, 2015).

68 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
70 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
72 species traits and environmental factors on these processes.

Background

74 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;
76 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,
78 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
80 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

82 Wilhelm, 1993; Jernvall and Fortelius, 2004; Pires et al., 2015), within/between clade comparisons
83 (Cantalapiedra et al., 2017; Fraser et al., 2015; Quental and Marshall, 2013; Silvestro et al., 2015;
84 Slater, 2015), and estimating the impact of environmental process on total diversity (Alroy et al.,
85 2000; Badgley and Finarelli, 2013; Badgley et al., 2017; Blois and Hadly, 2009; Eronen et al., 2015;
86 Fraser et al., 2015; Janis, 1993; Janis and Wilhelm, 1993). Each of these studies provide a limited
87 perspective on the macroevolutionary and macroecological processes shaping diversity and
88 diversification. Integration across perspectives is necessary for producing a holistic and internally
89 consistent picture of how the North American mammal species pool has changed through time. One
90 of the goals of this study is to present a framework for approaching hypotheses about diversity and
91 diversification through multiple lenses simultaneously through a joint model so that any inferences
92 are better constrained and the relative importance of species' ecological function, taxonomic
93 affinities, and environmental context may be better elucidated.

94 The narrative of the diversification of North American mammals over the Cenozoic is one of
95 gradual change. Instead of being concentrated at specific time intervals, species turnover has been
96 found to be distributed through time (Alroy, 1996, 2009; Alroy et al., 2000; Eronen et al., 2015;
97 Janis, 1993). The basic expectation given this narrative is that turnover events or periods of rapid
98 diversification or depletion should not occur simultaneously for all functional groups under study.
99 Additionally, changes to mammal diversification seem to be primarily driven by changes to
100 origination rate and not to extinction (Alroy, 1996, 2009; Alroy et al., 2000).

The climate history of the Cenozoic can be broadly described as a gradual cooling trend, the
102 expansion of grasslands, and the formation of polar ice-caps during the Neogene (Cramer et al.,
103 2011; Zachos et al., 2008, 2001). There are of course exceptions to this pattern such as the
104 Paleocene-Eocene thermal maximum, the Early Eocene Climatic Optimum, cooling at the
105 Eocene/Oligocene boundary, and the mid-Miocene climatic optimum (Zachos et al., 2008, 2001). In
106 terms of the North American biotic environment, the Cenozoic is additionally characterized by
107 major transition from having closed, partially forested biomes being common in the Paleogene to
108 the landscape being dominated by savannah and grasslands biomes by the Neogene (Blois and
Hadly, 2009; Janis, 1993; Janis et al., 2000; Strömberg, 2005).

¹¹⁰ PETM and EECO have been hypothesized to drive major changes in mammalian diversity (Clyde
and Gingerich, 1998; ?). At local scales, the PETM is hypothesized to be causally related to an
¹¹² increase diversity at the beginning of the Eocene. In contrast, the cooling at the end of the EECO
is hypothesized to be a direct cause of a decrease in functional diversity and evenness. PETM:
¹¹⁴ Taxonomic groups of importance are creodonts, primates, artiodactyls perissodactyls. peak in
browsing herbivores and terrestrial taxa. drop in insectivores. phenacodonids and plesiadapids
¹¹⁶ replaced by terrestrial herbivores/frugivores. EECO: beginning - \downarrow increase in rodents, euprimates,
pholidotans. high turnover. middle - \downarrow euprimates, hypercarnivores, artiodactyla, perrisodactyla. end
¹¹⁸ - \downarrow loss of diversity, decrease in functional evenness. Both of these hypotheses predict that
temperature is the causal mechanism behind diversification by facilitating migration and the
¹²⁰ expansion of opportunity. Plants don't explain the pattern well enough.

The Eocene-Oligocene cooling event marks the transition from the Paleogene to the Neogene.
¹²² Additionally, this transition marks the approximate start of Antarctic ice sheets, which were
previously absent (Zachos et al., 2008). This transition is hypothesized to be associated with
¹²⁴ extinction of many ungulate taxa (Janis, 2008). The mechanisms which drive this pattern are
theorized to be some combination of tectonic activity driving environmental change such as the
¹²⁶ 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., 2017; Blois and Hadly,
¹²⁸ 2009; Eronen et al., 2015; Janis, 2008).

In addition to the in the expansion of grasslands, the North American landscape changed
¹³⁰ dramatically during the Cenozoic due mountain uplift and other tectonic actives in Western North
America (Badgley and Finarelli, 2013; Badgley et al., 2017; Blois and Hadly, 2009; Eronen et al.,
¹³² 2015; Janis, 2008; ?). This type of geological activity affects both local climates as well as
continental weather patterns while also mobilizing increased grit into the environment, something
¹³⁴ which may be responsible for increasing trend of hypsodonty (high crowned teeth) among ungulate
and rodent herbivores (Damuth and Janis, 2011; Janis, 1993; Jardine et al., 2012; Jernvall and
¹³⁶ Fortelius, 2002). Tectonic processes and mountain uplift in particular have been implicated in the
increasing diversification at the MMCO (Badgley and Finarelli, 2013; Finarelli and Badgley, 2010;

¹³⁸ Janis, 2008; ?; ?) and the differences in mammal diversity and diversification between North America and Eurasia CITATIONS. Given these observations, I hypothesize that fossorial functional
¹⁴⁰ groups and unguligrade and digitigrade herbivores would increase in standing and/or relative diversity following the MMCO. Which and how the other mammal functional groups change at or
¹⁴² following the MMCO events is unknown.

The effect of (global) temperature on mammal diversity and its accompanying diversification process
¹⁴⁴ has been the focus of considerable research with a slight consensus favoring mammal diversification being more biologically-mediated than climate-mediated when considering the entire Cenozoic
¹⁴⁶ (Alroy et al., 2000; Clyde and Gingerich, 1998; Figueirido et al., 2012). However, differences in temporal and geographic scale seem to underly the contrast between these two perspectives. For
¹⁴⁸ example when the mammal fossil record analyzed at small temporal and geographic scales a correlation between diversity and climate is observable (Clyde and Gingerich, 1998; ?). However,
¹⁵⁰ when the record is analyzed at the scale of the continent and most of the Cenozoic this correlation disappears (Alroy et al., 2000). This result, however, does not go against the idea that there may be
¹⁵² short periods of correlation between diversity and climate and that this relationship can change or even reverse direction over time; this type result means that there is no single direction or longterm
¹⁵⁴ correlation between diversity and climate (Figueirido et al., 2012). In the case of a fluctuating correlation between diversity and climate it is hard to make the argument for an actual causal link
¹⁵⁶ between the two without modeling the underlying ecological differences between species; after all, species respond differently based on their individual ecologies (Blois and Hadly, 2009).

¹⁵⁸ 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
¹⁶⁰ 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
¹⁶² species is constant and high for the entire Cenozoic or the Paleogene and Neogene represent different regimes and extinction risk increased in the Neogene, thus driving up the Cenozoic average
¹⁶⁴ extinction risk. These two possible explanations have clear and testable predictions with respect to the diversity history of arboreal taxa: 1) if arboreal taxa always have an elevated extinction risk

¹⁶⁶ when compared to other taxa, then the diversity history of arboreal taxa is expected to be constant
with time, albeit possibly at low diversity; and 2) if the Paleogene and Neogene represent difference
¹⁶⁸ selective regimes with the former being associated with lower extinction risk than the latter, then
the diversity history of arboreal taxa are expected to be present in the Paleogene but depleted or
¹⁷⁰ 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
¹⁷² the diversification processes, specifically extinction (Liow et al., 2008, 2009; Smits, 2015; Tomiya,
2013). Species body size is frequently framed as an important biological descriptor because of its
¹⁷⁴ correlation with other important and relevant ecological traits such as metabolic rate and home
range size (Brown, 1995). It is also relatively easy to estimate for extinct species using proxy
¹⁷⁶ measures and regression equations, as was done in this study (see below). However, body size is
normally analyzed without simultaneous reference to other relevant species traits (Huang et al.,
¹⁷⁸ 2017; Liow et al., 2008; Raia et al., 2012; Smith et al., 2004), but see (Smits, 2015); this combined
with the high amount of correlation between life history traits and body size limits process-based
¹⁸⁰ inference, because the actual causal mechanisms underlying an observed pattern are obscured or
missing.

¹⁸² Foreground

The fourth-corner problem is conceptual and statistical framework to explaining the patterns of
¹⁸⁴ either species abundance or presence/absence in a community as a product of species traits,
environmental factors, and the interaction between traits and environment (Brown et al., 2014;
¹⁸⁶ Jamil et al., 2013; Pollock et al., 2012; Warton et al., 2015); effectively uniting climate-based species
distribution modeling (SDMs) with trait-based community assembly models (CATS, MaxEnt). The
¹⁸⁸ fourth-corner problem is normally phrased in modern ecological studies as understanding how traits
and environment interact to predict the occurrence of species at localities distributed across a
¹⁹⁰ region (Jamil et al., 2013; Pollock et al., 2012).

This conceptual framework can be extended to include time when considering occurrence as a

192 three-dimensional: species at localities in space over time. However, the temporal limitations of
193 modern ecological studies limit studying species over their entire durations, where speciation and
194 extinction govern the occurrence of species. By considering the patterns of fossil occurrences in the
195 geological record the macroevolutionary processes governing species' (macro)ecology can be better
196 understood. One limitation of the fossil record, however, is a lack of spatial resolution for most
197 taxonomic groups and periods of time. As such, paleontological data "looks" at a different side of
198 the three-dimensional occurrence matrix of the extended fourth-corner problem than modern
199 ecological data.

200 In this study, I model how mammal functional groups respond to environmental change by
201 estimating differences in origination and survival of species over time and how environmental
202 context can affect these macroevolutionary processes (Fig. 1). Additionally, I also consider the
203 incompleteness of the fossil record and the static effect of other species descriptors not related to
204 functional group on origination and survival.

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

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

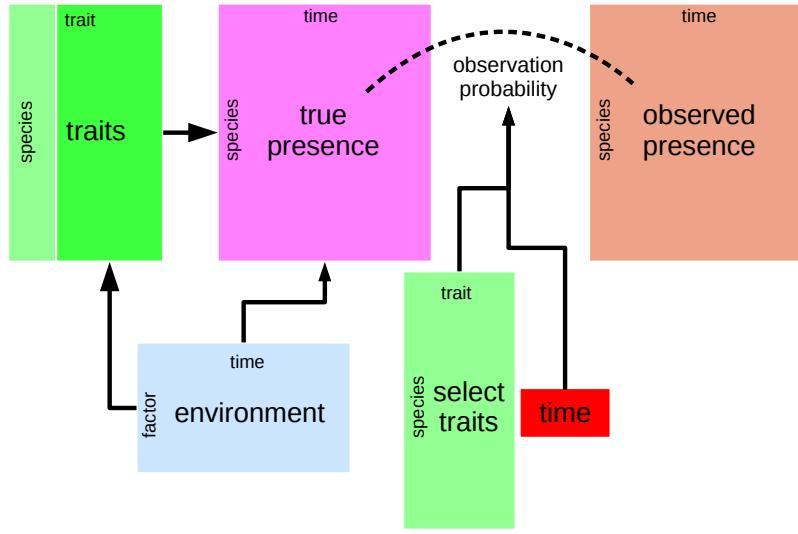


Figure 1: Conceptual diagram of the analysis at the center of this study. The observed presence matrix (orange) is the empirical presence/absence pattern for all species for all time points; this matrix is an incomplete observation of the “true” presence/absence pattern (purple). This observation process 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).

species ecology can mediate selective pressures due to its environmental context.

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

account the fundamental incompleteness of the fossil record.

230 Ultimately, the goals of this analysis are to understand when different functional groups
enriched or depleted in the North American mammal regional species pool and how these changes
232 in functional diversity are related to changes in species' environmental context. In the analysis
performed here, I consider multiple covariates which describe a species' macroecology and
234 environmental context. In order to analyze this complex, multi-level question and accompanying
highly-structured data set, I developed a hierachal Bayesian model combing the fourth-corner
236 modeling approach with a model of an observation-occurrence or observation-originatation-extinction
process.

