Appendix B from S. Tomiya, "Body Size and Extinction Risk in Terrestrial Mammals Above the Species Level" (Am. Nat., vol. 182, no. 6, p. E196)

Technical Notes on Material and Methods

Determination of Observed Temporal Ranges

Each locality and all generic occurrences from that locality are assigned a range of possible ages that were obtained by radioisotopic, magnetostratigraphic, or, most frequently, biochronologic dating. For the purpose of this study, the following assumptions were made with regard to locality ages: (1) the true age of each locality is geologically instantaneous (or practically so relative to durations of genera, which are generally on the order of 10^6 years or greater in the data set analyzed here), (2) the uncertainty in the age of each locality is sufficiently captured by its age range reported in the MIOMAP and FAUNMAP databases (Carrasco et al. 2005; Graham and Lundelius 2010), and (3) the age of each locality *i* is assumed to have a continuous uniform distribution with the probability density function (fig. B3A):

$$f_i(t) = \begin{cases} \frac{1}{T_{\max,i} - T_{\min,i}} & \text{if } T_{\max,i} > t > T_{\min,i} \\ 0 & \text{otherwise} \end{cases},$$
(B1)

where $T_{\min,i}$ and $T_{\max,i}$ are the minimum and maximum ages for the locality, respectively, and the unit of time is million years ago (e.g., t = 20 is equivalent to 20 myr ago; note that following the paleontological convention, the time axis is reversed such that the value of t decreases as time progresses, and $t = -\infty$ stands for time at ∞). Then, for each taxon, the joint probability of at least one occurrence across all localities i = 1, ..., n (only the localities that have yielded the taxon are considered) by time t is

$$p(t) = 1 - \prod_{i=1}^{n} \int_{t} f_i(t) dt.$$
 (B2)

The median unbiased estimate for the first appearance date (FAD) $t = T_{FAD}$ of the taxon is the point in time at which the probability p(t) reaches 0.5. Thus, \hat{T}_{FAD} was obtained by numerically solving (fig. B3B)

$$p(\hat{T}_{FAD}) = 1 - \prod_{i=1}^{n} \int_{\hat{T}_{FAD}}^{\cdot} f_{i}(t) dt = 0.5$$
(B3)

Similarly, the last appearance date $t = T_{LAD}$ for each taxon was estimated by solving

$$q(\hat{T}_{LAD}) = \prod_{i=1}^{n} \int_{-\infty}^{\hat{T}_{LAD}} f_i(t) dt = 0.5,$$
(B4)

which represents the probability of the taxon's last occurrence before \hat{T}_{LAD} .

The first and last appearance dates of a taxon thus obtained are merely the age estimates for the observed first and last appearances. Realistically, the sampling of taxonomic occurrences in the fossil record is expected to be incomplete, which makes the observed temporal range from \hat{T}_{FAD} to \hat{T}_{LAD} a truncated subset of the taxon's true temporal range. Further, it is likely that taxonomic ranges are differentially truncated because of ecological and taphonomic variations, as discussed below.

Adjustment of Temporal Ranges for Sampling Bias

Confidence Interval Method

Unless the sampling of taxonomic occurrences is complete, the observed duration of a taxon in the fossil record underestimates its true duration in geologic time. Although this study is primarily concerned with relative durations of genera across a body-mass spectrum, it is important to derive sampling-adjusted durations because (1) incomplete sampling disproportionately shortens truly short temporal ranges (fig. B4; see also Foote and Raup 1996), and (2) fossil recovery potential (Marshall 2010) may vary substantially across taxa and over time at the scale of millions of years. The approach of this study therefore follows Marshall's (1997, 2010) generalized confidence interval method, first deriving fossil recovery potential functions and then using this information to calculate the 50% confidence interval for the temporal range of each genus, extending the observed first and last appearance dates.

Of particular concern here is the possible body-size bias in fossil recovery potential. Such a bias may stem from different methods that are employed to collect large versus small mammalian fossils and the relative ease of finding large mammalian fossils in the field. It should also be noted that intensive collecting of small mammalian fossils using screenwashing techniques commenced relatively late in the history of North American vertebrate paleontology with the work of Claude W. Hibbard in the 1930s (McKenna et al. 1994). Based on these field-practical and historical factors (see also Alroy 2003), the Cenozoic fossil record of small mammals may be suspected to be less complete than that of large mammals. To date, however, such a bias has not been quantitatively demonstrated at the scale of this study, and previous studies of diversity dynamics in the mammalian fossil record have generally avoided these problems by conducting separate analyses for large and small mammals (e.g., Barry et al. 2002) or by focusing on large mammals only (e.g., Jernvall and Fortelius 2004; Carotenuto et al. 2010; Raia et al. 2012). I addressed this issue instead by quantifying the per-myr sampling probability separately for classes of small (estimated body mass of less than 1,000 g) and large (\geq 1,000 g) taxa. Some of the genera for which body mass estimates were not available were assigned to one of the two classes based on their taxonomic affiliations: specifically, all dipodids, heteromyids, murids, lagomorphs, and lipotyphlans were placed in the small-size class, and all nonmustelidan carnivoramorphans, artiodactyls, perissodactyls, xenarthrans, and proboscideans were placed in the large-size class. A few canids in the data set have estimated body masses of less than 1,000 g, but the only genus lacking dental measurements (Epicyon) can securely be placed in the large-size class based on other skeletal measurements reported by Wang et al. (1999). In addition, the following genera were assigned to the large-size class based on the size ranges of their extant species: Enhydra, Lutra, and Hydrochoerus. Other genera lacking body mass estimates (e.g., some castorid rodents) were excluded from this study. Separate estimation of range-through sampling probability for finer categories (e.g., herbivores and carnivores within large mammals) would be ideal, but further subdivision of the data set would substantially increase the uncertainties in the estimates.

