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Supplementary Materials for

The end-Cretaceous mass extinction restructured functional diversity but failed to configure the modern marine biota

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This PDF file includes:

Supplementary Text

Sensitivity test: analyzing shifts in functional structure using only those genera in the Recent biota with a known fossil record

Compared to the end-Cretaceous fossil biota, the different configuration of the relatively richer Recent biota might reflect, in part, stronger taxon sampling, molecular genetic data, and direct observations of life habits. However, only two functional groups in the Recent biota are composed entirely of genera lacking a known fossil record (group numbers 47 and 48; Fig. S3A); no extinct genera occurring within the Cenozoic are known to occupy these life habits, and each contains a single genus (*Dacosta* and *Vadumodiolus*, respectively), each restricted to a limited geographic area, implying that they have likely evolved only very recently. The 272 genera occurring in the Recent biota that lack a known fossil record are distributed throughout the rank order of functional groups, but most are concentrated in the richest groups (Fig. S3A). Genera within the Galeommatoidea (i.e. most of the diversity within functional groups 11 and 33) show the highest proportion of genera lacking a known fossil record (still less than 50% of the diversity within each function). Taken at face value, this might indicate a failure to sample small, aragonitic shells in the fossil biotas (unlikely given that other small, aragonitic shells are well-known and sampled from end-Cretaceous faunas). Alternatively, lagged taxonomic evaluation of fossil members in this group using Recent concepts might inflate its apparent increase in genus-richness. However, the diversities of functional groups 11 and 33 in the end-Cretaceous biota would need to triple in order to match their diversity ranks in the Recent biota (Fig. S3B). Accepting that level of diversity increase would remove the largest shift in the structures of the fossil and Recent biotas, but it would strengthen the observation that low-diversity functions have remained so, and that reshuffling of rank order was concentrated among the richest functional groups. Overall, the shift in rank order of functional groups between the end-Cretaceous and Recent biotas holds when only genera with a known fossil record are considered (Fig. S3C).

Topological hypotheses for grafting additional families to the Crouch et al. (*76*) family-level bivalve tree

Stratigraphic ranges of families below based on their occurrences of their first and last known genera from Foote et al. (*21*). Stage ages from the 2012 Geologic Timescale (*83*).

PTERIOMORPHIA

†Buchiidae

Stratigraphic Range. 250–66 Ma

Topology. Sister to †Oxytomidae herein, based on the composition of Hyporder †Monotoidei in Carter et al. (*84*), as other members in that monophyletic group do not enter into this analysis. †Oxytomoidea is derived from †*Eumorphotis* in †Aviculopectinidae by Lutikov et al. (*85*) (and in Hyporder †Aviculopectinoidei by Carter et al. (*84*)); we tentatively place Oxytomidae + Buchiidae in Order Pectinida close to Neitheidae+Pectinidae and related groups.

†Eligmidae

Stratigraphic Range. 170.3–15.97 Ma

Topology. Sister to Ostreidae herein, reflecting placement within Ostreoidea in Carter et al. (*84*); we operationally incorporate Arctostreidae and Flemingostreidae into Ostreidae herein.

†Inoceramidae

Stratigraphic Range. 201.3–66 Ma

Topology. Basal to Ostreida herein. †Inoceramidae are within Megaorder Myalinata according to Carter et al. (*84*), which is sister to their Megaorder Ostreata. The association of inoceramids with ostreids and pterioids is further supported by Knight & Morris (*86*), who use muscle scar morphology to place †Inoceramidae “in the same clade as the Isognomonidae and Ostreidae, of the Pteriomorphia”, citing also Tëmkin (*87*), Bieler et al. (*88*) and Combosch et al. (*16*). Bieler et al. (*89*) place †Inoceramidae within †Ambonychioidea within Pteriida,
The potential ancestral taxon †*Atomodesma* was put variously in †Atomodesmatidae within †Inoceramoida by Carter et al. (*84*) and (as †Ambonychiidae) in Pteriida within †Ambonychioidea by Bieler et al. (*89*).

