

# Dinosaurs in decline tens of millions of years before their final extinction

Manabu Sakamoto<sup>a,1</sup>, Michael J. Benton<sup>b</sup>, and Chris Venditti<sup>a,1</sup>

<sup>a</sup>School of Biological Sciences, University of Reading, Reading RG6 6BX, United Kingdom; and <sup>b</sup>School of Earth Sciences, University of Bristol, Bristol BS8 1RJ, United Kingdom

Edited by Zhonghe Zhou, Chinese Academy of Sciences, Beijing, China, and approved March 1, 2016 (received for review October 30, 2015)

**Whether dinosaurs were in a long-term decline or whether they were reigning strong right up to their final disappearance at the Cretaceous–Paleogene (K–Pg) mass extinction event 66 Mya has been debated for decades with no clear resolution. The dispute has continued unresolved because of a lack of statistical rigor and appropriate evolutionary framework. Here, for the first time to our knowledge, we apply a Bayesian phylogenetic approach to model the evolutionary dynamics of speciation and extinction through time in Mesozoic dinosaurs, properly taking account of previously ignored statistical violations. We find overwhelming support for a long-term decline across all dinosaurs and within all three dinosaurian subclades (Ornithischia, Sauropodomorpha, and Theropoda), where speciation rate slowed down through time and was ultimately exceeded by extinction rate tens of millions of years before the K–Pg boundary. The only exceptions to this general pattern are the morphologically specialized herbivores, the Hadrosauriformes and Ceratopsidae, which show rapid species proliferations throughout the Late Cretaceous instead. Our results highlight that, despite some heterogeneity in speciation dynamics, dinosaurs showed a marked reduction in their ability to replace extinct species with new ones, making them vulnerable to extinction and unable to respond quickly to and recover from the final catastrophic event.**

dinosaurs | evolution | speciation | phylogeny | Bayesian methods

Nonavian dinosaurs met their demise suddenly, coincident with the Chicxulub impact in Mexico around 66 Mya; however, whether there was any long-term trend toward declining diversity leading to the Cretaceous–Paleogene (K–Pg) boundary has been controversial and debated for decades (1–14). This long-standing dispute has been prolonged partly because of differences in fossil datasets from different parts of the world and difficulties in rock dating but most importantly, methodological weaknesses—previous attempts have been nonphylogenetic, and analyses were conducted on simple time-binned tabulated data, resulting in a lack of statistical rigor (phylogenetic and temporal nonindependence have not been considered), and did not truly investigate evolutionary dynamics, such as speciation and extinction rates. In fact, patterns of speciation and extinction in dinosaurs have gone largely unstudied (8). Here, we study speciation dynamics (relationship between speciation and extinction rates) using an exclusively phylogenetic approach in a Bayesian framework.

If speciation and extinction rate were constant (but speciation was higher), we would expect to see a linear increase through time in the logarithm of the number of speciation events along each path of a phylogenetic tree (linear) (*Materials and Methods* and Fig. 1, model A). If speciation rate decreased through time but remained above extinction rate, then we would expect a curvilinear relationship (Fig. 1, models B and C). Such a relationship would reach an asymptote (speciation equals extinction) (Fig. 1, model B) and eventually, turn down as extinction rate surpasses speciation during the evolutionary history of the clade (Fig. 1, model C). The latter would correspond to a long-term pre–K–Pg demise in the case of dinosaurs. The distinction

between such evolutionary dynamics can only be made using phylogenies with taxa sampled through time.

## Results and Discussion

Using a phylogenetic generalized linear mixed model (GLMM) in a Bayesian framework (15) and three recent large comprehensive dinosaur phylogenies comprising 420 (8) and 614 taxa [two trees (16)], respectively, we found that the data are significantly better explained by a model, in which extinction rate exceeds speciation rate from ~24 My before the K–Pg boundary, than the simpler alternative model [difference in deviance information criterion ( $\Delta$ DIC) between linear and quadratic models >11] (Fig. 2A and Table S1). Our findings are qualitatively identical across all three trees, and we report on results from one of the 614-taxon trees (16).