The fossil recovery potential was approximated based on the range-through sampling probability R_j (Paul 1982; Foote 2000). The latter was calculated for 1-myr intervals j = 1, ..., m as

$$R_j = \frac{N_{j,rts}}{N_{j,rt}},\tag{B5}$$

where $N_{j,rt}$ is the number of genera that range all the way through the given time interval *j* and $N_{j,rts}$ is their subset that were actually sampled. Thus, occurrences of a taxon in the 1-myr intervals that contain the taxon's first and last appearances are not counted; consequently, those genera whose observed temporal ranges lie within two consecutive time intervals are not informative for the calculation of R_i and are therefore excluded from this step.

For each 1-myr interval, the value of R_j estimates the probability of at least one occurrence of a taxon being ultimately reported in the MIOMAP or FAUNMAP database, assuming the taxon's existence throughout the interval (cf. Foote 2000). This probability likely reflects diverse paleontological factors such as taxonomic abundance, paleoenvironmental potentials for fossil preservation, geographic extent and distribution of accessible outcrops, fossil collection methods, and intensity of collection and reporting efforts. The calculation of range-through sampling probabilities assumes the continuous presence of each genus in the continental United States between its first and last appearances there. Although major shifts and contractions in geographic ranges could cause temporary disappearances of genera from the study area, this is (1) difficult to demonstrate with incomplete data and (2) unlikely if the typically interregional distributions of extant mammalian genera in North America also characterized the fossil genera considered here (see also Hadly et al. 2009 on the stability of genus-level geographic ranges in North America through the last glacial-interglacial transition). Indeed, the faunal inertia at the million-year time scale that renders the framework of North American land mammal ages biologically meaningful also supports the above assumption, if only in the most general sense.

As mentioned above, locality ages are known with varying levels of uncertainty, affecting the estimation of rangethrough sampling probability. To take these uncertainties into account, 1,000 sets of instantaneous ages for 9,685 localities were drawn from the set of probability density functions for these localities (eq. [B1]). Then, for each set of locality ages, the sampling probability through time was estimated separately for large and small mammals. For each 1-myr interval, the median of 1,000 estimates was selected for use in the calculation of sampling-adjusted temporal-range endpoints, as

Appendix B from S. Tomiya, Body Size and Mammalian Extinction

explained below. In addition, the bootstrap estimate of bias-corrected ninety-fifth percentile confidence interval (Efron 1981) was calculated separately for large and small mammals in each time interval, as well as for the difference in sampling probability between the two size classes to test its statistical significance.

Assuming that taxonomic occurrences (i.e., instances of positive sampling) within each 1-myr interval follow the Poisson process, the discrete range-through sampling probability R_j described above can be converted to a continuous-time function (Foote 2000):

$$r_i(t) = 1 - e^{-\kappa_j(T_j - t)},\tag{B6}$$

such that $R_j = r_j(t = T_j - 1)$, where κ_j is the expected number of occurrences of a taxon per million years ("preservation rate" of Foote 2000), and T_j is the age of the beginning of interval*j*. Equation (B6) is a cumulative distribution function, so the corresponding probability density function—which is adopted here as the fossil recovery potential function (Marshall 2010)—can be expressed as

$$g_j(t) = \frac{\mathrm{d}}{\mathrm{d}t} r_j(t) = \kappa_j e^{-\kappa_j(T_j - t)},\tag{B7}$$

within a time interval *j*, where $\kappa_j = -\ln(1 - R_j)$. Graphically, $r_j(t)$ corresponds to the area under the curve defined by the function $g_j(t)$ (fig. B5). By extension, the sampling probability r(t) across multiple time intervals can be obtained from the function g(t) that combines $g_i(t)$ for different intervals.

Using the generalized confidence interval method of Marshall (1997, 2010), the amount of temporal extension x for an observed range endpoint (in this study, the first or last appearance date of a genus) for the fossil recovery potential function g(t), confidence level C, and number of fossil horizons H can be derived as

$$x^* = r^*[(1 - C)^{(1/(H-1))} - 1],$$
(B8)

where $r^* = \int_{T_{\text{FAD}}}^{T_{\text{EAD}}} g(t) dt$ and $x^* = x^*_{\text{FAD}} = \int_{T_{\text{FAD}}}^{T_{\text{FAD}}} g(t) dt$ for the extension of first appearance date or $x^* = x^*_{\text{LAD}} = \int_{T_{\text{LAD}}}^{T_{\text{EAD}}} g(t) dt$ for the extension of last appearance date. Note that, for the extension of first appearance date backward in time, both the fossil recovery potential function and the corresponding cumulative distribution function must be inverted within each 1-myr interval along the time axis, such that $g_j(t) = \kappa_j e^{-\kappa_j(t-(T_j-1))}$ and $r_j(t) = 1 - e^{-\kappa_j(t-(T_j-1))}$ (fig. B5). For joint estimation of sampling-adjusted range endpoints, equation (B8) can be modified (after Strauss and Sadler 1989) as

$$C = 1 - 2\left(\frac{r^*}{r^* + x^*}\right)^{H-1} + \left(\frac{r^*}{r^* + 2x^*}\right)^{H-1},$$
(B9)

where $x^* = x^*_{FAD} = x^*_{LAD}$ but x_{FAD} does not necessarily equal x_{LAD} (see fig. B5 for illustration).