†Neitheidae

Stratigraphic Range. 145–66 Ma

Topology. Within Pectinida and basal to Pectinoidea herein following Bieler et al. (*89*) and Carter et al. (*84*). Waller (*90*) places †Neitheidae as sister to †Tosapectinidae, and that pair as sister to Pectinidae+Spondylidae

†Oxytomidae

Stratigraphic Range. 289.9–66 Ma

Topology. Sister to †Buchiidae herein, based on the composition of Hyporder †Monotoidei in Carter et al. (*84*), as other members in that monophyletic group do not enter into this analysis.

PALAEOHETERODONTA

†Myophorellidae

Stratigraphic Range. 201.3–66 Ma

Topology. Sister to Trigoniidae herein, following Bieler et al. (*89*) and Carter et al. (*84*) both of whom place Trigonioidea and †Myophorelloidea together in Trigoniida. We group all trigonioid families as a single unit sister to Myophorelloidea therefore to Myophorellidae.

ARCHIHETERDONTA

ANOMALODESMATA

†Pleuromyidae

Stratigraphic Range. 251.1–66 Ma

Topology. Sister to Pholadomyidae herein, following Bieler et al. (*89*), who group them within the Pholadomyoidea, but contra Carter et al. (*84*) who place them, with †Ceratomyidae, within the Pholadoidea. Carter et al.'s (*84*) placement appears not to have been widely adopted; most subsequent papers follow the Bieler et al. (*89*) classification (e.g. Ayoub-Hannaa et al. (*91*); Tiwari et al. (*92*); Hodges (*93*); Moussavou (*94*); Morton & Machado (*95*), but see Scott & Claggett (*96*)).

IMPARIDENTIA

Hippuritida + Megalodontida

Here, we follow relationships outlined in the revised Treatise on Invertebrate Paleontology by Skelton (*26*). For a more complex view of the relationships among rudist genera see Rineau et al. (*97*). Our results are not sensitive to these alternatives given the monophyly of Hippuritida+Megalodontida.

†Antillocaprinidae

Stratigraphic Range. 85–66 Ma

Topology. Sister to Caprinidae herein, following Skelton (*26*).

†Caprinidae

Stratigraphic Range. 133.9–66 Ma

Topology. Sister to Antillocaprinidae herein, following Skelton (*26*).

†Dicerocardiidae

Stratigraphic Range. 245.23–66 Ma

Topology. Most modern authors, led by foundational insights from Skelton, derive the 'rudist' families ultimately from the †Megalodontoidea. Accordingly, †Dicerocardiidae, the only family within †Megalodontida that reaches the K/Pg, are placed herein as sister taxon to the rudist families, and this clade is within Imparidentia but above the Lucinida, congruent with Carter et al. (*84*) who place them within their Megaorder Cardiata (Neoheterodontei of Taylor et al. (*98*)) and above modiomorphids, Morris (*99*), who derives †Megalodontidae from modiomorphids, and Nevesskaja (*100*) who associates †Megalodontidae with Order Carditida.

†Hippuritidae

Stratigraphic Range. 93.9–66 Ma

Topology. Sister to Trechmanellidae herein.

†Monopleuridae

Stratigraphic Range. 145–56 Ma

Topology. Sister to Radiolitidae herein.

†Plagioptychidae

Stratigraphic Range. 93.9–66 Ma

Topology. Sister to Hippuritidae+Trechmannellidae herein.

†Radiolitidae

Stratigraphic Range. 132.1–66 Ma

Topology. Sister to Monopleuridae herein.

†Requieniidae

Stratigraphic Range. 154.9–66 Ma

Topology. Most basal of the 'rudist' families herein, which are all sister to Dicerocardiidae.

†Trechmannellidae

Stratigraphic Range. 75.93–66 Ma

Topology. Sister to Hippuritidae herein.