238 Materials and Methods

Taxon occurrences and species-level information

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

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

254 Many species taxonomic assignments as present in the raw PBDB data were updated for accuracy
and consistency. Species present in the PBDB have some taxonomic information, including possible
256 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
258 family and order assignemnts as present in the Encyclopedia of life (<http://eol.org>) was
downloaded using the *taxize* package for R CITATION; 2) for species not present in the EoL or not
260 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
262 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
264 associated with this study.

Species functional group is defined as the combination of locomotor and diet categories; the goal is
266 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
268 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
270 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
272 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
274 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
276 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
278 observed ecotypes out of a possible 24.

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. Assignments are considered uniform within that taxonomic group unless there is a non-ground dwelling assignment for a species in the PBDB.

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.

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
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

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Table 2 – continued from previous page

Family	Stance
Cervidae	unguligrade
Cimolodontidae	scansorial
Coryphodontidae	plantigrade
Cricetidae	plantigrade
Cylindrodontidae	plantigrade
Cyriacotheriidae	plantigrade
Dichobunidae	unguligrade
Dinocerata	unguligrade
Dipodidae	digitigrade
Elephantidae	digitigrade
Entelodontidae	unguligrade
Eomyidae	plantigrade
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

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Table 2 – continued from previous page

Family	Stance
Hyaenodontidae	digitigrade
Hypertragulidae	unguligrade
Ischyromyidae	plantigrade
Jimomyidae	plantigrade
Lagomorpha	digitigrade
Leptictidae	plantigrade
Leptochoeridae	unguligrade
Leptomerycidae	unguligrade
Mammutidae	unguligrade
Megalonychidae	plantigrade
Megatheriidae	plantigrade
Mephitidae	plantigrade
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

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Table 2 – continued from previous page

Family	Stance
Oromerycidae	unguligrade
Oxyaenidae	digitigrade
Palaeomerycidae	unguligrade
Palaeoryctidae	plantigrade
Pampatheriidae	plantigrade
Pantolambdidae	plantigrade
Peritychidae	digitigrade
Perissodactyla	unguligrade
Phenacodontidae	unguligrade
Primates	plantigrade
Procyonidae	plantigrade
Proscalopidae	plantigrade
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

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Table 2 – continued from previous page

Family	Stance
Zapodidae	plantigrade

280 Estimates of species mass used in this study were sourced from multiple databases and papers,
especially those focusing on similar macroevolutionary or macroecological questions (Brook and
282 Bowman, 2004; Freudenthal and Martín-Suárez, 2013; McKenna, 2011; Raia et al., 2012; Smith
et al., 2004; Tomiya, 2013); this is similar to Smits (2015). When a species' mass was not available,
284 proxy measures were used to estimate their mass. For example, given a measurement of a mammal
tooth size, it is possible and routine to estimate its mass given some regression equation (Table 3).
286 The PBDB has one or more body part measures for many species. These were used as body size
proxies for many species, as was the case in Smits (2015). Mass was log-transformed and then
288 rescaled by first subtracting mean log-mass from all mass estimates, then dividing by two-times its
standard deviation; this insures that the magnitude of effects for both continuous and discrete
290 covariates are directly comparable (Gelman, 2008; Gelman and Hill, 2007).

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

All fossil occurrences from 64 to 2 million years ago (Mya) were binned into the 18 North American
294 Land Mammal Ages (NALMA) covered by this interval CITATION. The choice of binning by
NALMA reflects the belief that these represent distinct communities or periods of mammal
296 evolution, something that is central to this study. The NALMA units in this study are listed in
Table 4.

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)

298 Environmental and temporal covariates

The environmental covariates used in this study are collectively referred to as group-level covariates
 300 because they predict the response of a “group” of individual-level observations (i.e. species). These

302 covariates are defined for temporal bins as they predict the individual parts of each species

304 occurrence history. The group-level covariates in this study are an estimate of global temperature
 and the Cenozoic “plant phases” defined by Graham (2011).

306 Global temperature across most of the Cenozoic was calculated from Mg/Ca isotope record from
 deep sea carbonates (Cramer et al., 2011). Mg/Ca based temperature estimates are preferable to

308 the frequently used $\delta^{18}\text{O}$ temperature proxy (Alroy et al., 2000; Figueirido et al., 2012; Zachos

et al., 2008, 2001) because Mg/Ca estimates do not conflate temperature with ice sheet volume and
 310 depth/stratification changes (Cramer et al., 2011; Ezard et al., 2016). The former is particularly

important to this analysis as the current polar ice-caps appeared and grew during the second half of
 312 the Cenozoic. These properties make Mg/Ca based temperature estimates preferable for

macroevolutionary and macroecological studies (Ezard et al., 2016). Temperature was calculated as
 the mean of all respective estimates for each of the NALMA units. The distributions of temperature

Table 4: Listed in order from oldest to youngest NALMA.:

NALMA	Start Age (Mya)
Torrejonian	63.3
Tiffanian	60.2
Clarkforkian	56.8
Wasatchian	55.4
Bridgerian	50.3
Uintan	46.2
Duchesnean	42
Chadronian	38
Orellan	33.9
Whitneyan	33.3
Geringian	30.8
Monroecreekian	26.3
Harrisonian	24.8
Hemingfordian	20.6
Barstovian	16.3
Clarendonian	13.6
Hemphillian	10.3
Blancan	4.9

Table 5: 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

was then rescaled by subtracting its mean from all values and then dividing by twice its standard

314 deviation.

The second set of environmental factors included in this study are the Cenozoic plant phases

316 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

318 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

320 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

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

Table 6: 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 π and survival ϕ .

322 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
324 temporal boundaries of these plant phases, their durations, and abbreviations are defined in Table 5.

Modelling species occurrence

326 At the core of the model used in this study is hidden Markov process where the latent process has
an absorbing state; also referred to as a discrete-time birth-death model (Allen, 2011) or a
328 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
330 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
332 an extinct species changing states is 0 (Table 6); see below for extended parameter explanations
(Tables 7, 8, and 9).

334 Basic model

I will begin defining the model used in this study by focusing on the basic machinery of the hidden
336 Markov process at the model’s core. This aspect of the model is similar to the well-known
Jolly-Seber capture-mark-recapture model from ecology CITATION which has three characteristic
338 probabilities: probability p of observing a species given that it is present, probability π of a species
surviving from one time to another, and probability ϕ of a species first appearing (Royle and
340 Dorazio, 2008) (Table 7). In this formulation, the probability of a species becoming extinct is $1 - \pi$.

Table 7: 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
ϕ	$N \times T$	probability of species originating from time t to $t + 1$ if it is not present
π	$N \times (T - 1)$	probability of species surviving at time t , given that it is already originated

The inclusion of species and temporal information means that all three of these probabilities are
 342 defined for every species at every time point (Table 7); how this is accomplished is described below.
 Importantly, only origination can occur during the first time step as nothing is already present to
 344 survive. This basic model is expressed as

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

The parameters in Equation 1 are described in Table 7; this formulation is identical to that
 346 described in Royle and Dorazio (2008). The product term that appears when calculating values of z
 not at $t = 1$ ensures that once a species goes extinct it does not re-originate.

348 Expanding on the basics

Expanding on the basic model involves modeling the observation, origination and survival
 350 probability as independent multi-level logistic regressions. Origination and survival probabilities
 share the same covariates and model structure, while observation probability is modeled as a
 352 function of a smaller selection of covariates.

The probability of observing a species given that it is present p is modeled as a logistic regression
 354 with a time-varying intercept with an additional varying-intercept for species’ functional group,

Table 8: Parameters for the first expansions

Parameter	dimensions	explanation
u	T	time-varying intercept
e	J	effect of functional group on observation
f^ϕ	$J \times T - 1$	intercept of log-odds ϕ , varies by time and functional group
f^π	$J \times T$	intercept of log-odds π , varies by time and functional group
o^ϕ	K	effect of species' order on log-odds of ϕ
o^π	K	effect of species' order on log-odds of π
β^ϕ	1	effect of species' mass on log-odds of ϕ
β^π	1	effect of species' mass on log-odds of π
m	N	species' mass estimates

respectively. The effect of species mass was also included through a regression slope term β^p .

- 356 The log-odds of a species originating (logit π) or surviving (logit ϕ) are modeled independently but
take the same form: a regression with an intercept that varies by both time and functional group,
358 an additional taxonomic order varying-intercept term, and the slope term for species mass.
Importantly, the time and functional group varying-intercept is itself modeled such that the
360 intercept for each functional group is a time series predicted by the group-level covariates
(described below).
- 362 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 group-level covariates are included in expanded model and the final choice of priors are
364 described below.

Complete model

- ³⁶⁶ The expanded model (Eq. 2) is still incomplete as it is missing the group-level covariates such as
global temperature, and it is missing all of the necessary final generative priors.
- ³⁶⁸ Here I describe how the effects of mammal functional group on origination and survival are
modeled. f^ϕ and f^π are modeled as the responses from a multivariate normal distribution, where
³⁷⁰ each functional group is modeled by a time-series regression. Temporal autocorrelation is modeled
as a random-walk prior for the varying intercept of the group-level regressions. The effects of the
³⁷² group-level covariates on origination and survival are included for each functional group through
regression coefficients. The expansion to include these group-level regression is described in
³⁷⁴ Equation 3, the parameters of which are described in Table 9.

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

- In hierarchical models like the one described here (Eq. 2, 3) it can be hard to distinguish between
³⁷⁶ the likelihood and prior as data and structure can enter the model through many different
parameters CITATION. For example, in Equation 2 the model of z can be considered a prior and
³⁷⁸ statements in Equation 3 can be considered priors for the parameters which predict ϕ and π . The
remaining priors necessary to this model, however, are not based on parameter expansion but are
³⁸⁰ prior estimates for the remaining unmodeled parameters and are sampling statements where no new

Table 9: 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
μ^ϕ	$J \times T$	time-series of the mean log-odds of ϕ for each functional group
μ^π	$J \times T$	time-series of the mean log-odds of π for each functional group
Σ^ϕ	$J \times J$	covariance matrix between functional groups for ϕ
Σ^π	$J \times J$	covariance matrix between functional groups for ϕ
α^ϕ	$J \times T$	time-varying intercept of μ^ϕ
α^π	$J \times T$	time-varying intercept of μ^π
σ^ϕ	J	scale of random-walk prior for α^ϕ
σ^π	J	scale of random-walk prior for α^π
γ^ϕ	D	group-level regression coefficients for μ^ϕ
γ^π	D	group-level regression coefficients for μ^π
U	T	matrix of group-level covariates

data enters the model. These prior choices are expressed in Equation 4 and are explained below.

- 382 For the regression coefficients, such as β^ϕ and γ^ϕ , the chosen priors are considered weakly
- informative as they concentrate most of the probability density between -2 and 2. Similarly, the
- 384 scale parameters, such as τ^ϕ and σ^ϕ , are also given weakly informative half-Normal priors which
- concentrate most of the probability density between 0 and -2. The covariance matrices, such as Σ^ϕ ,
- 386 are decomposed into a vector of scale terms (e.g. τ^ϕ) and correlation matrices (e.g. Ω^ϕ) which were
- then given weakly informative priors. This approach and choice of LKJ priors for the correlation
- 388 matrices follows the Stan User Manual CITATION. For parameter vectors which are presented with

only a single prior (e.g. β^ϕ), that prior statement is for each of the elements of that vector.

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

- 390 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
392 model posterior inference is possible.

Posterior inference and model adequacy

394 A computer program that implements joint posterior inference the model described above (Eqs. 2,
3, and 4) was written in the probabilistic programming language Stan (Stan Development Team,
396 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.
398 In order to infer the values of the matrix of latent discrete parameters z (Tables 7) the log posterior
probabilities of all possible states of the unknown values of z were calculated and summed (i.e.
400 marginalized) (Stan Development Team, 2016).

Species durations at minimum range through from a species first appearance to their last
402 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
404 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
406 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
408 range-through and then estimating the (log) probability of all possible range extension due to
incomplete sampling.

410 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
412 inference is computationally slow. Instead, an approximate Bayesian approach was used: variational
inference. A recently developed automatic variational inference algorithm called “automatic
414 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
416 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
418 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.