The sampling-adjusted duration of a genus is here defined as the length of time encompassed by the median unbiased estimates for its temporal-range endpoints. These endpoints, henceforth denoted as T_{FAD50} (= $T_{\text{FAD}} + x_{\text{FAD}}$) and T_{LAD50} (= $T_{\text{LAD}} - x_{\text{LAD}}$), correspond to the 50% confidence interval for the temporal range of the genus and are obtained by numerically solving

$$\left(\frac{\int_{T_{\text{FAD}}}^{T_{\text{LAD}}} g(t)dt}{\int_{T_{\text{FAD}}}^{T_{\text{LAD}}} g(t)dt}\right)^{H-1} + \left(\frac{\int_{T_{\text{FAD}}}^{T_{\text{LAD}}} g(t)dt}{\int_{T_{\text{FAD}}}^{T_{\text{LAD}}} g(t)dt}\right)^{H-1} - \left(\frac{\int_{T_{\text{FAD}}}^{T_{\text{LAD}}} g(t)dt}{\int_{T_{\text{FAD}}}^{T_{\text{LAD}}} g(t)dt}\right)^{H-1} = 1 - C = 0.5$$
(B10)

for the values of x_{FAD} and x_{LAD} that satisfy $\int_{T_{FAD}+x_{FAD}}^{T_{LAD}} g(t)dt = \int_{T_{FAD}}^{T_{LAD}-x_{LAD}} g(t)dt$. Note that this method is not applicable to genera that are known from a single occurrence (which makes the area $r^* = 0$). Sampling-adjusted ranges were thus calculated for 276 genera that are each represented by multiple occurrences, and for which body size data were available.

Metric Variables and Allometric Equations for Body Mass Estimation

Table B1 summarizes the dental dimensions and allometric equations that were used to estimate the body masses of fossil taxa. Both the body masses (original data in units of g) and dental measurements (original data in mm) were natural log transformed. The body mass of each genus was obtained by taking the mean of estimated masses of its constituent species except those lacking dental measurements.

Generalized Least Squares Regression Method

The basic linear model considered here has the form of

$$D_i = \beta M_i + \varepsilon_i,$$

where D_i and M_i are the natural log-transformed duration and body mass of taxon *i*, and ε_i represents the residual error. The phylogenetic structure of the data, if present, is incorporated into the regression analysis through the specification of the residual variance-covariance matrix, in which the diagonal elements are

$$\mathbf{var}(\varepsilon)_i = t_i \sigma^2,$$

and the off-diagonal elements are

$$\mathbf{cov}(\varepsilon)_{ij} = \lambda_{\varepsilon} t_{ij} \sigma^2,$$

where t_i is the branch length from the root of phylogeny to the terminal node represented by the taxon*i*, t_{ij} is the branch length on the phylogeny that is shared between a pair of taxa *i* and *j*, σ^2 is the variance expected from the constantvariance random-walk (i.e., Brownian-motion) model of trait evolution for a unit time, and λ_e is a parameter that measures the strength of phylogenetic signal relative to the expectation from the random walk model; thus, $\lambda_e = 0$ would indicate no phylogenetic structure in the residual error, and $0 < \lambda_e < 1$ would correspond to cases in which trait variation is more weakly correlated with phylogeny (Pagel 1999; Freckleton et al. 2002).

Because of the varying total branch lengths from the root to the terminal nodes of the composite cladogram, the diagonal elements of the variance-covariance matrix for the residual error in the generalized least squares regression are nonidentical regardless of the value of λ . Consequently, it would be inappropriate to apply this evolutionary model when there is no detectable phylogenetic signal in the residual error. Thus, the data subsets that yielded estimates of λ with the 95% confidence intervals of [0, 0] were reanalyzed by the ordinary least squares regression method.

Examination of Western Eurasian Fossil Record and Survival Analysis

So far as possible, the analytical procedure of Liow et al. (2008*a*) was followed; see also Liow and Nichols 2010). The geographic scope was confined to the area of western Eurasia within 30.86°–55.0°N and 9.13°W to 58.9°E. Most genera were assigned to either "large" or "small" size class based on their taxonomic affiliations (Liow et al. 2008*a*) or estimated body masses in cases they were provided by the NOW database. The following rodents were assigned to the "large" size class: *Agnotocastor* (based on the estimated mass for the same genus in North America), *Stenofiber* (based on m1 measurements reported by Mörs and Stefen 2010), *Anchitheriomys* (based on p4-m3 measurements reported by Stefen and Mörs 2008, and allometric equation of Hopkins 2008*b*). For the calculation of range-through sampling probabilities for Eurasian taxa, extant genera that have been extirpated from the region were treated in the same manner as extinct genera.

Notes on Taxonomy and Cladistic Hypotheses

Occurrences of unpublished new genera reported in the MIOMAP database were excluded from this study, and those of unpublished new species belonging to known genera were included as unidentified species. Table B2 summarizes the primary sources of information on the classifications and cladistic relationships of fossil mammals. Additional taxonomic comments follow the table.