Other Imparidentia

†Kalenteridae
Stratigraphic Range. 407.6–7.25 Ma

Topology. The phylogenetic position of the extinct family Kalenteridae remains uncertain. We place this family basal to Imparidentia less Lucinida, as in Crouch et al. (*76*) (see also Carter et al. (*84*)); but it may belong in the Anomalodesmata (the sister group to Imparidentia), as in Morris et al. (*101*), Fang & Morris (*102*), Kelly et al. (*103*), Griffin & Pastorino (*104*); in the Archiheterodonta (the sister group to Imparidentia + Anomalodesmata), as in Chavan (*105*), Newell (*106*), Cox et al. (*107*), Nevesskaja (*100*), Kaim & Schneider (*108*), Jenkins et al. (*109*), Kiel (*110*), Amano et al. (*111*); in the Palaeoheterodonta (the sister group to Archiheterodonta + Imparidentia + Anomalodesmata), as in Hautmann (*112*, *113*) and Friesenbichler et al. (*114*); and some authors place the family and related taxa in an unspecified position within the Heteroconcha (=Palaeoheterodonta + Archiheterodonta + Imparidentia + Anomalodesmata), as in Jenkins et al. (*115*). Our results are not sensitive to any of these alternatives.

†Icanotiidae

Stratigraphic Range. 139.4–66 Ma

Topology. Sister to †Tancrediidae herein, together sister to Donacidae. Derived from †Tancrediidae in Casey (*116*). Bieler et al. (*89*) and Carter et al. (*84*) likewise place them within

Tellinoidea but without comment on any relationships between families within that group. Pohlo (*117*) also lacks any specific comment on relationships between †Icanotiidae and other tellinoid families despite extensive discussion of evolution within the group.

†Mactromyopsisidae

Stratigraphic Range. 248.6–66 Ma

Topology. Sister to Lucinidae herein. As Mactromyidae, this family is included in Lucinoidea by Bieler et al. (*89*) and Carter et al. (*84*). Hodges (*93*) removed †*Mactromya* from the group of genera set out by Chavan (*118*) as comprising the Mactromyidae, thus necessitating a new type genus– *†Mactromyopsis* – and the new name Mactromyopsisidae.

†Veniellidae

Stratigraphic Range. 143.5–31 Ma

Topology. Sister to Arcticidae herein. Included within Arcticoidea by Bieler et al. (*89*) and Carter et al. (*84*). †Veniellidae Dall 1895 (originally †Veniellinae and containing *†Veniella* Stoliczka 1870, †*Venilicardia* Stoliczka 1870, and (*Cyprina*=) *Arctica* Schumacher 1817 [*Arctica* has subsequently been removed to its own family Arcticidae along with †*Venilicardia*]) has a junior homonym †Veniellidae Gardner 2005 (containing †*Veniella* Stoliczka 1870, †*Roudairia* Munier-Chalmas 1881, †*Cicatrea* Stoliczka 1870, and †*Epicyprina* Casey 1952 but NOT †*Venilicardia*, which Gardner (*119*) instead includes in †Isocyprinidae). †Veniellidae Dall has been consistently treated as a member of Arcticoidea, but Gardner (*119*) considers his †Veniellidae to be a member of Veneroidea, with Arcticoidea a synonym of Veneroidea, a concept which has not been adopted widely and which we do not follow herein.

Assigning ecological functional groups

The functional ecology of each genus was evaluated using the primary literature on the behavioral/life-habits of specific taxa and aspects of their shell and soft-body morphologies. Families were not assumed to be homogenous in the functions of their genera unless no other information was available. Details on bivalve ecologies vary among genera—those taxa exploited for human food are often well-known, and are useful models for inferring the life habits of other, less well-known taxa. Known relationships of morphological features to functions (e.g. symmetry and auricle shape in pectinids regarding swimming or non-swimming ability, as discussed in Stanley (*13*) and subsequent literature) were used to make inferences where direct observations are unavailable. Where the primary literature and observational data support functional differences of species within genera, all known fossil and recent species within that genus were assessed. Notes on functional group assignments for each genus (and relevant species) are available in Dataset S1 (see the field "functional_reference"). Below are the operational definitions for functional group axes. All assignments were based on behavioral observations or interpreted functional morphologies of adults.*Axis: mobility*

mobile. Individuals capable of actively repositioning themselves if disturbed, e.g. reburial if dislodged from burrow or relocation if byssal attachment is lost (e.g. *Mytilus*, a byssate genus, can relocate if detached and is thus scored 'mobile').