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

Of additional concern for posterior inference is the partial identifiability of observation parameters
 422 $p_{t=1}$ 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
 424 “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
 426 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
 428 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
 430 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 θ and origination ϕ at $t = 1$ and estimates of θ , ϕ

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

Finally, after obtaining approximate estimation of the model posterior using ADVI, model
436 adequacy and quality of fit were assessed using a posterior predictive check (Gelman et al., 2013).
437 By simulating 100 theoretical data sets from the posterior estimates of the model parameters and
438 the observed covariate information the congruence between predictions made by the model and the
439 observed empirical data can be assessed. These datasets are simulated by starting with the
440 observed states of the presence-absence matrix at $t = 1$; from there, the time series roll forward as
441 stochastic processes with covariate information given from the empirical observations. Importantly,
442 this is fundamentally different from observing the posterior estimates of the “true”
443 presence-absence matrix z . The posterior predictive check used in this study is to compare the
444 observed average number of observations per species to a distribution of simulated averages; if the
445 empirically observed value sits in the middle of the distribution then the model can be considered
446 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
448 posterior predictive checks because parameter estimates do not reflect the true posterior
449 distribution and are instead just an approximation (Gelman et al., 2013). Because of this, posterior
450 predictive estimates are themselves only approximate checks of model adequacy. The posterior
451 predictive check that is used in this study focuses on mean occurrence and not to any scale
452 parameters that might be most affected by the ADVI assumptions.

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

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

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

- ⁴⁶⁰ Total regional standing diversity can also be partitioned into the standing diversity of each of the functional groups.

⁴⁶² Results

Posterior parameter estimates

- ⁴⁶⁴ The model used here in this study has an approximately adequate fit to the data based on the results of the posterior predictive check (Fig. 3). Simulated datasets as estimated from the models' ⁴⁶⁶ posterior appears similar in terms of average number of occurrences per species to the observed number of occurrences in the empirical mammal dataset.

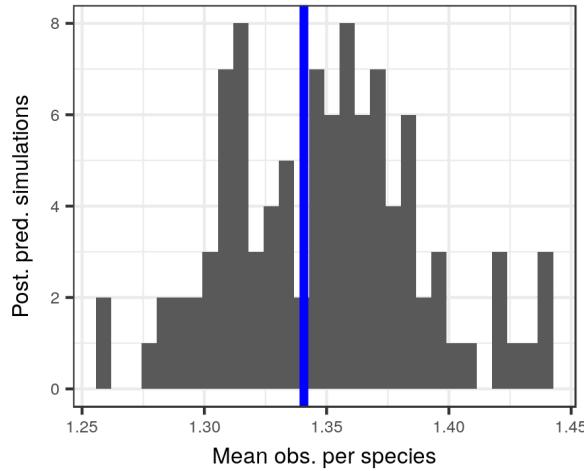


Figure 3: Comparison of the average observed number of occurrences per species (blue line) to the average number of occurrences from 100 posterior predictive datasets simulated from draws from the posterior parameter estimates from the model used in this study. The model is considered to have adequate fit to this aspect of the data if the observed value of the test statistic is approximately centered in the simulated distribution of test statistic values.

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

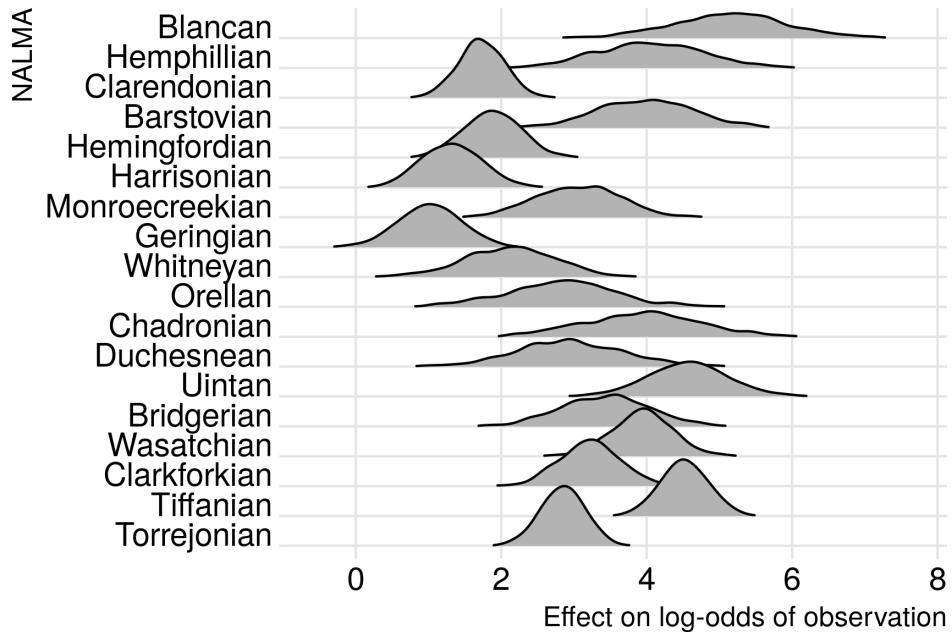


Figure 4: Ridgeline density plots of the estimates for the log-odds of observation from the time-varying intercept term. Each of the named time units are North American land-mammal ages. The oldest land-mammal age is at the bottom of the stack and the youngest is at the top. Higher values correspond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

474 In comparison to temporal variation, there is little variance in the effect of functional group on the
 475 log-odds of observing a species that is present (Fig. 5). The only functional group with substantially
 476 less than expected log-odds of observation is scansorial insectivores, indicating that the fossil record
 477 of this group is the least complete of all the functional groups studied. A few functional groups have
 478 marginally better than expected log-odds of observation, the other insectivorous functional groups
 have marginally greater than average log-odds of observation; this is also the case for plantigrade
 479 omnivores. These results indicate that the observation histories of these functional groups are

expected to be relatively more complete than most other functional groups. However, it is
 482 important to note that for many functional groups, their estimated log-odds of observation are poorly constrained with great uncertainty indicating little structure in how observation probability varies by functional groups (Fig. 5).

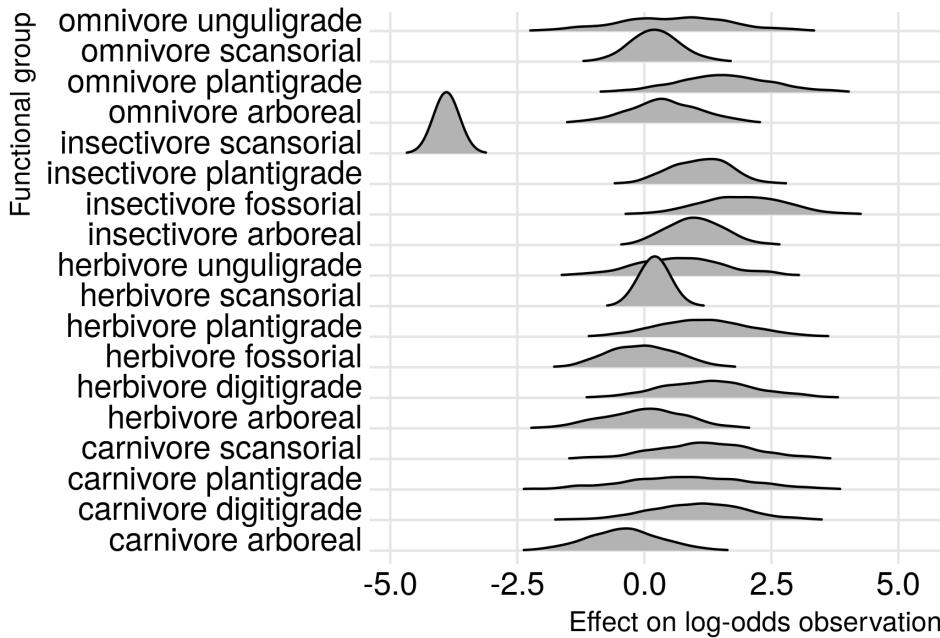


Figure 5: Ridgeline density plots of the estimated effects of species' functional group on log-odds of observing that species given that it is present. Each of the rows correspond to a different functional group as indicated by the dietary and locomotor category combination. Positive values correspond to greater than average log-odds of observation, while negative values indicate lower than average log-odds of observation.

484

Species mass is found to have a possible positive effect on probability of observing a species that is
 486 present ($P(\beta^p 0) = 0.849$; 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.
 488 However, this estimate does not necessarily translate to substantial differences in the estimated probability of observation because observation probability is so high for most of the Cenozoic (Fig.
 490 4). In fact, it is only when observation probability is low that the effect of mass is easily observable. It is important to remember the effect of mass on observation was considered constant over time
 492 and that all differences in 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 small differences in actual probability.

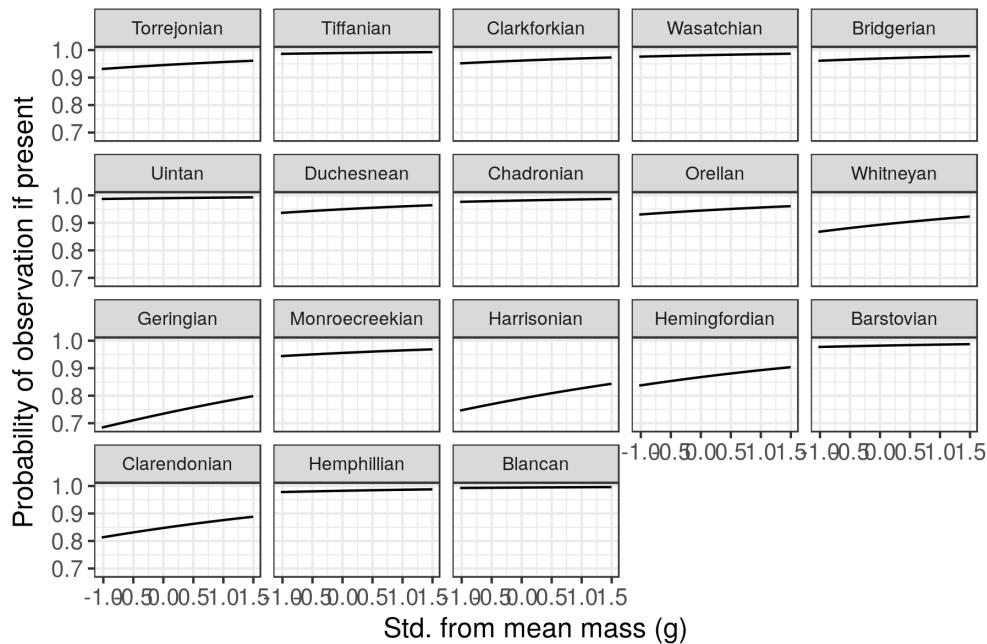


Figure 6: Estimates of the effect of species mass on probability of observing a species that is present (p). Mass has been log-transformed, centered, and rescaled; this means that a mass of 0 corresponds to the mean of log-mass of all observed species and that values are in units of standard deviations. The effect of mass on observation was considered constant over time, and variation in observation probability is due to the temporal effect (Fig. ??).

494

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

Most of the functional groups have peak origination probability at the present (Fig. 7); new species
506 in these functional groups are being added to the species pool through out the Cenozoic. In the case
of some functional groups, such as digitigrade carnivores and fossorial herbivores, this is the
508 culmination of those groups continued growth in the species pool. For other functional groups, such
as arboreal herbivores, this peak is a reversal from previously relatively low origination probability;
510 this indicates an expansion of these functional groups following a decline.

Five of the functional groups do not have peak origination probabilities at the end of the observed
512 period: arboreal carnivores, arboreal insectivores, plantigrade insectivores, scansorial insectivores,
and unguligrade omnivores. All the arboreal functional groups reach peak origination probability in
514 the Paleogene, after which mean origination probabilities approach and remain at 0.50, reflecting
the loss of these functional groups from the species pool as origination probability never again
516 increases. Additionally, the uncertainty surrounding in the estimates of origination probability is
very large, especially in the Neogene. Large uncertainty in probabilities can reflect complete
518 separation which results from that functional group leaving the species pool and therefore it's
absence is without ambiguity CITATION. The patterns evinced by the other functional groups have
520 similar properties but reach peak origination probability early in the Neogene. Of note is that
origination probability of scansorial insectivores has effectively two peaks, once in the late
522 Paleogene and again in the early Neogene. Additionally, as will be discussed later in the context of
standing diversity, all five of these functional groups decrease in diversity through the Cenozoic.