Because nonhomogeneity in evolutionary rates is widespread and common in nature (17–19) and dinosaurs are diverse—from the bipedal, carnivorous theropods to the quadrupedal, mega-herbivorous sauropods—we might expect to find different speciation dynamics in the different dinosaurian subclades. When model parameters were estimated separately for each of the three main subclades (Ornithischia, Sauropodomorpha, and Theropoda), the same general pattern as in the total Dinosauria model was recovered but with extinction rates exceeding speciation rates earlier at 48–53 My before the K–Pg boundary ( $\Delta$ DIC > 12) (Fig. 2B and Table S1). Ornithischia here refers to nonhadrosauriform, nonceratopsid ornithischians, because the two Cretaceous subclades, Hadrosauriformes and Ceratopsidae, show speciation patterns distinct from other ornithischians; Lloyd et al. (8) also identified significant diversification shifts at the base of comparable clades [i.e., Euhadrosauria (here Hadrosauriformes) (*SI Text*) and Ceratopsidae]. In line with this finding, these two subclades show no signs of speciation slowdowns or downturns

## Significance

**Whether dinosaurs were in decline before their final extinction 66 Mya has been debated for decades with no clear resolution. This dispute has not been resolved because of inappropriate data and methods. Here, for the first time to our knowledge, we apply a statistical approach that models changes in speciation and extinction through time. We find overwhelming support for a long-term decline across all dinosaurs and within all three major dinosaur groups. Our results highlight that dinosaurs showed a marked reduction in their ability to replace extinct species with new ones, making them vulnerable to extinction and unable to respond quickly to and recover from the final catastrophic event 66 Mya.**

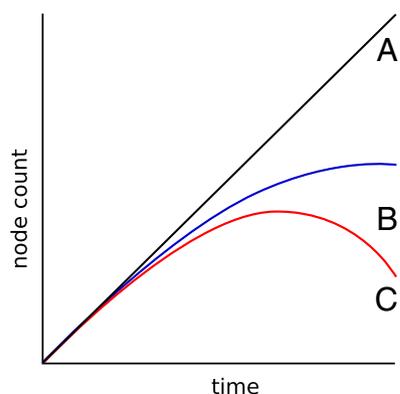
Author contributions: M.S., M.J.B., and C.V. designed research, performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

<sup>1</sup>To whom correspondence may be addressed. Email: m.sakamoto@reading.ac.uk or c.d.venditti@reading.ac.uk.

This article contains supporting information online at [www.pnas.org/lookup/suppl/doi:10.1073/pnas.1521478113/-DCSupplemental](http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1521478113/-DCSupplemental).



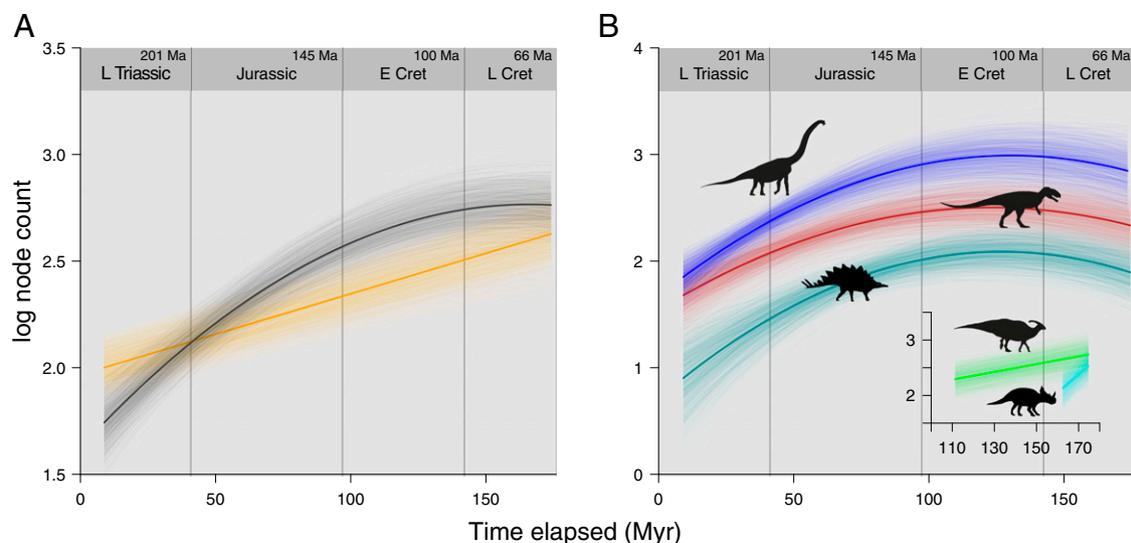
**Fig. 1.** Theoretical models of speciation through time. If speciation and extinction rate were constant through time (but speciation was higher) in dinosaurian history, we would expect to see a linear increase through time in the logarithm of the number of speciation events along each path of a phylogenetic tree (model A). If speciation rate decreased through time but remained above extinction rate, then we would expect a curvilinear relationship (models B and C). Such a relationship would reach an asymptote (speciation equals extinction; model B) and eventually, turn down as extinction rate surpassed speciation during the evolutionary history of the clade (model C). The latter would correspond to a long-term pre-K-Pg demise in the case of dinosaurs.