immobile. Individuals incapable of actively repositioning themselves if disturbed.

swimming. Individuals capable of self-propulsion through water, even if this is not a routine component of their life habits, e.g. the deeply buried but capable swimmers in the Solenidae. Fossils may be scored as swimmers if their relevant shell morphology (i.e. shell symmetry, thickness etc.) is close to that of a confamilial known to swim.

Axis: attachment

unattached. Free living, i.e. individuals are not attached to their substratum by a byssus (as an adult) or via cementation.

byssate. Living attached to the substratum via a byssal apparatus as an adult. Includes taxa known to detach and re-attach. In fossil taxa, the byssate condition is inferred from the presence of a byssal notch, ctenolium, or other such structure.

cemented. Individuals that attach to the substratum via rigid fixation of one valve to the substratum, which forms a permanent bond, see Harper (2012:1) (*120*); includes taxa having a calcified byssus. Cementation in extinct taxa is determined via observations of well-developed cementation scars in adults.

Axis: substratum use

epifaunal. Living position such that both valves are almost entirely above the substratum-water interface. Reclining taxa where one valve is partially embedded in the substratum are treated as epifaunal.

semi-infaunal. Living position such that both valves are partially enclosed by the substratum. Rudists with the conical lower valve mostly within the substratum—such that the bulk of the animal is interred—are treated as semi-infaunal.

nestler. Most often referred to in the literature as an individual "nestled" into a crevice or among rocks. Given the difficulty in recovering such behaviors in fossil data, nestling is used here to mean living in a pre-made enclosure that affects the growth of the shell. Most often this is indicated by irregular exterior shell surfaces, as nestlers lack the ability to modify their enclosures. Note that nestling in pre-existing boreholes and crevices is directly observed in the fossil record.

commensal. Living position within or upon a host. Rare in the Bivalvia, this trait is primarily known from direct observations and inferred from phylogenetic context in the fossil record.

borer. Living position reached via active mechanical and/or chemical modification of the substratum such that the animal becomes enclosed in the boring. Any taxon capable of actively enlarging or modifying its enclosure is treated as a borer as opposed to a nestler (for instance *Pedum spondyloideum*, which modifies its coral home, is included here as a borer rather than a nestler).

infaunal asiphonate. Living position fully enclosed within the substratum, but constrained to be within contact of the substratum-water interface due to the animal's lack of siphons. Compare with shallow infaunal siphonate below, for which taxa may live at the substratum water interface but are capable of burrowing deeper at need and maintaining contact with the water column via extensible siphons.

shallow infaunal siphonate. Stanley 1970:67 (*13*) sets the convention for shallow burial as less than 2 to 3 cm below the substratum-water interface. The 3cm delimitation is used here, using the Euclidean distance from the substratum-water interface to the nearest point on the shell valves. For the majority of taxa in this category, that is the posterior end, but may be the umbo in certain taxa, e.g. many of the lucinids that live ventral margin down, and the lateral-most points on many tellinids that live with their commissure parallel to the substratum-water interface. The criteria for determining burial depth vary by taxon, and may include overall shell length and relative size of the pallial sinus, inflation, and any permanent gapes, all of which are considered in combination with observational data where available.

deep infaunal asiphonate. Living position deeper than 3cm, following the same framework defined above for *shallow infaunal siphonate*.