524 Origination probability varies greatly amongst mammal orders (Fig. 8). These estimates reflect
differences origination probability as well as the relative rarity of that order in the fossil record; if
526 there are few members of that order and they are distributed through time then they would have
an inherently lower probability of origination. Orders with greater than average log-odds of
528 origination include Multituberculata, Dinocerata, Didelphimorphia, Creodonta, Condylarthra,
Cimolesta, and Acreodi; orders that are considered major components of the Paleogene fossil record.
530 Orders with lower than average log-odds of origination include Rodentia, Pilosa, Lagomorpha,
Eulipotyphla, Cingulata, Carnivora, and Artiodactyla; orders characterized by small body size or
532 primarily Neogene records. Additionally, the variance between orders is vary large ranging from -2.5

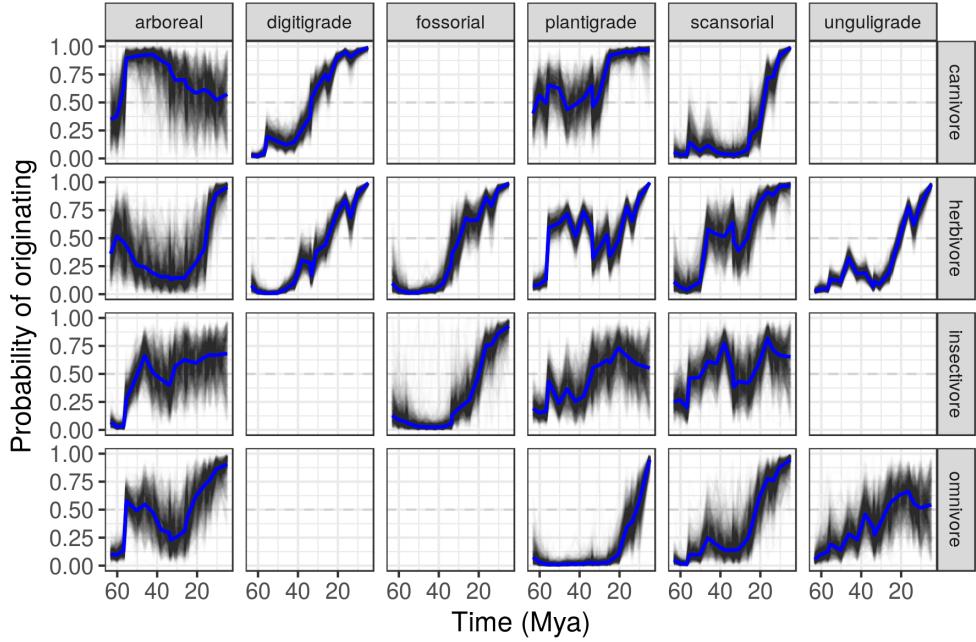


Figure 7: Probability of a species first originating based on functional group. Origination probability is graphed as 100 time-series drawn from the model’s posterior estimates. A greater density of the posterior estimates indicates increased certainty. The blue line is the mean origination probability as predicted by just the group-level predictors. The columns are by locomotor category and rows by dietary category.

to 2.5 log-odds of origination; this large of variance reflects how species within these orders have

534 very different patterns of origination independent from their origination based on functional ecology
(Fig. 7).

536 Species mass is estimated to have a negative relationship with origination probability ($P(\beta^\phi < 0) = 1$; Fig. 9) meaning that species with greater than average mass have a lower probability of

538 originating at any point in time than species with below average mass. This result is sensible given the left-skewed distribution of mammal species body sizes where large body sizes form the

540 right-hand tail. There are fewer large body-sized mammals which have ever originated than small body sized mammals. Interestingly, many of the orders with small body sizes (e.g. Rodentia,

542 Lagomorpha) have below average origination probabilities (Fig. 8); when this result is considered together with the effect of mass on origination these effects could be counteracting each other.

544 These results continue to add to the understanding of the heterogeneity and nuance associated with

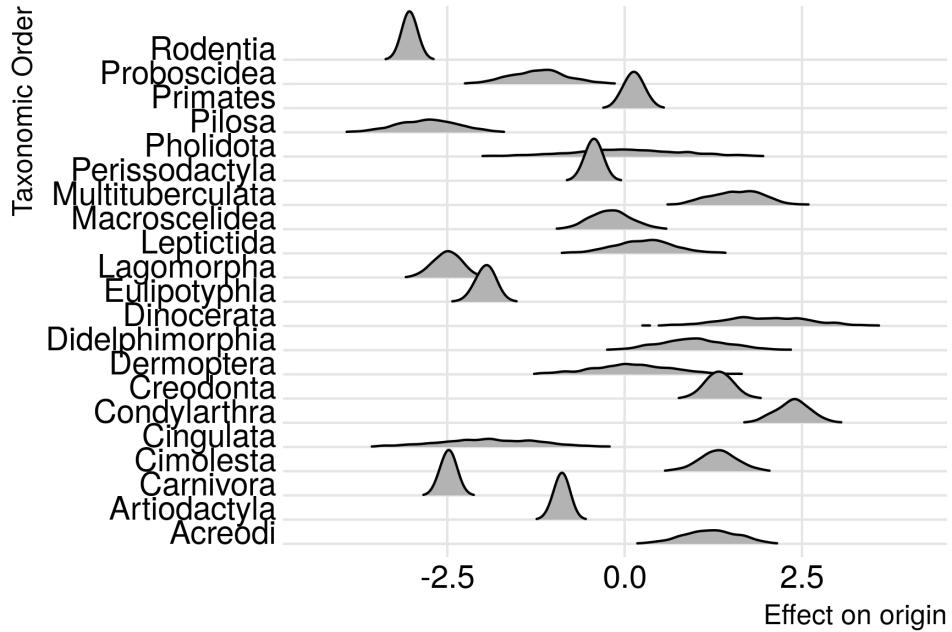


Figure 8: Ridgeline density plots of estimated log-odds of origination based on mammal orders. Positive values correspond to greater log-odds origination than average, while negative values correspond to lower log-odds of origination than average. Importantly, origination probability corresponds to the rarity of that order in the fossil record as well as differences in origination due to species' order (rare orders have few origination)

species origination dynamics.

- 546 For many of the functional groups, the group-level covariates for origination probability are
estimated with high probability (> 0.80) of being different from 0 (Fig. 10). These results mean
- 548 that the environmental factors analyzed here are expected to shape changes in origination
probabilities over time.
- 550 At least two of the three plant phases are possibly associated with differences in origination
probability for 14 of the 18 functional groups (> 0.85 probability; Table 10). The Paleocene-Eocene
552 phase is found to be associated with differences in origination probability from the
Miocene-Pleistocene for ten of the functional groups, all of which are expected to have lower
554 origination probability than the latter (Table 10). The Eocene-Miocene phase is found to be
associated with differences in origination probability from the Miocene-Pleistocene for nine of
556 functional groups: eight with a greater origination probability than the latter, and one with a lower

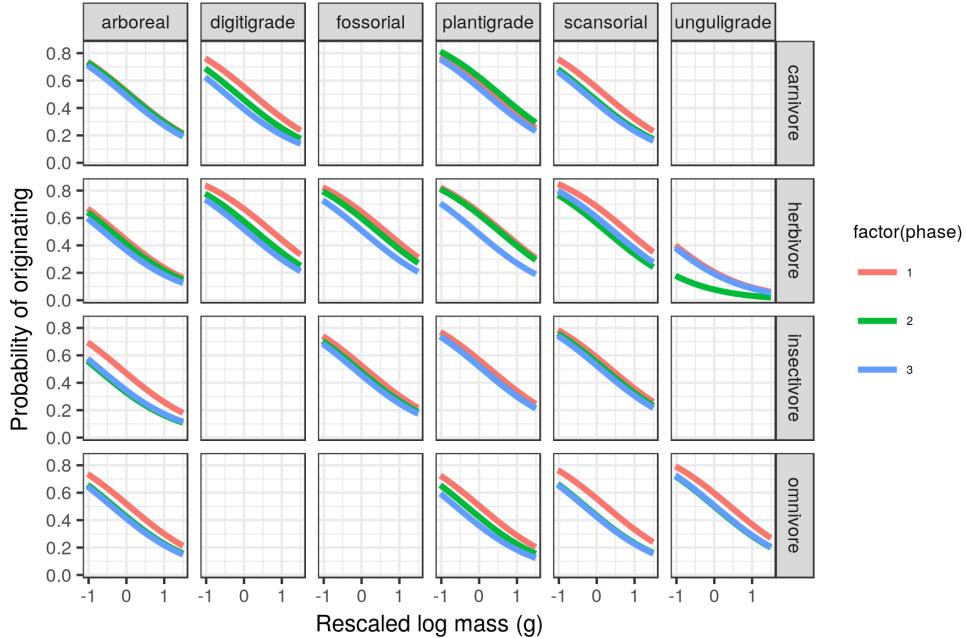


Figure 9: Mean estimates of the effect of species' mass on the probability of a species originating, plotted for each of the three plant phases. While the effect of mass is considered constant over time, each plant phases corresponds to a different intercept of the relationship between mass and origination. 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 of these estimates is plotted.

origination probability than the latter (Table 10). The Eocene-Miocene phase is expected to be

558 associated with a greater origination probability than the Paleocene-Eocene for 13 of the functional
groups (Table 10).

560 Temperature is estimated with probability greater than 0.85 to have negative relationship with
origination probability for ten of the 18 functional groups (Table 11). This result means that for an
562 increase in temperature it is a plausible expectation that origination probability decreases.

Considering that, on average, temperature decreases through the Cenozoic CITATION, this implies
564 that the origination probability of these ten functional groups may be tracking this long-term trend
as opposed to the other functional groups which increase in origination probability independently of
566 temperature.

The origination probabilities of the functional groups are not estimated to be correlated (Fig. 11).

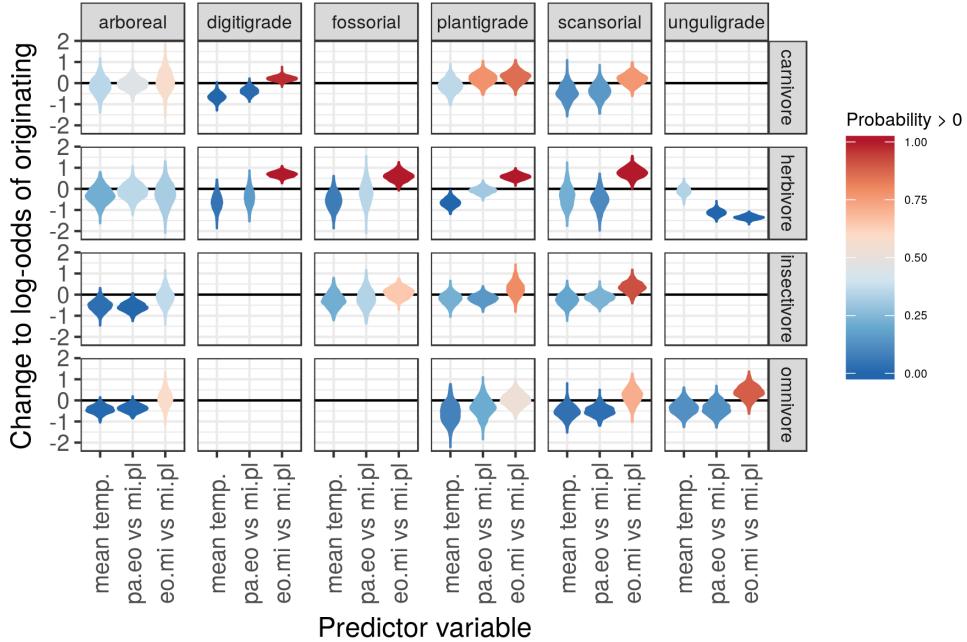


Figure 10: Estimated effects of the group-level covariates describing environmental context on log-odds of species origination. The violin densities that are plotted are based on 1000 samples from the approximate posterior. The color of the violin corresponds to the probability that the covariates effect is estimated to be greater than 0; red values correspond to greater than 0.50 probability of being positive, blue values correspond to less than 0.50 probability of being positive.

568 This result indicates that functional groups have independent origination probability histories for
 the Cenozoic. This result does not preclude the possibility of short term similarities in the increase
 570 or decrease of origination probability or shared peaks and troughs of origination probability.
 Additionally, if the relationship between two functional groups changes over time (e.g. from positive
 572 correlation to negative correlation), then it would yield no overall correlation for the Cenozoic.
 Finally, it is important to remember that these correlation estimates is based on origination
 574 probability and not origination rate or diversity.