Artiodactyla General

Cladistic relationships among extant families of artiodactyls were adopted mainly from Bininda-Emonds et al. (2007, 2008). It should be noted that many parts of the family-level phylogeny of Artiodactyla are highly uncertain (Geisler and Uhen 2005; Geisler et al. 2007; O'Leary and Gatesy 2008). Furthermore, no single cladogram is available in the literature that includes all the families of extant and extinct artiodactyls recognized in Janis et al. (1998). With respect to extinct families, I followed the combined molecular and morphological tree of Spaulding et al. (2009, fig. 2) and placed (1) protoceratids and anthracotheres as successive outgroups to Ruminantia within Ruminantiamorpha, (2) oreodonts as the sister group to the clade consisting of *Cainotherium* and camelids, and (3) entelodonts as an outgroup to the clade consisting of Cetaceamorpha and Hippopotamidamorpha. Included in Ruminantia are (1) the family Palaeomerycidae as the sister group to the Cervidae (Prothero and Liter 2007) and (2) gelocids *Pseudoceras* and *Floridameryx* (Webb 2008). Two representatives of leptochoerines were placed outside all other artiodactyls in the data set following the placement of family suggested by Geisler et al. (2007).

Camelidae

The problematic genus *Pliauchenia* was removed from the data set (cf. Honey et al. 1998). The cladistic relationships of genera within the Lamini follow those of Scherer (2013).

Appendix B from S. Tomiya, Body Size and Mammalian Extinction

Entelodontidae

The genus Dinohyus is regarded here as a junior synonym of Daeodon (Foss 2007).

Chalicotheriidae

The chalicothere *Moropus* was placed outside the clade containing all other perissodactyls in the data set, following Hooker and Dashzeveg (2004).

Equidae

Five additional species of *Cormohipparion—C. fricki*, *C. johnsoni*, *C. matthewi*, *C. merriami*, and *C. skinneri*—were included (Woodburne 2007). The cladistic positions of *Acritohippus*, *Parapliohippus*, *Heteropliohippus*, and "*Pliohippus*" *tehonensis* follow those proposed by Kelly (1998, fig. 9).

Amphicyonidae

The family Amphicyonidae was positioned as a sister group to all other caniforms in the data set (Tomiya 2011). The daphoenine *Adilophontes* was provisionally positioned as the sister taxon to *Daphoenodon* following Hunt (2002).

Ursidae

Note that Hunt (1998b) considered the North American species "Hemicyon" barbouri to be generically distinct from the Old World Hemicyon.

Mustelidae

Two Arikareean genera, *Acheronictis* and *Arikarictis*, were tentatively placed in a polytomy at the base of Mustelida (Hayes 2000). Following Wang et al. (2005*a*), leptarctines and oligobunines were placed as successive outgroups to the crown group Mustelidae. The genus *Miomustela* was here allied with Mephitidae rather than Mustelidae (cf. Hall 1930). Although Wang et al. (2005*b*) presented an alternative hypothesis regarding basal skunks, the absence of several genera in their cladogram precluded it from being incorporated into this study. Simocyonines were positioned as the sister group to Ailuridae instead of within Procyonidae (Wang et al. 2005*a*).

Aplodontoidea

Two additional taxa, Ansomys cyanotephrus and Ansomys nevadensis (Korth 2007b), were included.

Castoroidea

The classification and cladistic hypothesis within the tribe Castoridini (Korth 2001) were modified according to Korth (2007*a*). Thus, *Eucastor dividerus, Eucastor lecontei*, and *Eucastor phillisi* of Flynn and Jacobs (2008) were here treated as *Prodipoides dividerus, Prodipoides lecontei*, and *Prodipoides phillisi*, respectively, and two additional species, *Prodipoides burgensis* and *Prodipoides katensis*, were recognized (Korth 2002, 2007*a*). The genus *Priusaulax* was tentatively placed in a polytomy with *Monosaulax* and other members of Castoridini (Korth and Bailey 2006). Additional taxa, *Euroxenomys galushai* (Korth 2002) and *Eutypomys wilsoni* (Korth 2007*c*), and *Monosaulax tedi* (Korth 1999) were included.

Cricetidae

Lindsay (2008) considered *Bensomys* to be a subgenus of *Callomys*; thus, *Bensomys lindsayi* (Kelly 2007) was classified as *Callomys lindsayi*. Two Pleistocene species, "*Synaptomys*" borealis and "*Synaptomys*" meltoni, were assigned to the genus *Mictomys* following Repenning and Grady (1988).

Geomorpha

The following additional taxa were included: *Cupidinimus smaragdinus* (Korth 1996); *Perognathus strigipredus* (Czaplewski 1990); *Proharrymys fedti, Proharrymys schlaikjeri*, and *Proharrymys wahlerti* (Korth and Branciforte 2007); *Tenudomys ridgeviewensis* and *Tenudomys titanus*, and *Tylionomys voorhiesi* and *Tylionomys woodi* (Korth and Branciforte 2007). The genus *Tylionomys* (Korth and Branciforte 2007) was tentatively considered as the sister taxon to *Mookomys* (*Heliscomys* of Korth and Branciforte 2007).

Erethizontidae

Following Flynn (2008c), occurrences of the genus Coendou are here recognized as those of Erethizon.