( $\Delta$ DIC between linear and quadratic models  $>5$  in favor of the linear model) (Figs. 2B, Inset and 3 and Table S1). Thus, the difference in the timing of the switch from slowdown to downturn in the Dinosauria model and for the three major clades is caused by the non-homogeneity in speciation processes across dinosaurian groups. However, these two subclades combined only represent 14% of dinosaur species; over time, dinosaurs overwhelmingly experienced a reduction in their capacity to replace extinct species with new ones—net speciation per 1 My at the time that dinosaurs went extinct (66 Mya) was significantly below zero (speciation rate is less than

extinction rate) (Fig. 3B) in the three major clades (Table S12)—and Hadrosauriformes and Ceratopsidae are the exceptions.

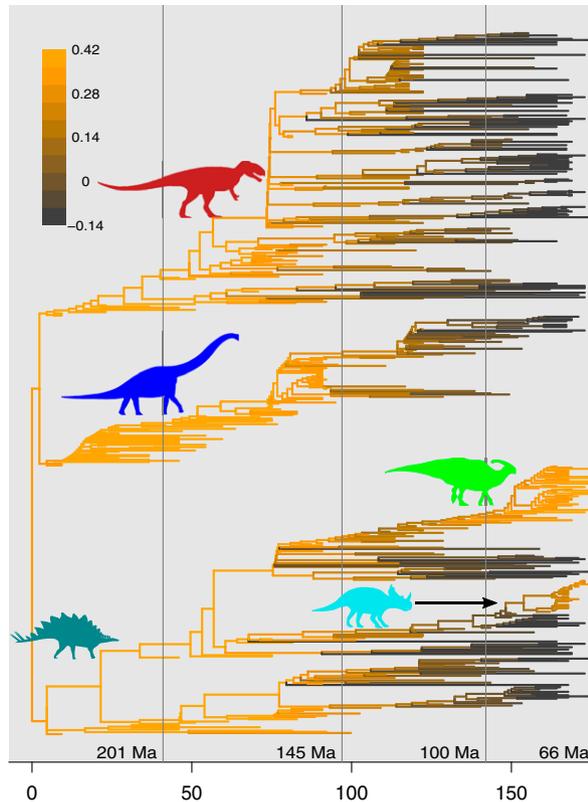
The most prominent downturn is seen in the sauropodomorphs, where speciation increases rapidly through the Triassic and Early Jurassic (an average of 0.137 speciation events for every 1 My) until  $\sim 195$  Mya; then, speciation rate starts to slow down, and extinction rate surpasses speciation rate at  $\sim 114$  Mya (Figs. 2B and 3). Early sauropodomorph lineages are numerous but not long-lasting, and taxa that originated earlier in geological time are successively replaced by younger ones. The near extinction of the diplodocoids at the end of the Jurassic 145 Mya did not affect high speciation rates (Fig. 3), and sauropodomorphs only began their decline  $\sim 30$  My into the Early Cretaceous (Fig. 3). The subsequent originations of titanosaurian taxa were not nearly enough to compensate for the continuous loss of sauropods throughout the remainder of the Cretaceous.