The survival probability time-series vary greatly by functional groups with each exhibiting a unique
 576 pattern (Fig. 12). Interestingly, unlike origination probability (Fig. 7), survival probability is
 frequently estimated with considerable uncertainty. When survival probability is below 0.50 then a
 578 species that is present is unlikely to survive from one time unit to the next, while when survival
 probability is greater than 0.50 species can be expected to survive to the next time unit. Finally,

Table 10: Probability of a plant phase having greater log-odds of originating than another. The first two columns are comparisons of that posterior estimate to zero, which corresponds to the probability of that plant phase having a greater log-odds of originating when compared to the Miocene-Pleistocene. The final columnn corresponds to the comparison in log-odds of originating between the Eocene-Miocene and the Paleocene-Eocene.

	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
fossorial 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
fossorial 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

- 580 when survival probability is approximately 0.50 then survival and extinction are equally likely. For
most mammal functional groups, survival probability is rarely estimated to be greater than 0.50
582 with any certainty. This result is consistent with the average occurrence being <1.35 time units per
species which means that a plurality of species have only a single temporal occurrence (Fig. 3).
584 The survival probability for many functional groups is frequently estimated to be approximately
0.50, indicating extinction is frequently random with respect to functional group (Fig. 12). For
586 example, the survival probability scansorial carnivores is approximately 0.50 for the entire time
series which indicates that there is no best or worst time for this functional groups survival. Similar
588 patterns can be observed for mean survival probability of arboreal omnivores, fossorial insectivores,
and plantigrade omnivores though all three of these groups have sudden drops in survival
590 probability by the Hemphillian 10.3 Mya.

Table 11: Probability that the two temperature covariates have an effect on the log-odds of functional group origination. Values greater than 0.50 correspond to the probability of that effect having positive relationship with origination, while values less than 0.5 correspond increasing certainty that that covariate has a negative relationship with origination.

	$P(\gamma_{temp\ mean} > 0)$
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

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 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 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.

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 uncertainty which indicates how apparent this event is. Digitigrade carnivores, digitigrade herbivores, plantigrade herbivores, scansorial insectivores, unculigrade herbivores, and unculigrade omnivores all peak in survival probability by the Monroecreekian 26.3 Mya. This peak in survival means that species of these functional groups which are unlikely to go extinct at this point,

potentially indicating favorable environmental conditions for these groups at the Paleogene-Neogene
604 transition. Additionally, this peak does not coincide with the change from one plant phase to
another (Table 5).

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

Species mass is estimated to possibly have a positive relationship with survival probability
614 ($P(\beta^\pi > 0) = 0.88$; Fig. 14). This result means that it is plausible that species with greater than
average mass have a greater extinction risk than those of average or below average mass. This
616 relationship is the opposite of that predicted by CITATION and is in contrast to those from
CITATION. However, because of the marginal plausibility of this result, it is not a strong refutation
618 of these previous results. Instead, it points to why there has been confusion as to the effect of mass
on survival; this effect might be very small relative to other factors such as functional ecology and
620 thus difficult to estimate the nature of this relationship with high certainty.

In contrast to the origination probability, there is little evidence that the group-level covariates
622 have large effects on functional group survival probabilities (Fig. 15). In fact, only the plant phases
are associated with differences in survival probability and only for a relatively small number of
624 functional groups. These results combined with those from the individual-level covariates (Fig. 12,
13, 14) imply that direct interactions (e.g. species-species) are potentially more important to long
626 term species survival than ambient environment (e.g. temperature tolerance). However, because the
estimate of temperature is global in nature, this interpretation is inherently speculative.
628 Average functional group survival probability is rarely estimated to be different between the three
plant phases (Table 12) with only five pair-wise comparisons having greater than 89% probability of

630 differences in survival between phases. Unuligrade herbivores have an approximately 89%
 probability of having lower survival probability during the Paleocene-Eocene than the
 632 Miocene-Pleistocene. For digitgrade herbivores, and unguligrade omnivores, the Eocene-Miocene
 phase have an approximately 90% probability of having greater survival probability than during the
 634 Miocene-Pleistocene phase. In contrast, unguligrade herbivores are estimated to have lower
 survival probability in the Eocene-Miocene phase than the Miocene-Pleistocene phase. Finally,
 636 unguligrade herbivores have an approximately 99% probability of having a lower survival
 probability during the Paleocene-Eocene than the Eocene-Miocene.
 638 As stated earlier, temperature is not estimated to have an effect on survival probability for any of
 the functional group (Table 13). This is congruent with previous studies which found no association
 640 between extinction and global temperature CITATION ALROY or no consistent, unidirectional
 relationship between extinction and global temperature CITATION.

Table 12: Probability of one plant phase having greater log-odds of survival than another. The first two columns are comparisons of that posterior estimate to zero, which corresponds to the probability of that plant phase having a greater log-odds of survival when compared to the Miocene-Pleistocene. The final column corresponds to the comparison in log-odds of survival between the Eocene-Miocene and the Paleocene-Eocene.

	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

Table 13: Probability that the two temperature covariates have an effect on the log-odds of functional group survival. Values greater than 0.50 correspond to the probability of that effect having positive relationship with survival, while values less than 0.5 correspond increasing certainty that that covariate has a negative relationship with survival.

	$P(\gamma_{temp\ mean} > 0)$
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

642 None of the time-series of functional group survival probability are estimated to be either positively
 or negatively correlated (Fig. 16); this mirrors the estimated correlations between functional group
 644 origination probabilities (Fig. 11). This result indicates that functional groups probably have
 ultimately independent survival histories for the entire study period. As with origination
 646 probability, this result does not preclude the possibility of short term similarities in expansion and
 decline of origination probability or shared peaks and troughs of survival probability. Additionally,
 648 if the relationship between two functional groups changes over time (e.g. from positive correlation
 to negative correlation), then it would yield no overall correlation for the Cenozoic. Finally, it is
 650 important to remember that this estimate correlation is based on survival probability and not
 extinction rate or diversity.

652 **Analysis of diversity**

Standing diversity of the North American mammal species pool estimated from this model exhibits
654 an initial increase in diversity followed by a decrease till approximately the Whitneyan 30Mya, after
which there is a marked increase till approximately the Barstovian 15Mya after which it decreases
656 slightly till it is equal to the overall mean diversity of the Cenozoic (Fig. 18). Per-unit standing
diversity is found to be different from average standing diversity for 12 of 18 time-units (> 85
658 probability; Table 14). Diversity is greater than average during the Tiffanian, Wasatchian,
Hemingfordian, Barsotvian, and Clarendonian while diversity is lower than average during the
660 Duchesnean, Chadronian, Orellan, Whitneyan, Geringian, Monroecreekian, and Harrisonian. The
nadir of diversity is the Orellan while the apex is the Barstovian (Fig. 18). Interestingly, the rise in
662 diversity among the sampled species from the Orellan to the Barstovian is unidirectional and is not
estimated to have any temporary dips in diversification for that entire approximately 15 million
664 year period.

Standing diversity when partitioned by ecotype reveals a lot of the complexity behind the pattern
666 of mammal diversity for the Cenozoic (Fig. 19). While each functional group has its own unique
diveristy history, there are some broad similarities as is similar to the estimates origination and
668 survival probability (Fig. 7, 12).

Arboreal ecotypes obtain peak diversity early in the Cenozoic and then decline for the rest of the
670 time series, becoming increasingly rare or absent as diversity approaches the Recent (Fig. 19).

Arboreal herbivores and omnivores obtain peak diversity at the beginning of the Cenozoic then go
672 into decline while remaining a small part of the species pool, while arboreal carnivores and
insectivores obtain peak diversity by the WAsatchian 55.4 Mya and then quickly decline and
674 become extremely rare or entirely absent from the species pool. The only arboreal functional group
estimated to not experience a complete disappearance from the species pool are arboreal herbivores.
676 This is consistent with increasing extinction risk in the Neogene compared to the Paleogene as
proposed by Smits (2015).

678 The diversity of plantigrade insectivores, scansorial insectivores, and scansorial omnivores are

Table 14: Probability that diversity during one NALMA N_t^{stand} is greater than average standing diversity for the whole Cenozoic $\overline{N^{stand}}$. NALMA is a North American Land Mammal age and is the temporal unit for this study. Values greater than 0.50 indicate support for the diversity at that NALMA being greater than average, while values less than 0.50 indicate support for diversity being less than average. These are listed from oldest to youngest NALMA.

NALMA	$P(N_t^{stand} > \overline{N^{stand}})$
Torrejonian	0.79
Tiffanian	0.95
Clarkforkian	0.50
Wasatchian	1.00
Bridgerian	0.69
Uintan	0.75
Duchesnean	0.00
Chadronian	0.01
Orellan	0.00
Whitneyan	0.00
Geringian	0.00
Monroecreekian	0.01
Harrisonian	0.11
Hemingfordian	0.96
Barstovian	1.00
Clarendonian	0.93
Hemphillian	0.63
Blancan	0.73

estimated to decrease through the Cenozoic (Fig. 19). Plantigrade herbivores and scansorial omnivores have peak diversity at the early Cenozoic and reach low diversity by the Orelan and Whitneyan approximately approximately 33 Mya, after which diversity never increases again. In contrast, scansorial omnivores have nearly constant, above average diversity for the beginning of the Cenozoic till approximately Orelan and Whitneyan, after which diversity drops and remaining below average diversity for the rest of the Cenozoic.

The fossorial functional groups included in this study are estimated to be rare or absent absent for the first half of the Cenozoic, fossorial herbivores probably having lower diversity than fossorial insectivores (Fig. 19). After fossorial herbivores increase in diversity till the Orelan and Whitneyan approximately 33 Mya, this functional group is estimated to quickly reach approximately constant standing diversity for the rest of the Cenozoic. In contrast, fossorial insectivores increase in diversity starting approximately at the Orelan and Whitneyan and reach max diversity at the

Barstovian 16.3 Mya, after which this group declines in diversity.

692 Plantigrade carnivores, scansorial herbivores and unguligrade omnivores are estimated to maintain
near constant standing diversity for most of the Cenozoic (Fig. 19). Of these three functional
694 groups, plantigrade carnivores have the greatest variance in standing diversity. Plantigrade
carnivores have greater than average standing diversity from the beginning of the Cenozoic till the
696 Bridgerian 50.3 Mya and from the Harrisonian 24.8 Mya till the Barstovian 16.3 Mya. This
functional group is estimated to be below average standing diversity from the Bridgerian till the
698 Orelan and Whitneyan approximately 30Mya, and then from the Hemphillian 10.3 Mya till the end
of the studied time period. Scansorial herbivores exhibit a similar patterns but with a reversed
700 diversity pattern for the first 30My of the studied period. Instead of near constant diversity,
scansorial herbivores are estimated to have lower than average diversity from the beginning of the
702 Cenozoic till the Bridgerian approximately 50.3 Mya, after which this group has approximately
average standing diversity for the rest of the Cenozoic. The unguligrade omnivore functional group
704 has slightly elevated diversity at the beginning of the Cenozoic and a possible decrease in diversity
after the Barstovian approximately 16.3 Mya.

706 Scansorial carnivores and plantigrade herbivores have below average standing diversity from the
beginning of the Cenozoic till the Hemingfordian approximately 20.6 Mya, after which both
708 functional groups increase in diversity till being well above average by the end of the study period
(Fig. 19). Plantigrade omnivores are estimated to be absent or extremely rare in the species pool,
710 only increasing in standing diversity beginning at the Hemingfordian approximately 24.8 Mya. In
contrast, scansorial carnivores are estimated to have been a rare but constant part of the species
712 pool diversity for the entire Cenozoic with an increase at the Hemingfordian.