Lipotyphla

Additional taxa, Amphechinus ellicottae and Brachyerix richi (Martin and Lim 2004), were included.



Figure B1: Geographic distributions of fossil-bearing localities. Data from the MIOMAP and FAUNMAP databases (Carrasco et al. 2005; Graham and Lundelius 2010). A total of 2,733 localities are shown that have collectively yielded the 276 genera considered in the comparative analysis of this study. Additional localities (not shown) were included in the derivation of fossil recovery potential curves (see text). For comparison, localities are plotted separately for large (left column) and small (right column) mammals and for three successive time intervals: 29–20 Ma (*bottom row*); 20–10 Ma (*middle row*); and 10–1 Ma (*top row*). Each locality is color coded according to its midpoint age (i.e., the mean of maximum and minimum possible ages).







Figure B2: One example of time-calibrated cladogram for 276 genera. *A*, Rodents, lagomorphs, and lipotyphlans; *B*, artiodactyls and perissodactyls; *C*, carnivorans. Filled circles indicate the nodes whose ages were fixed by molecular divergence-date estimates of Bininda-Emonds et al. (2007, 2008). The ages of remaining nodes and their associated branch lengths were randomly selected in each simulation. Black and gray bars represent the observed and sampling-adjusted temporal ranges, respectively. Original estimated masses in units of grams.



Figure B3: Determination of median unbiased first/last observed taxonomic occurrence. *A*, Probability density functions f(t) for ages of two localities that have yielded a taxon of interest. Each locality age is bounded by the maximum (T_{max}) and minimum (T_{min}) possible ages. *B*, Cumulative density functions p(t) describing the probability of the taxon's first occurrence taking place before the time *t* at locality 1 alone (blue) versus across localities 1 and 2 (red). The median unbiased estimate for the first occurrence T_{FAD} (FAD = first appearance date) corresponds to the cumulative density of 0.5.



Figure B4: Disproportionate impact of incomplete sampling on short temporal ranges. The same probability of sampling results in proportionately greater range truncation for truly short ranges. In other words, deterioration in sampling quality tends to exaggerate the

difference in duration between short-lived and long-lived taxa. Consequently, both absolute and relative durations of taxa are distorted by incomplete sampling.



Figure B5: Illustration of Marshall's (2010) generalized confidence interval method as applied to this study. The fossil recovery potential curve g(t) is derived from per-myr range-through sampling probabilities and the assumption of a constant sampling probability within each 1-myr interval. Terms T_{FAD} and T_{LAD} are observed first and last appearance dates, respectively, and x_{FAD} and x_{LAD} are their corresponding temporal extensions for a given confidence level. Terms T_{FAD50} and T_{LAD50} mark the median unbiased confidence interval estimates for the first and last appearance dates. The gray and black areas under the curve represent x^* and r^* , as discussed in the text.

Group	Ν	Predictor	Intercept	Slope	R^2	Reference
Primates	42	m1LxW	3.577	1.490	.933	Legendre 1986; table 1
Rodentia	19	m1LxW	2.172	1.767	.962	Legendre 1986; table 1
Lagomorpha	27	LARL	-2.671	3.671	.964	S. Tomiya, unpublished data
Lagomorpha	27	m1L	3.002	4.468	.937	S. Tomiya, unpublished data
Lipotyphla	40	m1LxW	1.726	1.628	.939	Bloch et al. 1998, p. 814
Carnivores	72	m1L	1.681	2.970	.689	Van Valkenburgh 1990; table 10.2
Canidae	14	m1L	4.099	1.820	.757	Van Valkenburgh 1990; table 10.2
Felidae	16	m1L	1.957	3.050	.903	Van Valkenburgh 1990; table 10.2
Ungulates	139	LMRL	-1.374	3.113	.942	Mendoza et al. 2006; appendix S1
Ungulates	139	M2L	2.475	3.004	.920	Mendoza et al. 2006; appendix S1
Ungulates	138	M2LxW	2.792	1.518	.940	Mendoza et al. 2006; appendix S1
Ungulates	138	m1LxW	3.757	1.516	.941	Mendoza et al. 2006; appendix S1
Ungulates	138	m2L	2.366	3.076	.940	Mendoza et al. 2006; appendix S1
Suiformes	8	m2L	3.701	2.445	.824	Mendoza et al. 2006; appendix S1

Table B1. Allometric equations for body mass estimation

Note: LARL = lower alveolar-row length; LMRL = lower molar-row length; M2LxW = product of the anteroposterior length and transverse width of the upper second molar; m2L = anteroposterior length of lower second molar; m1LxW = product of the anteroposterior length and transverse width of the lower first molar; N = number of extant species included in ordinary least squares regression analysis.