Axis: feeding

Feeding behaviours are difficult to infer from shell morphology alone and are almost always derived in this dataset either from direct observations recorded in the literature, or by extrapolation from what is known of the feeding behaviors of closely related genera. Dataset

S1's "functional_reference" column details for each genus if direct observation or inference was used.

subsurface deposit. Nutrition sourced via organic detritus within the substratum.

surface deposit. Nutrition sourced via organic detritus lying on the substratum.

suspension. Active intake and ingestion of suspended plankton from the water column. Also referred to as "filter feeding."

mixed deposit/suspension. Facultative use of both deposit- and suspension-feeding. See for example tellinids and mactrids.

carnivore. Capture of live animal prey (e.g. copepods, not phytoplankton).

photosymbiotic. Obligate or facultative associations with photosymbionts for nutrient acquisition. This has been inferred in fossil taxa by some authors using shell morphology.

chemosymbiotic. Obligate or facultative associations with chemosymbionts for nutrient acquisition. This has been inferred in fossil taxa by some authors using shell morphology—e.g. the space between the pallial line and adductor muscle scar hosts lucinid chemosymbionts and can be seen in fossils.

Supplemental Figures

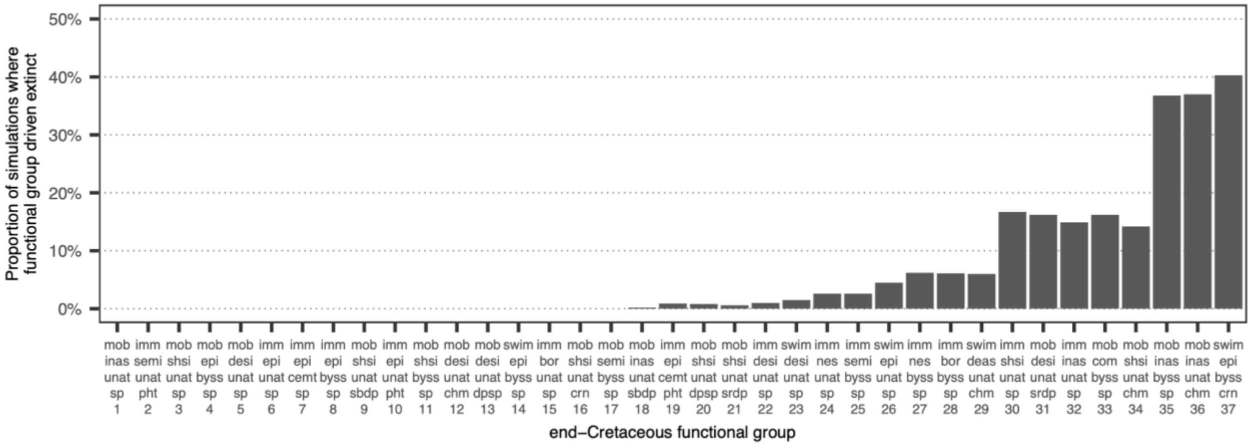

Figure S1. Proportion of extinction simulations where an end-Cretaceous (Maastrichtian) functional group was driven extinct by the random loss of its constituent genera. Functional abbreviations with functional group numbers as in Fig. 1B.