714 Digitigrade carnivores, plantigrade herbivores, and unguligrade herbivores functional groups
maintain relatively high standing diversity through out the entire Cenozoic though each exhibits
716 periods of greater than average and below average standing diversity (Fig. 19). Digitigrade
carnivore diversity is estimated to begin the study period below average and then quickly rise to
the first peak in diversity at the Wasatchian 55.4 Mya. After this, ditigrade carnivore diversity

718 decreases to below average diversity till the Orellan and Whitneyan approximately 33 Mya, after
which diversity increases till a second greater peak in diversity at the Barstovian 16.3 Mya. After
720 this second peak in diversity, ditigrade carnivore diversity declines until the end of the study period.
Unguligrade herbivores exhibit a similar pattern though with considerably less uncertainty. In
722 contrast, while plantigrade herbivores have a similar increase and peak in diversity during the first
half of the Cenozoic, the functional group does not experience a second peak in functional diversity
724 till the end of the study period. Additionally, plantigrade herbivores have a longer period of above
average standing diversity during the first half of the Cenozoic, only experiencing a decrease in
726 diversity starting at the Orellan and Whitneyan approximately 33 Mya.

The digitigrade herbivore functional group is estimated to be the only group with a near constant
728 increase in standing diversity through most of the Cenozoic (Fig. 19). There are two periods of
decrease in the standing diversity of digitigrade herbivores: from the start of the study period till
730 the Wasatchian 55.4 Mya, and a sudden decrease at the Clarendonian 13.6 Mya. Beyond these two
decreases, this functional group exhibits a remarkable increase in diversity from relative rarity at
732 the Wasatchian and Bridgerian till peak diversity at the Hemingfordian and Barstovian. Diversity
even appears to begin to rebound after the sudden decrease at the Clarendonian 13.6 Mya.

734 The waxing and waning of the mammal ecotypes is obvious when comparing changes to estimated
relative log-mean diversity (Fig. 20). While the relative diversity of functional groups changes
736 gradually over time, there are definite patterns associated with a few functional groups and axes of
functional diversity that are interesting. There are many expansions and retractions of functional
738 group relative diversity, some of which are coincidental. Only in the case of digitigrade carnivores,
plantigrade herbivores, and scansorial omnivores are their functional groups maintained as
740 relatively constant proportions of the species pool (Fig. 20).

Eight of the 18 functional groups expand in relative diversity over the Cenozoic (Fig. 20).
742 Digitigrade herbivores have an obvious increase in relative diversity at the Uintan 46.2 Mya, after
which it remains a substantial part of the species pool. Fossiliferous herbivores, and fossiliferous
744 insectivores increase in relative diversity at the Orellan and Whitneyan approximately 33 Mya,

after which these groups are maintained as parts of the species pool. Plantigrade omnivores, and
746 scansorial carnivores are both a relatively small fraction of the species pool until the Hemingfordian
20.6 Mya where these functional groups increase in relative diversity for the rest of the time
748 analyzed. Scansorial herbivores expand their relative diversity starting at the Harrisonian 24.8 Mya,
after which this functional group has an approximately constant relative diversity. Scansorial
750 insectivores experience an increase in relative diversity after the Bridgerian 50.3 Mya. Finally, unlike
other functional groups, unguligrade herbivores slowly increase in their relative diversity for the
752 entire Cenozoic.

Six of the 18 functional groups are estimated to experience a decrease in relative diversity over the
754 Cenozoic (Fig. 20). As expected from the diversity time-series for the functional groups (Fig. 19),
the relative diversity of all four arboreal functional groups declines from the beginning of the
756 Cenozoic until the Orellan and Whitneyan approximately 33 Mya, after which only arboreal
herbivores remain in any capacity (Fig. 20). In addition to the arboreal groups, there are other
758 functional groups which decrease in relative diversity over the Cenozoic (Fig. 20). Plantigrade
carnivores are a relatively constant portion of the species pool until after the Barstovian 16.3 Mya,
760 after which this functional group decreases in relative diversity. Plantigrade insectivores decrease in
their relative diversity, experience greatest winnowing starting approximately at the Geringian till
762 the Barstovian, after which this functional group becomes absent from the species pool. Finally,
unguligrade omnivores begin to decrease in relative diversity starting at the Hemingfordian 20.6
764 Mya, after which they continue to decrease until they are only a small portion of the relative
diversity of the species pool.

766 Discussion

Both the composition of a species pool and its environmental context change over time, though not
768 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
770 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
772 of interactions species within that grouping participate in. The diversity of species within an
functional group can be stable over millions of years despite constant species turnover (Jernvall and
774 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
776 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
778 even evidence that functional groups are at least partially self-organizing and truly emergent
(Scheffer and van Nes, 2006).

780 The goal of this study has been to understand how macroevolutionary processes are affected by
species ecology as well as environmental context, and how these interactions shape macroecological
782 patterns such as regional functional diversity that we observe in the fossil record and the present.

The results of the analysis presented here add considerable nuance to our understanding of mammal
784 macroevolution and macroecology over the Cenozoic.

This analysis reveals how functional groups respond differently to environmental factors through
786 changes to origination probability but not survival probability.

I focus on functional diversity because of its importance to macroecological patterns McGill
788 CITATION. By analyzing mammals species in the context of their functional ecologies, the
complexity of species response to environmental change can be better elucidated. Additionally, by
790 analyzing all of them simultaneously these results are all directly comparable as they are estimated
relative to each other.

792 Over the entity of the studied period, each functional group demonstrates its own origination and
survival history with no evidence of any longterm cross-correlations. Of course, lack of correlation
794 over the Cenozoic does not preclude similarities in response to individual events; it is just that
these correlations are ephemeral and indicate that there is no one relationship between climate and
796 diversity.

Not always the same functional group associated. That's why breaks down over entire cenozoic.
798 individual events aren't series. can affect moments, but not time. sudden shifts vs long term
patterns. Respond sometimes, but not others; thus no correlation for Cenozoic; doesn't preclude
800 process association.

Instead, there are individual periods in time that are characterized by similar changes to absolute
802 or relative diversity. Additionally, it is not always the same functional groups that appear to
experience changes in abundance at these time points.

804 The environmental covariates are found to effect the origination probability of some functional
groups, but only effect the survival probability of relatively few groups.

806 Plant phases: biggest difference is higher origination probability in the Eocene-Miocene phase than
the Paleocene-Eocene phase (13 of 18 with $P \geq 0.85$). Lower origination probability in the
808 Paleocene-Eocene than the Miocene-Pleistocene (10 of 18 with $P \geq 0.85$). Higher origination in the
Eocene-Miocene than Miocene-Pleistocene (8 of 18 $P \geq 0.85$) exception that 1 of 18 $P \geq 0.85$ has lower.

810 There is no evidence that the estimate of global temperature used in this study is not estimated to
be a strong predictor of survival probability. Additionally, there is very little evidence (3 of 18 for
812 min 1 phase comparison) of survival probability being different between two plant phases.

Temperature is estimated to be a predictor of origination probability for many functional groups
814 which either decrease or increase in diversity over the Cenozoic. For example, arboreal and
digitigrade herbivores have close opposite diversity histories, but there are similarities in origination
816 probability for which temperature is estimated to be a good predictor. The contrast between these
two groups appears in their survival histories; arboreal herbivores have flat survival probabilities for
818 the Cenozoic while digitigrade herbivores have peak in survival approximately 33 Mya.

The result that temperature does not affect the survival probability of most functional groups is
820 consistent 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
822 Alroy et al. (2000). 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,
824 assuming it hasn't 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).
826 Origination or extinction rates have very different properties than the origination probabilities
estimated here brought upon by the difference both in definition and units. Origination probability
828 is the expected 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
830 capita rates are 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
832 defined for the 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
834 of some functional groups (Fig. 7. However, it is still possible that the finding that temperature has
an effect on origination may simply be because as time approaches the present the number of
836 species which have originated increases and not because of climatic forcing of origination.

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

Mass affects observation and origination probability, but not survival probability.

848 There are three major time units during the Cenozoic important points in time stick out: the
Wasatchian, Orellan/Whitneyan, and the Barstovian. The Wasatchian and Barstovian NALMA

850 mark the two major peaks in mammal diversity as estimated by my model, while the
Orellan/Whitneyan are estimated to be time lowest diversity during the Cenozoic. Each of these
852 time units mark changes in absolute and relative diversity; for example, the Wasatchian marks peak
relative diversity of arboreal carnivores and scansorial herbivores increase in relative diversity after
854 this time point. Here I discuss which functional groups are associated with important changes to
the regional species pool at these three periods of time as well as their environmental context.

856 The Wasatchian

- peak in all arboreal, peak in digitigrade carnivores, expansion digitigrade herbivores after, peak
858 plantigrade carnivore, peak plantigrade herbivores, high plantigrade insectivores, high scansorial
carnivores

860 - Changes at 55: peak arboreal carnivore, low fossorial herbivore, expansion scansorial herbivores
after

862 Orellan and Whitneyan is lowest diversity, but is a moment of change in diversity. Marks the loss of
some, marks the expansion of others. This also marks a peak in survival for some groups. Are these
864 the groups that expand in the Neogene? Six functional groups are estimated to have peaks in
survival probability at these points. Eocene/Oligocene boundary

866 - loss/bottom out of all arboreal groups, dip unguligrade herbivore, mark expansion of fossorial
groups + plantigrade omnivores, drop off of plantigrade insectivore, scansorial insectivore,
868 scansorial omnivore

- Changes as 33: increase digitigrade carnivores, digitigrade herbivores, fossorial herbivores, fossorial
870 insectivores, start of increase scansorial omnivores; decrease scansorial insectivores, loss arboreal
insectivore

872 The Barstovian Mid-Miocene Climatic Optimum

- peak unguligrade herbivore, peak digitigrade carnivore, peak digitigrade herbivore, peak fossorial
874 insectivore

- Changes at 15: increase arboreal insectivore, plantigrade omnivores, decrease digitigrade herbivores, loss unguligrade omnivore, loss plantigrade insectivore.

Mammal species are short lived with average duration being only slightly more than one NALMA.
876 This short a duration means that observation probability is very high for most of the Cenozoic,
with it being greater than 0.50 for the entire Cenozoic while also being greater than 0.80 for most of
880 the Cenozoic. Time is associated with greater variation in observation probability than functional
group. Scansorial insectivores are estimated to have a substantially lower observation probability
882 than the other functional groups.

Conclusions

884 Is origination driven by ecological opportunity while survival is driven by differences in species-level
fitness?

886 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 functional diversity is shaped more
888 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
890 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
892 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
894 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
896 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
898 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
900 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
902 the complex processes underlying that diversity.

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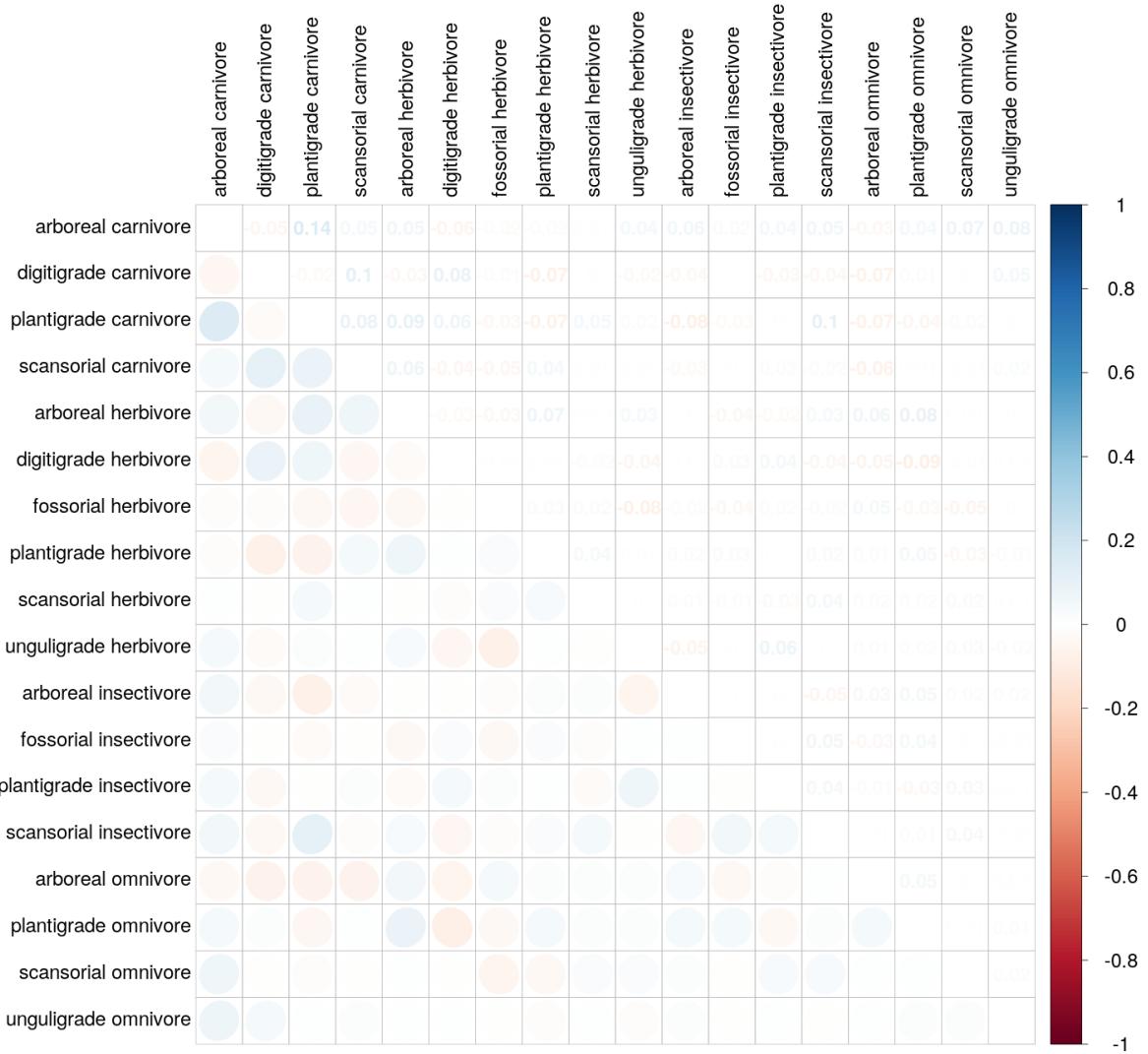