Table B2. Primary taxonomic references

Order, group	Primary reference				
Artiodactyla:					
Dichobunidae	Stucky 1998				
Entelodontidae	Effinger 1998				
Anthracotheriidae	Kron and Manning 1998				
Tayassuidae	Wright 1998				
Oreodontoidea	Lander 1998				
Protoceratidae	Prothero 1998a				
Camelidae	Honey et al. 1998				
Dromomerycidae	Janis and Manning 1998b				
Antilocapridae	Janis and Manning 1998a				
(other ruminants)	Webb 1998				
Perissodactyla:					
Equidae	MacFadden 1998; Janis et al. 2008				
Chalicotheriidae	Coombs 1998				
Tapiridae	Colbert and Schoch 1998; Albright 1998; Janis et al. 2008				
Rhinocerotidae	Prothero 1998b, 2005; Prothero and Rasmussen 2008				
Carnivora:					
Amphicyonidae	Hunt 1998a				
Canidae	Wang 1994; Wang et al. 1999; Tedford et al. 2009				
Procyonidae	Baskin 1998b, 2004				
Mustelidae	Baskin 1998a				
Mephitidae	Baskin 1998a				
Ursidae	Hunt 1998b				
Nimravidae	Martin 1998b				
Felidae	Martin 1998a				
Lipotyphla	Gunnell et al. 2008				
Lagomorpha:					
Leporidae	Dawson 2008				
Ochotonidae	Dawson 2008				
Rodentia:					
Sciuridae	Goodwin 2008				
Aplodontoidea	Hopkins 2008a				
Castoroidea	Flynn and Jacobs 2008				
Dipodidae	Flynn 2008a				
Eomyidae	Flynn 2008b				
Geomorpha	Flynn et al. 2008				
Cricetidae	Lindsay 2008				
Arvicolinae	Martin 2008				
Erethizontidae	Flynn 2008c				

Literature Cited Only in Appendix B

- Albright, L. B. 1998. New genus of tapir (Mammalia: Tapiridae) from the Arikareean (earliest Miocene) of the Texas Coastal Plain. Journal of Vertebrate Paleontology 18:200–217.
- Barry, J. C., M. E. Morgan, L. J. Flynn, D. Pilbeam, A. K. Behrensmeyer, S. M. Raza, I. A. Khan, C. Badgley, J. Hicks, and J. Kelley. 2002. Faunal and environmental change in the late Miocene Siwaliks of northern Pakistan. Paleobiology 28(spec. issue 3):1–71.
- Baskin, J. A. 1998a. Mustelidae. Pages 152–173 in C. M. Janis, K. M. Scott, and L. L. Jacobs, eds. Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- ——. 1998b. Procyonidae. Pages 144–151 *in* C. M. Janis, K. M. Scott, and L. L. Jacobs, eds. Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- ———. 2004. Bassariscus and Probassariscus (Mammalia, Carnivora, Procyonidae) from the early Barstovian (middle Miocene). Journal of Vertebrate Paleontology 24:709–720.
- Bloch, J. I., K. D. Rose, and P. D. Gingerich. 1998. New species of *Batodonoides* (Lipotyphla, Geolabididae) from the early Eocene of Wyoming: smallest known mammal? Journal of Mammalogy 79:804–827.
- Colbert, M. W., and R. M. Schoch. 1998. Tapiroidea and other moropomorphs. Pages 569–582 *in* C. M. Janis, K. M. Scott, and L. L. Jacobs, eds. Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- Coombs, M. C. 1998. Charicotheriidae. Pages 560–568 *in* Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- Czaplewski, N. J. 1990. The Verde local fauna: small vertebrate fossils from the Verde Formation, Arizona. San Bernardino County Museum Association Quarterly 37:1–39.
- Dawson, M. R. 2008. Lagomorpha. Pages 293–310 in C. M. Janis, G. F. Gunnell, and M. D. Uhen, eds. Evolution of Tertiary mammals of North America. Vol. 2. Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge.
- Effinger, J. A. 1998. Entelodontidae. Pages 375–380 *in* Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- Flynn, L. J. 2008a. Dipodidae. Pages 406–414 in C. M. Janis, G. F. Gunnell, and M. D. Uhen, eds. Evolution of Tertiary mammals of North America. Vol. 2. Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge.
 - ——. 2008b. Eomyidae. Pages 415–427 in C. M. Janis, G. F. Gunnell, and M. D. Uhen, eds. Evolution of Tertiary mammals of North America. Vol. 2. Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge.
- ——. 2008c. Hystricognathi and Rodentia incertae sedis. Pages 498–506 in C. M. Janis, G. F. Gunnell, and M. D. Uhen, eds. Evolution of Tertiary mammals of North America. Vol. 2. Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge.
- Flynn, L. J., and L. L. Jacobs. 2008. Castoroidea. Pages 391–405 in C. M. Janis, G. F. Gunnell, and M. D. Uhen, eds. Evolution of Tertiary mammals of North America. Vol. 2. Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge.
- Flynn, L. J., H. Lindsay, Everett, and R. A. Martin. 2008. Geomorpha. Pages 428–455 in C. M. Janis, G. F. Gunnell, and M. D. Uhen, eds. Evolution of Tertiary mammals of North America. Vol. 2. Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge.
- Foote, M. 2000. Origination and extinction components of taxonomic diversity: general problems. Paleobiology 26:74–102.
- Foote, M., and D. M. Raup. 1996. Fossil preservation and the stratigraphic ranges of taxa. Paleobiology 22:121–140.
- Foss, S. E. 2007. Family Entelodontidae. Pages 120–129 *in* D. R. Prothero and S. E. Foss, eds. The evolution of artiodactyls. Johns Hopkins University Press, Baltimore.
- Geisler, J. H., J. M. Theodor, M. D. Uhen, and S. E. Foss. 2007. Phylogenetic relationships of cetaceans to terrestrial artiodactyls. Pages 19–31 *in* D. R. Prothero and S. E. Foss, eds. The evolution of artiodactyls. Johns Hopkins University Press, Baltimore.
- Geisler, J. H., and M. D. Uhen. 2005. Phylogenetic relationships of extinct cetartiodactyls: results of simultaneous analyses of molecular, morphological, and stratigraphic data. Journal of Mammalian Evolution 12:145–159.