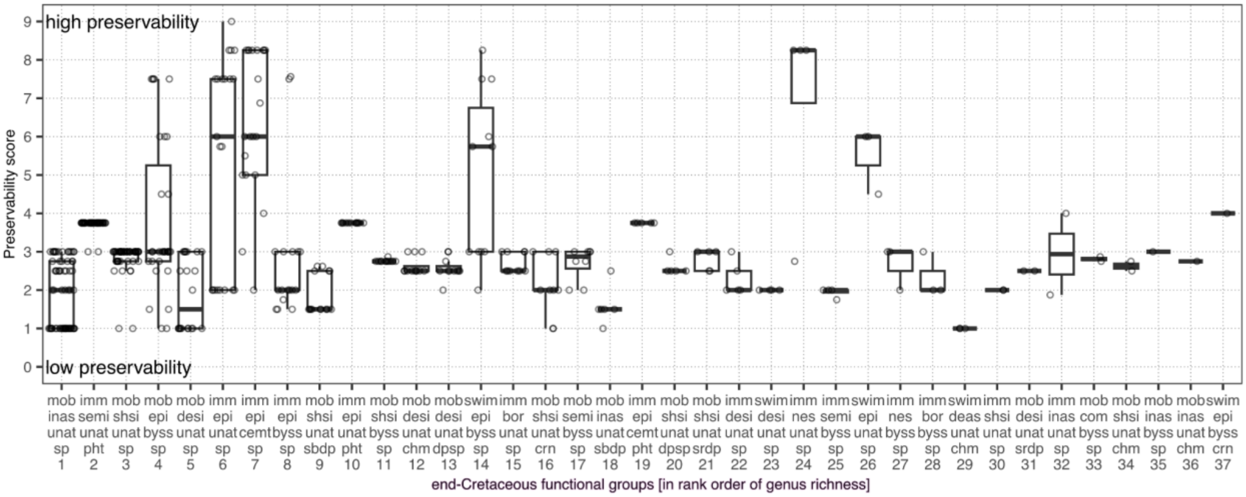

Figure S2. The rank order of genus richness within each end-Cretaceous functional group is not related to the preservation potential of genera within them. Aragonitic mineralogy and high organic content reduce preservation potential (*79*, *80*), giving an expectation of an inverse relation between genus richness and preservability score. Preservability scores as the product of mineralogy and organic content scores in ref. (*79*). Functional abbreviations as in Fig. 1B.