Figure 11: Posterior estimate of mean correlations in origination probability between the mammal functional groups. The lower triangle of the matrix is populated with ellipses corresponding to the level of correlation between the two functional groups, while the upper triangle of the matrix corresponds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

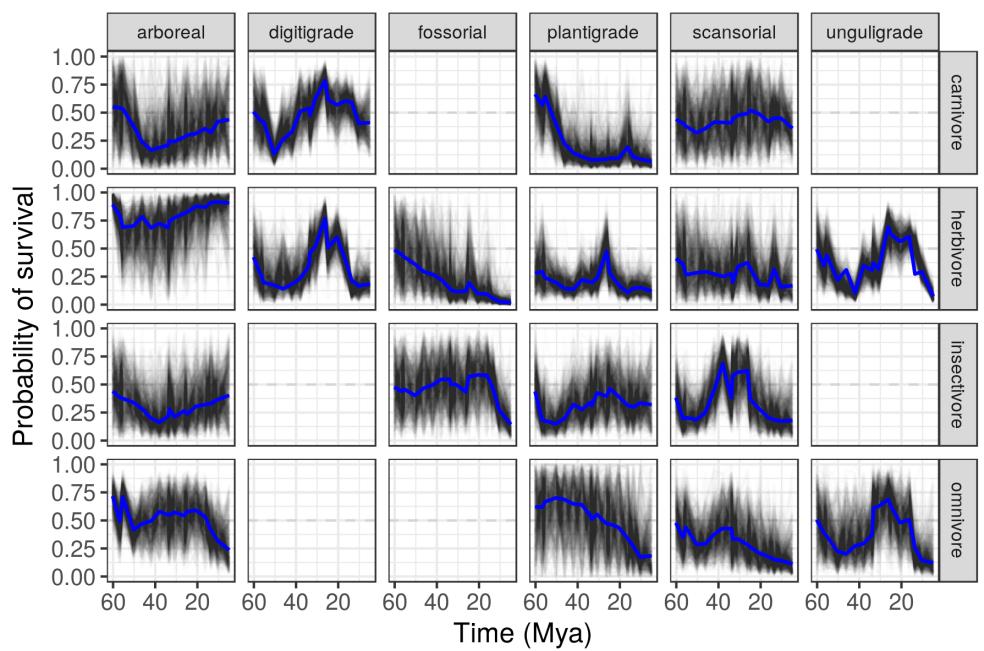


Figure 12: Probability of a species continued survival based on functional groups. Survival probability is graphed as 100 time-series drawn from the model's posterior estimates. A greater density of the posterior estimates indicates increased certainty. The blue line is the mean survival probability as predicted by just the group-level predictors. The columns are by locomotor category and rows by dietary category.

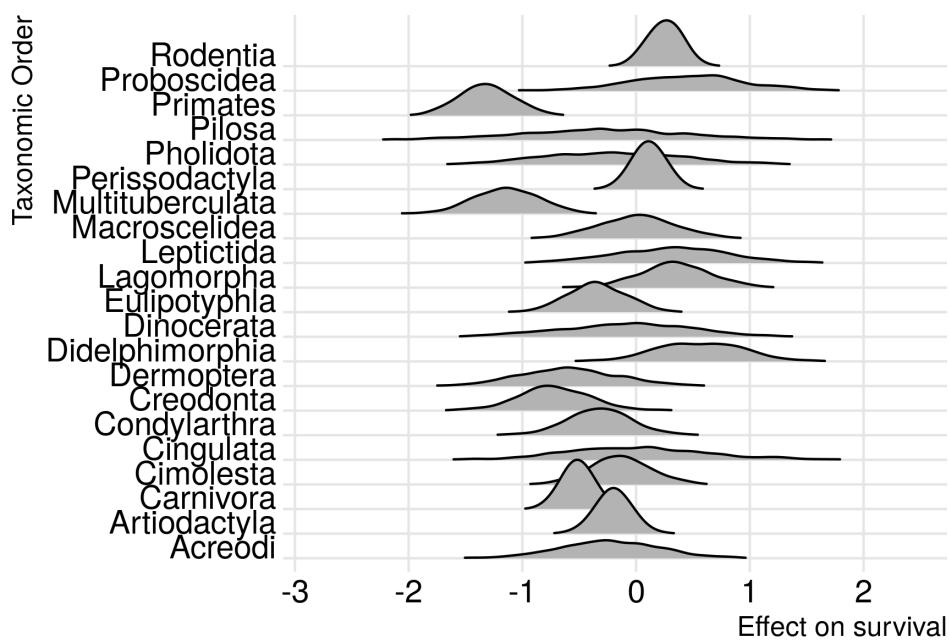


Figure 13: Differences in log-odds of survival based on mammal orders. Positive values correspond to greater log-odds survival than average, while negative values correspond to lower log-odds of survival than average.

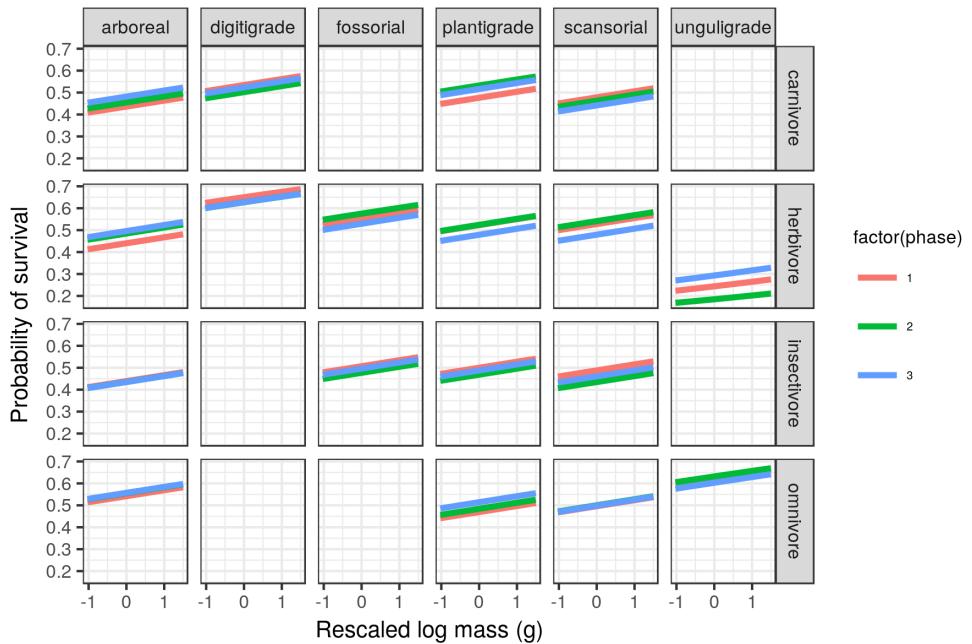


Figure 14: Mean estimates of the effect of species' mass on the probability of a species surviving, plotted for each of the three plant phases. While the effect of mass is considered constant over time, each plant phases corresponds to a different intercept of the relationship between mass and survival. 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 of these estimates.

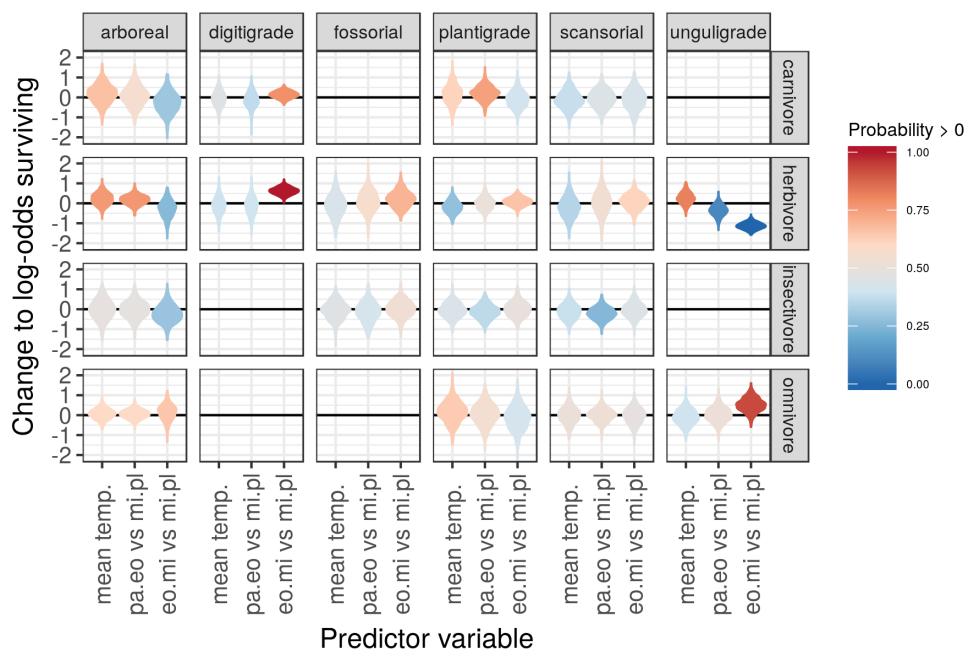


Figure 15: Estimated effects of the group-level covariates describing environmental context on log-odds of species survival. The violin densities that are plotted are based on 1000 samples from the approximate posterior. The color of the violin corresponds to the probability that the covariates effect is estimated to be greater than 0; red values correspond to greater than 0.50 probability of being positive, blue values correspond to less than 0.50 probability of being positive.