- Goodwin, H. T. 2008. Sciuridae. Pages 355–376 in C. M. Janis, G. F. Gunnell, and M. D. Uhen, eds. Evolution of Tertiary mammals of North America. Vol. 2. Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge.
- Gunnell, F., Gregg, T. M. Bown, J. H. Hutchison, and J. I. Bloch. 2008. Lipotyphla. Pages 89–125 in C. M. Janis, G. F. Gunnell, and M. D. Uhen, eds. Evolution of Tertiary mammals of North America. Vol. 2. Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge.
- Hall, E. R. 1930. Three new genera of Mustelidae from the later Tertiary of North America. Journal of Mammalogy 11: 146–155.
- Hayes, F. G. 2000. The Brooksville 2 local fauna (Arikareean, latest Oligocene): Hernando County, Florida. Bulletin of the Florida Museum of Natural History 43:1–47.
- Honey, J. G., J. A. Harrison, D. R. Prothero, and M. S. Stevens. 1998. Camelidae. Pages 439–462 in C. M. Janis, K. M. Scott, and L. L. Jacobs, eds. Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.

Hooker, J. J., and D. Dashzeveg. 2004. The origin of chalicotheres (Perissodactyla, Mammalia). Palaeontology 47:1363–1386.

Hopkins, S. S. B. 2008*a*. Phylogeny and evolutionary history of the Aplodontoidea (Mammalia: Rodentia). Zoological Journal of the Linnean Society 153:769–838.

——. 2008b. Reassessing the mass of exceptionally large rodents using toothrow length and area as proxies for body mass. Journal of Mammalogy 89:232–243.

- Hunt, R. M., Jr. 1998a. Amphicyonidae. Pages 196–227 in C. M. Janis, K. M. Scott, and L. L. Jacobs, eds. Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- ——. 1998b. Ursidae. Pages 174–195 in C. M. Janis, K. M. Scott, and L. L. Jacobs, eds. Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- ——. 2002. New amphicyonid carnivorans (Mammalia, Daphoeninae) from the early Miocene of southeastern Wyoming. American Museum Novitates 3385:1–41.

Janis, C. M., and E. Manning. 1998a. Antilocapridae. Pages 491–507 in Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
 ——. 1998b. Dromomerycidae. Pages 477–490 in Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial

carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.

Kelly, T. S. 1998. New middle Miocene equid crania from California and their implications for the phylogeny of the Equini. Contributions in Science, Natural History Museum of Los Angeles County 473:1–44.

———. 2007. A new species of *Bensomys* (Rodentia, Cricetidae) from the late early Hemphillian (late Miocene), Coal Valley Formation, Smith Valley, Nevada. Paludicola 6:125–138.

Korth, W. W. 1996. Geomyoid rodents (Mammalia) from the Bijou Hills Local Fauna (Barstovian), South Dakota. University of Wyoming Contributions to Geology 31:49–55.

——. 1999. A new species of beaver (Rodentia, Castoridae) from the earliest Barstovian (Miocene) of Nebraska and the phylogeny of *Monosaulax* Stirton. Paludicola 2:258–264.

——. 2001. Comments on the systematics and classification of the beavers (Rodentia, Castoridae). Journal of Mammalian Evolution 8:279–296.

——. 2002. Review of the castoroidine beavers (Rodentia, Castoridae) from the Clarendonian (Miocene) of north central Nebraska. Paludicola 4:15–24.

------. 2007*a*. A new genus of beaver (Rodentia, Castoridae) from the Miocene (Clarendonian) of North America and systematics of the Castoroidinae based on comparative cranial anatomy. Annals of Carnegie Museum 76:117–134.

——. 2007b. A new species of *Ansomys* (Rodentia, Aplodontidae) from the late Oligocene (latest Whitneyan–earliest Arikareean) of South Dakota. Journal of Vertebrate Paleontology 27:740–743.

——. 2007*c*. Mammals from the Blue Ash local fauna (late Oligocene), South Dakota. Rodentia, pt. 1: families Eutypomyidae, Eomyidae, Heliscomyidae, and *Zetamys*. Paludicola 6:31–40.

Korth, W. W., and B. E. Bailey. 2006. Earliest castoroidine beaver (Rodentia, Castoridae) from the late Arikareean (early Miocene) of Nebraska. Annals of Carnegie Museum 75:237–245.

Korth, W. W., and C. Branciforte. 2007. Geomyoid rodents (Mammalia) from the Ridgeview local fauna, early-early Arikareean (late Oligocene) of western Nebraska. Annals of Carnegie Museum 76:177–201.

Kron, D. G., and E. Manning. 1998. Anthracotheriidae. Pages 381–388 *in* Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.