Speciation in theropods follows a slower increase ( $\sim 0.07$  speciation events for every 1 My) with an early onset of speciation slowdown from the Late Triassic  $\sim 215$  Mya to the Early Cretaceous  $\sim 120$  Mya, when extinction rate exceeds speciation rate (Figs. 2B and 3). Although Theropoda contains one of the most morphologically diverse dinosaurian clades, the coelurosaurs, which include the giant carnivorous tyrannosaurs, parrot-like oviraptorosaurs, large pot-bellied therizinosaurs, ostrich-like ornithomimosaurs, small sickle-clawed dromaeosaurs, and birds (most of which are Cretaceous in age), they originated in the Early to Middle Jurassic (Fig. 3), much earlier than expected from apparent fossil occurrences (8). Clades appearing even earlier (e.g., ceratosaurs, megalosauroids, and allosauroids) also persist into the Late Cretaceous, all of which might suggest that the theropod speciation pattern would be a classic “early burst” or adaptive radiation-type speciation (20) with long protracted branches (8), corresponding to a speciation slowdown model. Although our results do show an initial burst of speciation events and a gradual and prolonged slowdown, consistent with an early burst model, the fact that extinction rate surpasses speciation

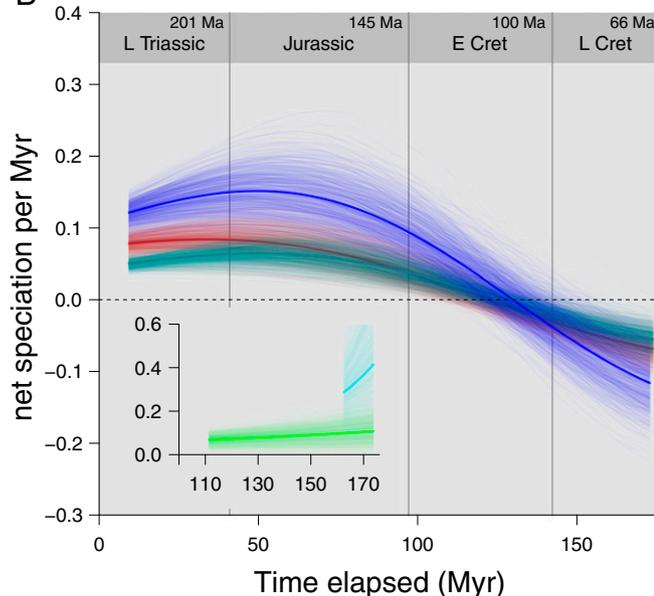


**Fig. 2.** Model predictions of speciation through time in Mesozoic dinosaurs. (A) Compared with the linear model (orange), the quadratic model displaying a speciation slowdown (dark gray) substantially improves model fit ( $\Delta$ DIC  $> 4$ ). (B) This pattern holds true in the three major clades [Ornithischia (green), Sauropodomorpha (blue), and Theropoda (red)] and further improves model fit. (B, Inset) Model fit significantly improves when separate model parameters are estimated for the ornithischian subclades Hadrosauriformes (light green) and Ceratopsidae (light blue) from other ornithischians, but the slowdown and downturn are not observed for the two Cretaceous ornithischian subclades. Posterior predictions (transparent lines) show the uncertainties in the model. Mean posterior values are shown as bold lines. Vertical lines indicate major stratigraphic boundaries (with their ages in millions of years ago). Silhouettes courtesy of [PhyloPic.org](http://PhyloPic.org) (CC BY 3.0) and Jack Mayer Wood (*Parasaurolophus*), Mathew Wedel (*Brachiosaurus*), Andrew A. Farke (*Stegosaurus* and *Ceratrosaurus*), and Martin Kevill (*Carcharodontosaurus*). E Cret, Early Cretaceous; L Cret, Late Cretaceous; L Triassic, Late Triassic.