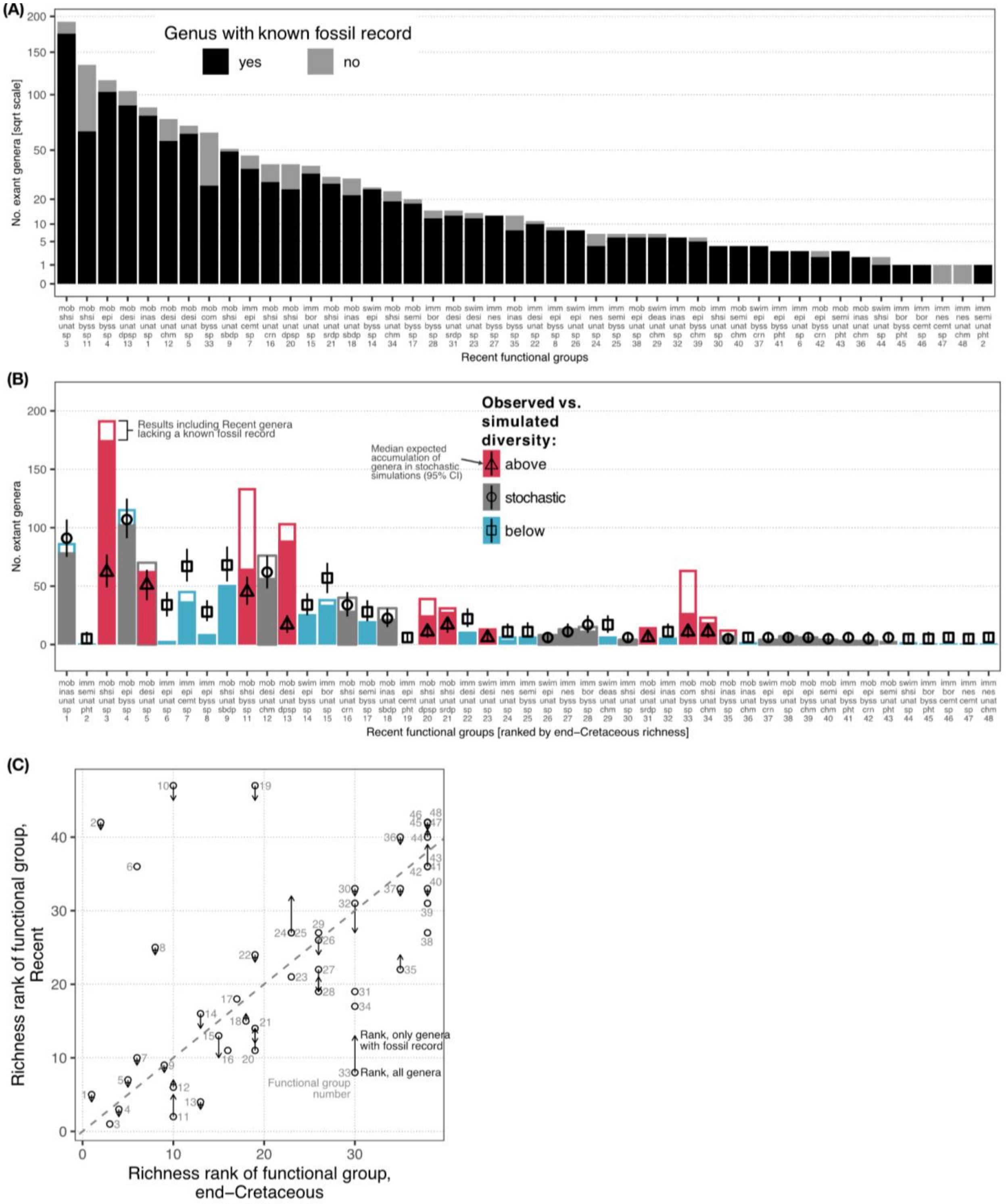

Figure S3. Sensitivity test: analyzing shifts in functional structure using only those genera in the Recent biota with a known fossil record. **(A)** Number of genera in Recent functional groups divided into those genera with and without a known fossil record. Functional group abbreviations and codes as in Fig. 1B. **(B)** Genus richness of functional groups today arrayed by their richness rank in the Late Cretaceous, with observed richness compared to the expectations from the random accumulation of genera from the survivor pool. Solid bars show results of an analysis using only genera with a known fossil record, and hollow bars show the results for all genera (i.e. the results in Fig. 3A). Functional abbreviations as in Fig. 1B. **(C)** Shifts in rank order of genus richness for functional groups shared between the end-Cretaceous and Recent biotas. Arrows show the change in rank order when analyzing only genera with a known fossil record.

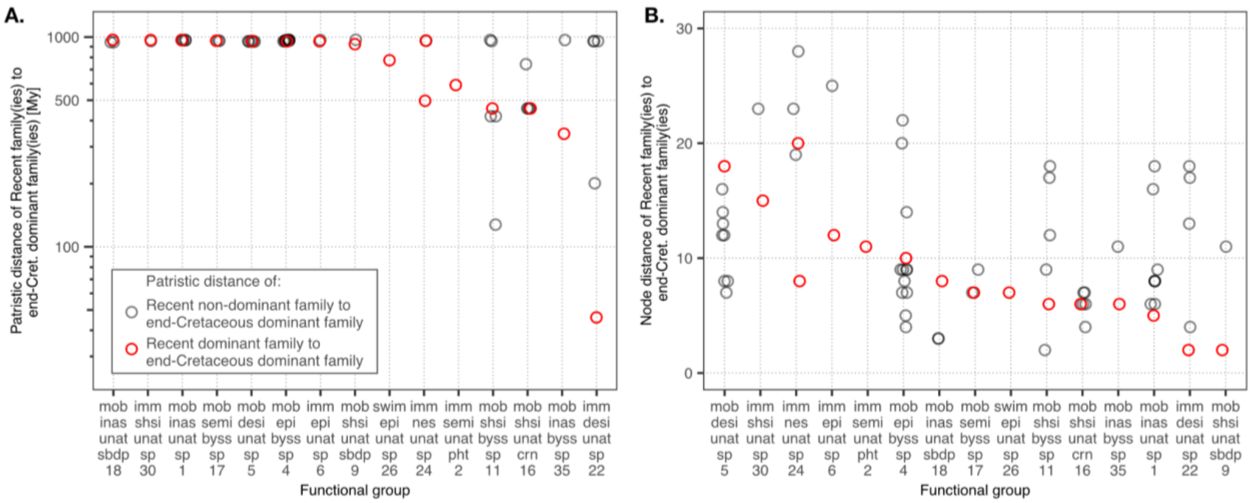

Figure S4. Patristic distances of families in functional groups that saw turnover in the dominant family between the Late Cretaceous and the Recent. **(A)** Patristic distances in millions of years. **(B)** Patristic distances in number of internodes.