- Lander, E. B. 1998. Oreodontoidea. Pages 402–425 *in* Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- Legendre, S. 1986. Analysis of mammalian communities from the Late Eocene and Oligocene of southern France. Palaeovertebrata 16:191–212.
- Lindsay, E. H. 2008. Cricetidae. Pages 456–479 in C. M. Janis, G. F. Gunnell, and M. D. Uhen, eds. Evolution of Tertiary mammals of North America. Vol. 2. Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge.
- MacFadden, B. J. 1998. Equidae. Pages 537–559 in C. M. Janis, K. M. Scott, and L. L. Jacobs, eds. Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- Martin, L. D. 1998a. Felidae. Pages 236–242 in C. M. Janis, K. M. Scott, and L. L. Jacobs, eds. Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
 - ——. 1998b. Nimravidae. Pages 228–235 in C. M. Janis, K. M. Scott, and L. L. Jacobs, eds. Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- Martin, L. D., and J. D. Lim. 2004. New insectivores from the Early Miocene of Nebraska, USA, and the Hemingfordian faunal exchange. Mammalian Biology 69:202–209.
- Martin, R. A. 2008. Arvicolinae. Pages 480–497 in C. M. Janis, G. F. Gunnell, and M. D. Uhen, eds. Evolution of Tertiary mammals of North America. Vol. 2. Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge.
- McKenna, M. C., A. R. Bleefeld, and J. S. Mellett. 1994. Microvertebrate collecting: large-scale wet sieving for fossil microvertebrates in the field. Pages 93–112 *in* P. Leiggi and P. May, eds. Vertebrate paleontological techniques. Vol. 1. Cambridge University Press, Cambridge.
- Mendoza, M., C. M. Janis, and P. Palmqvist. 2006. Estimating the body mass of extinct ungulates: a study on the use of multiple regression. Journal of Zoology 270:90–101.
- Mörs, T., and C. Stefen. 2010. The castorid *Stenofiber* from NW Germany and its implications for the taxonomy of Miocene beavers. Acta Palaeontologica Polonica 55:189–198.
- O'Leary, M. A., and J. Gatesy. 2008. Impact of increased character sampling on the phylogeny of Cetartiodactyla (Mammalia): combined analysis including fossils. Cladistics 24:397–442.
- Paul, C. R. C. 1982. The adequacy of the fossil record. Pages 75–117 in K. A. Joysey and A. E. Friday, eds. Problems of phylogenetic reconstruction. Academic Press, London.
- Prothero, D. R. 1998a. Protoceratidae. Pages 431–438 *in* Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- ——. 1998b. Rhinoceratidae. Pages 595–605 *in* Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- _____. 2005. The evolution of North American rhinoceroses. Cambridge University Press, Cambridge.
- Prothero, D. R., and M. R. Liter. 2007. Family Palaeomerycidae. Pages 241–248 *in* D. R. Prothero and S. E. Foss, eds. The evolution of artiodactyls. Johns Hopkins University Press, Baltimore.
- Prothero, D. R., and D. L. Rasmussen. 2008. New giant rhinoceros from the Arikareean (Oligocene-Miocene) of Montana, South Dakota and Wyoming. New Mexico Museum of Natural History and Science Bulletin 44:323–330.
- Repenning, C. A., and F. Grady. 1988. The microtine rodents of the cheetah room fauna, Hamilton Cave, West Virginia, and the spontaneous origin of *Synaptomys*. United States Geological Survey Bulletin 1853:1–32.
- Scherer, C. S. 2013. The Camelidae (Mammalia, Artiodactyla) from the Quaternary of South America: cladistic and biogeographic hypotheses. Journal of Mammalian Evolution 20:45–56.
- Spaulding, M., M. A. O'Leary, and J. Gatesy. 2009. Relationships of Cetacea (Artiodactyla) among mammals: increased taxon sampling alters interpretations of key fossils and character evolution. PLoS ONE 4:e7062.
- Stefen, C., and T. Mörs. 2008. The beaver *Anchitheriomys* from the Miocene of central Europe. Journal of Paleontology 82:1009–1020.
- Strauss, D., and P. M. Sadler. 1989. Classical confidence-intervals and Bayesian probability estimates for ends of local taxon ranges. Mathematical Geology 21:411–421.
- Stucky, R. K. 1998. Eocene bunodont and bunoselenodont Artiodactyla. Pages 358–374 in Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.
- Tomiya, S. 2011. A new caniform (Carnivora: Mammalia) from the middle Eocene of North America and remarks on the phylogeny of early carnivorans. PLoS ONE 6:e24146.

- Van Valkenburgh, B. 1990. Skeletal and dental predictors of body mass in carnivores. Pages 181–205 in J. Damuth and B. J. MacFadden, eds. Body size in mammalian paleobiology: estimation and biological implications. Cambridge University Press, Cambridge.
- Wang, X., M. C. McKenna, and D. Dashzeveg. 2005a. Amphicticeps and Amphicynodon (Arctoidea, Carnivora) from Hsanda Gol Formation, central Mongolia and phylogeny of basal arctoids with comments on zoogeography. American Museum Novitates 3483:1–57.
- Wang, X., D. P. Whistler, and G. T. Takeuchi. 2005b. A new basal skunk *Martinogale* (Carnivora, Mephitinae) from Late Miocene Dove Spring Formation, California, and origin of New World mephitines. Journal of Vertebrate Paleontology 25:936–949.
- Webb, S. D. 1998. Hornless ruminants. Pages 463–476 *in* Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.

———. 2008. Revision of the extinct Pseudoceratinae (Artiodactyla: Ruminantia: Gelocidae). Bulletin of the Florida Museum of Natural History 48:17–58.

Wright, D. B. 1998. Tayassuidae. Pages 389–401 in Evolution of Tertiary mammals of North America. Vol. 1. Terrestrial carnivores, ungulates, and ungulatelike mammals. Cambridge University Press, Cambridge.