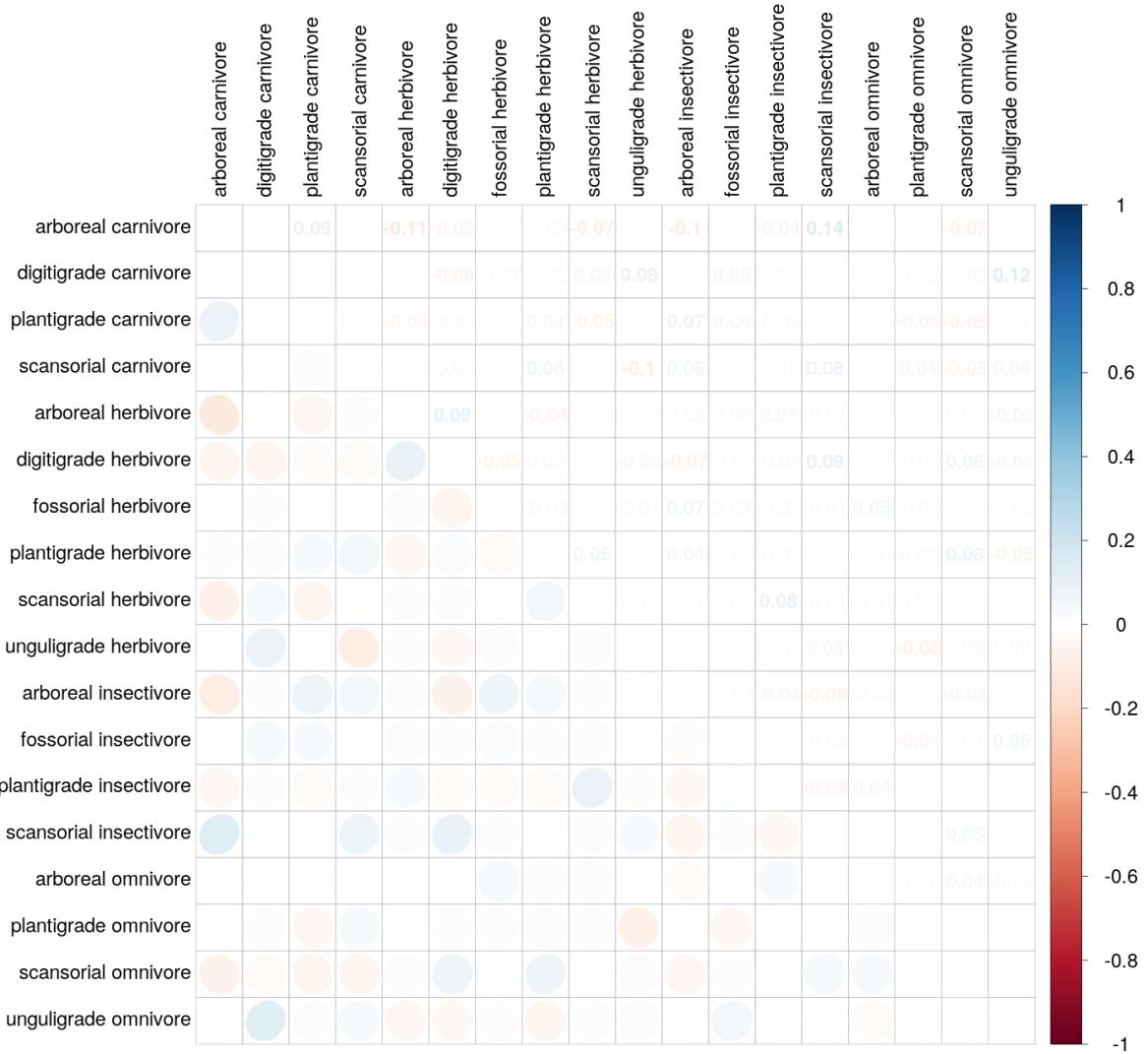


Figure 16: Posterior estimate of mean correlations in survival probability between the mammal functional groups. The lower triangle of the matrix is populated with ellipses corresponding to the level of correlation between the two functional groups, while the upper triangle of the matrix corresponds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

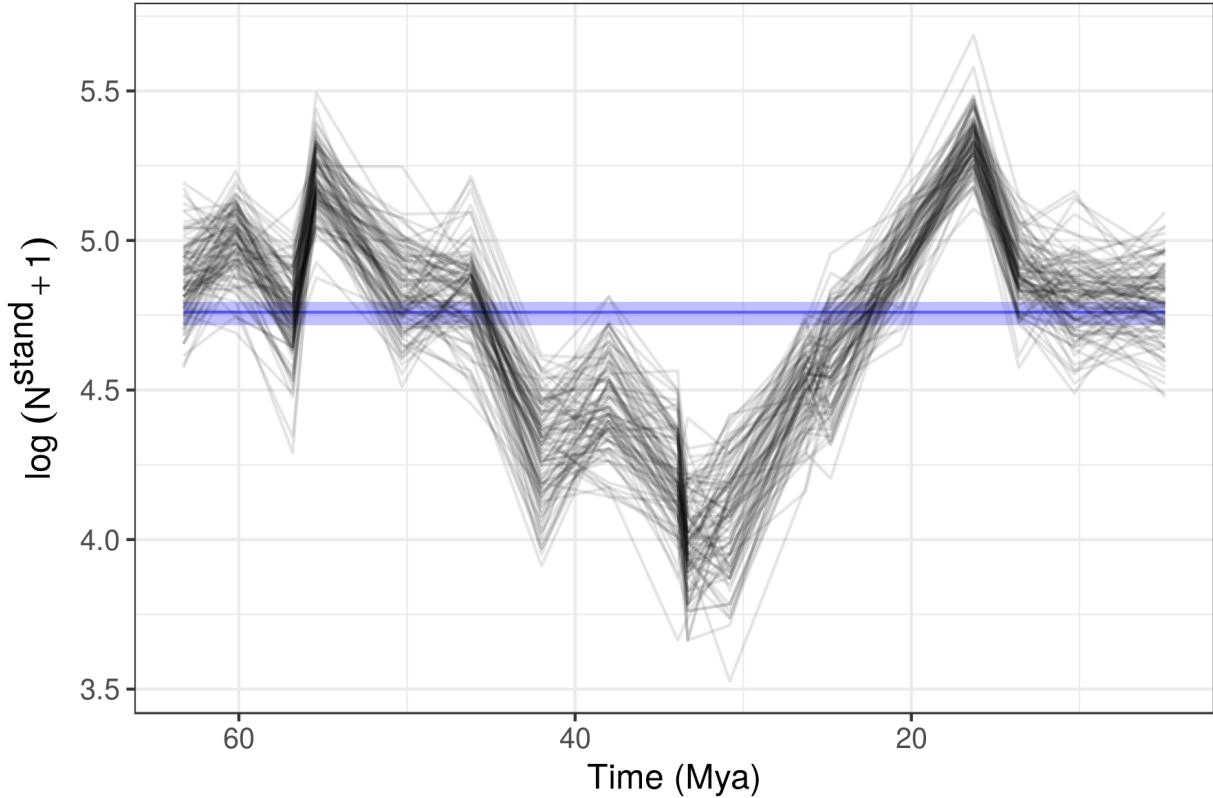


Figure 17: Log diversity

Figure 18: Estimated standing diversity of Cenozoic mammals based on the 1400 species analyzed in this study. Estimates are based on 100 posterior draws of the “true” occurrence matrix z (Table 7). The blue horizontal strip corresponds to the median and 80% credible interval of estimated mean standing diversity for the entire time period studied.

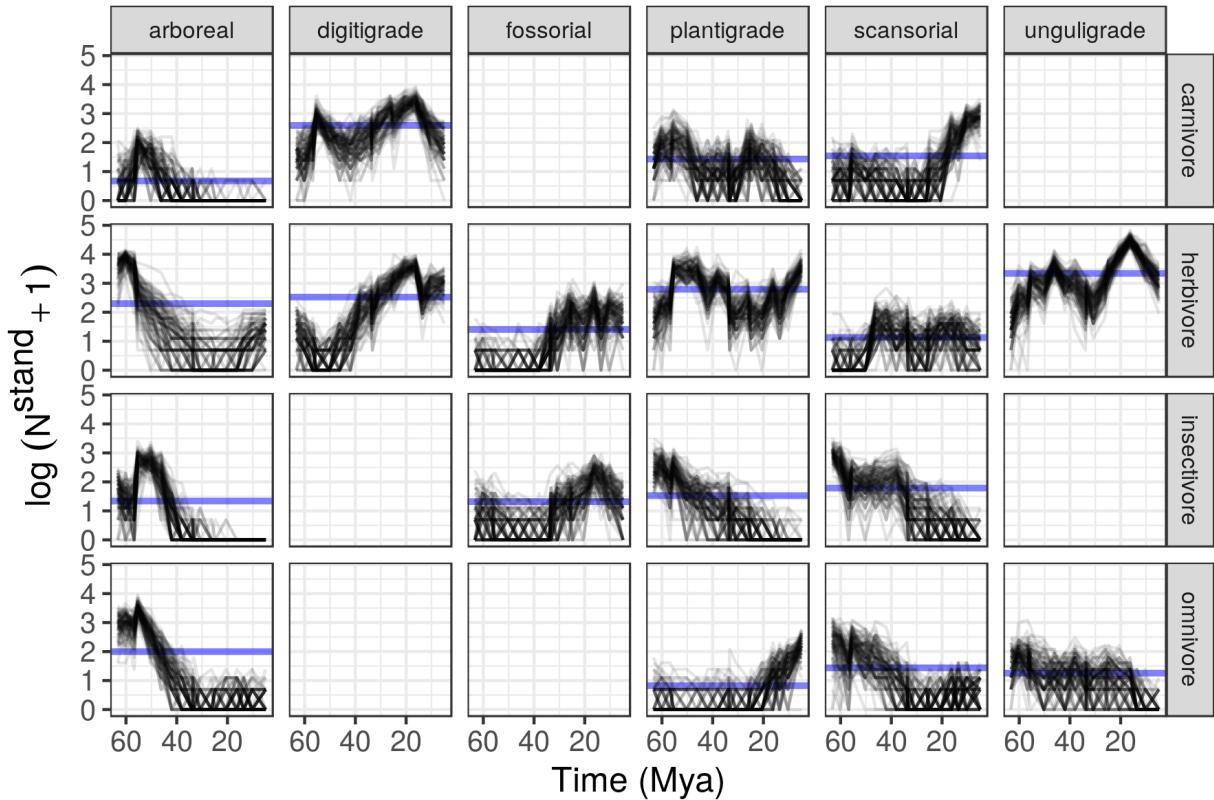


Figure 19: Estimated standing log-diversity of North American mammals by functional group for the Cenozoic. Diversity is represented as 100 posterior draws plotted over time. Density of time-series indicates congruence in estimates. The blue line corresponds to average standing diversity for that functional group for the entire Cenozoic.

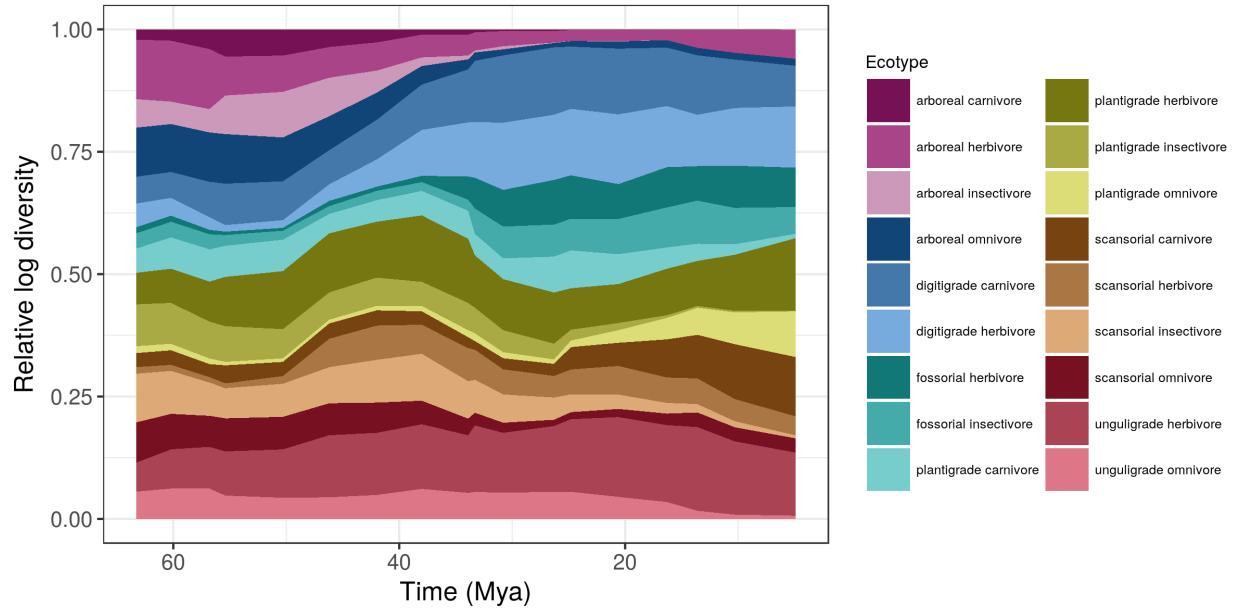


Figure 20: Relative diversity of the mammal functional groups for the Cenozoic. Relative diversity was calculated from the mean posterior estimate of standing diversity (Fig. 19) and is plotted here without uncertainty. These estimates are calculated from 100 posterior estimates of the true occurrence matrix z (Table 7).