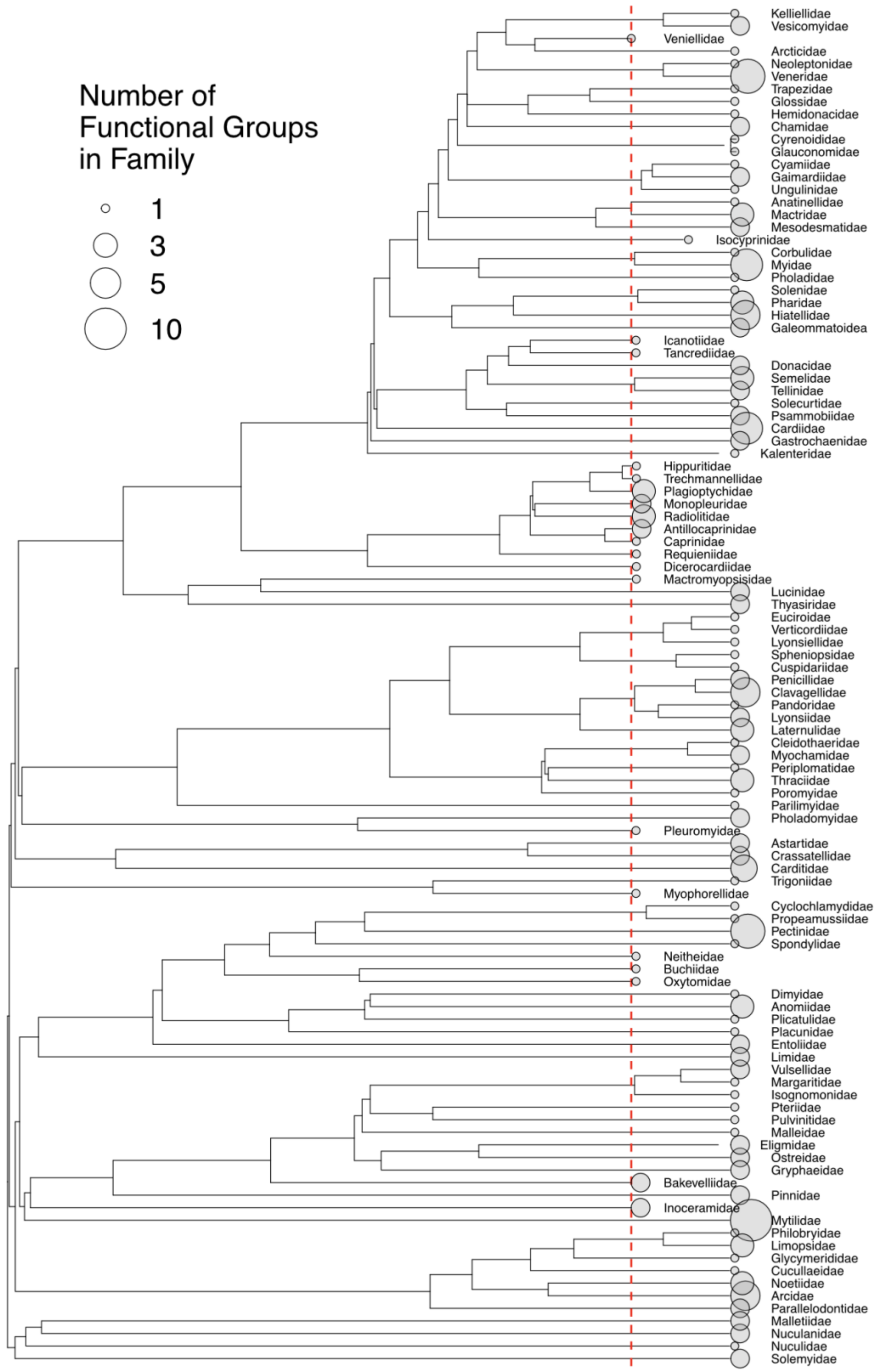

Figure S5. Number of functional groups present in families for the end-Cretaceous and Recent biotas.

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