A



B



**Fig. 3.** Net speciation per 1 Myr through time in Mesozoic dinosaurs. Net speciation per 1 Myr can be calculated from model predictions (Fig. 2B) as differences between intervals (here, per 1 Myr). (A) Each branch of a dinosaurian phylogeny was assigned a net speciation per 1-Myr value based on its temporal location and group membership and plotted on a color gradient. Earlier branches have higher net speciation per 1 Myr (orange), whereas later branches have lower net speciation per 1 Myr (dark gray), except in Hadrosauriformes and Ceratopsidae, in which net speciation per 1 Myr increases with time. (B) The three major dinosaur groups [Sauropodomorpha (blue), Theropods (red), and nonhadrosauriform, nonceratopsid Ornithischia (green)] show an early onset of speciation slowdown until the middle of the Early Cretaceous, when speciation rates are exceeded by extinction rate (net speciation per 1 Myr falls below zero; dashed horizontal line). Values above zero indicate increases in species counts,

rate highlights a more complex process in theropods (Figs. 2B and 3).

Because birds underwent a radiation in the Early Cretaceous after their appearance in the Middle to Late Jurassic, one might expect that their pattern of speciation would be distinct from that of nonavian theropods. However, when we allow separate coefficients (intercept, slope, and quadratic terms) in our model to be estimated for birds and nonavian theropods, the resulting regression parameters were not significant: in other words, the speciation dynamics in Mesozoic birds are not distinct from those of nonavian theropods (Tables S1–S10). This result is in line with recent findings of a high, sustained rate of change from the Late Triassic to the Early Cretaceous in the entire theropod lineage leading to *Archaeopteryx* and among the earliest birds (21, 22).

Ornithischians show a similar increase to theropods ( $\sim 0.06$  speciation events for every 1 Myr) to  $\sim 192$  Mya followed by a slowdown to  $\sim 114$  Mya, at which point extinction rate exceeds speciation rate (Figs. 2B and 3). Key morphofunctional features in oral food processing distinguish hadrosauriforms and ceratopsids from other ornithischians, permitting them to exploit major new food sources (23, 24). Whether these herbivores were exploiting the new, small, fast-growing herbaceous angiosperms that became common and widespread as early as the Aptian–Albian (125–109 Mya) of the Early Cretaceous (25) is much debated. The powerful jaws and massive dental batteries of these herbivores might have been adapted to other tougher nonangiosperm plant food, and they benefited from a new adaptive complex in food processing.

Our results showing high levels of speciation in hadrosauriforms and ceratopsids, although consistent with previous findings (8), seem to contradict more recent work that suggests that these groups underwent a decline in morphological diversity during the last two stages of the Cretaceous of North America (13, 26). These dinosaur species are morphologically and ecologically (at least at the family level) conserved (27), with most of the derived characteristics concentrated in their crania (24). Speciation can be high in these groups, despite the potentially low morphological diversity, because Cretaceous dinosaurs exhibited increased provincialism (28) (speciation arising from geographic isolation rather than sympatric niche partitioning), increased  $\alpha$ -diversity (many more species with subtly varying skulls but identical postcrania sharing the herbivorous ecospace in single localities), and changing taxonomic composition of stable ecological community structures [ecological niches remain constant, but taxa filling those niches changed through time (27, 29)].

An ecological limit on speciation or the filling of available niches (30, 31) is commonly invoked to explain speciation slowdowns. Members of the same clade are more likely to compete for similar if not the same ecological niche or portions of ecospace (32, 33), and the more numerous the number of contemporary lineages, the fewer the number of available niches. We tested such an effect by including a measure of intraclade niche competition—cladewise lineage diversity or the number of contemporary branches (including internal branches) for each taxon—in the model (SI

whereas those below zero indicate decreases in species counts. (B, Inset) Hadrosauriforms (light green) show a slow increase in net speciation per 1 Myr through time, whereas ceratopsians (light blue) show a highly variable but on average, rapid increase toward the end of the Cretaceous. Posterior predictions (transparent lines) show the uncertainties in the model. Mean posterior values are shown as bold lines. Vertical lines indicate major stratigraphic boundaries (with their ages in millions of years ago) like those in Fig. 2. Silhouettes courtesy of [PhyloPic.org](http://PhyloPic.org) (CC BY 3.0) and Jack Mayer Wood (*Parasaurolophus*), Mathew Wedel (*Brachiosaurus*), Andrew A. Farke (*Stegosaurus* and *Centrosaurus*), and Martin Kevill (*Carcharodontosaurus*). E Cret, Early Cretaceous; L Cret, Late Cretaceous; L Triassic, Late Triassic.

*Text*). However, we find that cladewise lineage diversity is not significantly associated with speciation, and it does not explain the observed downturn; physical restrictions, such as geography or range sizes, could be more important.

We can indirectly assess the influence of geography, such as segregation by geographic barriers (30), using Mesozoic eustatic sea-level reconstructions (34) as an additional covariate in our models. Although various hypotheses have been proposed regarding the influence of sea level on biodiversity in dinosaurs (35), the most compelling suggests that increasing sea level results in fragmentation of large landmasses and can alter geographical distributions of habitats. In turn, continental fragmentation can lead to geographical segregation, reproductive isolation, and ultimately, speciation (30). Our results, for the first time to our knowledge, support this hypothesis—we find a significant positive effect of sea level on speciation [ $\Delta$ DIC (five-group quadratic – five-group + sea-level models)  $>16$ ; the proportion of the posterior distribution of the Markov-chain Monte Carlo (MCMC) estimates that crosses over zero multiplied by two (p-MCMC)  $<0.0010$ ] (Tables S1–S10)—although the effect is small; for every 1-meter increase in sea level, speciation events increased by 0.2–0.25%. Horner et al. (29) observed that the emergence of transitional morphotypes coincides with marine transgressions in Late Cretaceous rocks of western North America, consistent with our finding that rising sea levels induce speciation. Importantly, the inclusion of sea level in any of our models does not diminish the temporal decline in species proliferation, despite the substantial rise of sea levels worldwide by some 150–200 m throughout the Cretaceous (Tables S2–S10).

Although we cannot positively identify a causal mechanism for the speciation downturn in dinosaurs, there are many possible global phenomena that occurred during the Cretaceous Period [e.g., the continued breakup of the supercontinents Laurasia and Gondwana (limiting free movement and eventual para- or peripatric speciation), intense prolonged volcanism (36), climate change (37–39), fluctuations in sea levels (34, 40), and ecological interaction with rapidly expanding clades (41)]. To accurately identify causal mechanisms of Mesozoic dinosaurian demise, we recommend that future studies focus on a longer time period than just the last 10–20 My of the Cretaceous (4, 13, 42, 43). In addition, our results highlight the importance of considering the expected increase in species number as clades expand and accounting for shared ancestry using phylogenetic approaches.

Our study represents the first, to our knowledge, explicitly phylogenetic statistical treatment of speciation dynamics in dinosaurs. Unlike previous nonphylogenetic attempts to study changes in dinosaur taxic diversity across geological time bins (8–10, 13, 35, 44, 45), our method is robust to sampling and other potentially confounding factors (*SI Text* and Tables S1–S10) and can statistically detect decreases in net speciation, which is difficult if not impossible to establish using conventional methods. Furthermore, by accounting for the effects of shared ancestry, we provide a more accurate picture of dinosaurian speciation dynamics than the simple summing of species records through time.

Our results show that dinosaurs were in decline for a much longer period than previously thought—extinction rate surpassed speciation rate at least 40 My before their final extinction. This prolonged demise leaves plenty of time for other animal groups to radiate and flourish as more and more ecological niches open up, most prominently the pre–K–Pg expansion of crown mammals (46). Although Mesozoic dinosaurs undoubtedly dominated the terrestrial megafauna until the end of the Cretaceous, they did see a reduction in their capacity to replace extinct species with new ones, making them more susceptible to sudden and catastrophic environmental changes, like those associated with the asteroid impact.

## Materials and Methods

**Phylogeny.** We used three recent large comprehensive dinosaur phylogenies comprising 420 (8) and 614 taxa [two trees (16)]. Trees were scaled according to the midpoint time of each terminal stratigraphic range (16) using the “equal” scaling method (47) implemented in the paleotree R package (48). Additionally, we scaled the trees using two alternative sets of terminal dates, the first appearance dates and the last appearance dates, to assess the effects of tree scaling on model results.

**GLMMs.** We fitted GLMMs in a Bayesian framework through MCMC using the MCMCglmm R package (15). The total number of speciation events (node count) along the phylogenetic path for each taxon was modeled as the response variable, with the corresponding path length (time elapsed from root to tip) as the main effects predictor variable—this model formulation forms the null linear model (Fig. 1, model A). We also fitted a speciation slowdown model with the addition of a quadratic term (time<sup>2</sup>) to the main effect. Incidentally, a quadratic model can also explain the opposite case, where speciation rate increases while extinction rate remains constant. We include phylogeny as a random effect to account for shared ancestry.

Separate intercepts, slopes, and quadratic terms were estimated for the three major dinosaurian clades (Sauropodomorpha, Theropoda, and Ornithischia; three-group model). Lloyd et al. (8) previously identified two significant diversification shifts in the Cretaceous ornithischians at the base of the clades Euhadrosauria (here Hadrosauriformes) and Ceratopsidae, and therefore, we estimated separate model coefficients (intercepts and slopes) for these groups from other ornithischians (five-group model).

Chains were run for 10<sup>6</sup> iterations, with sampling at every 1,000th iteration. We fitted a GLMM with a Poisson link to appropriately account for error structure in count data—although we discuss predicted curve shapes in log space, we did not log-transform node count for model fitting (49). MCMCglmm automatically accounts for overdispersion in the count data distribution. We used default priors ( $\mu = 0$  and  $V = I \times 10^{10}$ , where  $I$  is an identity matrix) for the fixed effects and parameter-expanded priors ( $V = 1$ ,  $\nu = 1$ ,  $\alpha\mu = 0$ , and  $\alpha V = 25^2$ ) for the phylogenetic random effects (15).

Model fit was assessed using deviance information criterion (DIC) and inspection of model parameter significance (using the proportion of the posterior distribution of the MCMC estimate that crosses over zero multiplied by two). We determined the best fit model as the model with the lowest DIC score and a difference in DIC score compared with that of a base model ( $\Delta$ DIC) that is greater than four. In the case where multiple models had non-significant differences in model fit (i.e.,  $\Delta$ DIC  $< 4$ ), we inspected the significance of model parameters and selected the model with significant covariates (i.e., nonsignificant covariates were removed).

**Extrinsic Factors.** Because the fossil record has long been known to be incomplete (50, 51), it is possible that the observed slowdown and downturn are byproducts of undersampling. This assumption would imply that there is a systematic downward bias in the phylogeny toward recent times, which would be counter to the usual expectation for poor sampling (50, 51). Here, to test the effect of such biases, we fitted additional models with appropriate covariates, including stage-level formation counts (because formation count is widely reported to be associated with sampling bias) (9, 10, 12, 35, 44, 52, 53), taxon-specific formation counts (the number of formations in which a taxon is found), taxon-specific collection count (the number of fossil collections in which a taxon is represented), cladewise valid taxa counts (the known underrepresentation in the phylogeny) (54), fossil quality scores (state of preservation) (55), and body size (smaller taxa are less likely to be preserved) (56).

As an indirect measure of the influence of geography on speciation dynamics, such as segregation by geographic barriers (30), we used Mesozoic eustatic sea-level reconstructions (34) as an additional covariate in our models (mean sea-level value along each terminal branch). We also tested the ecological limit on clade diversification or the possible effects of niche saturation by adding a measure of intraclade diversity taken as the number of contemporary branches (including internal branches) for each taxon (the number of tips in time-sliced trees) (48). All data files are available in [Datasets S1–S13](#).

**ACKNOWLEDGMENTS.** We thank Joanna Baker, Ciara O'Donovan, Mark Pagel, Andrew Meade, and Stuart Humphries for discussion. We also thank two anonymous reviewers and the editor for improving this manuscript. This work was supported by Natural Environment Research Council Standard Grant NE/I027630/1 (to M.J.B.) and Leverhulme Trust Research Project Grant RPG-2013-185 (to C.V.).

- Sloan RE, Rigby JK, Jr, VAN Valen LM, Gabriel D (1986) Gradual dinosaur extinction and simultaneous ungulate radiation in the hell creek formation. *Science* 232(4750):629–633.
- Dodson P (1990) Counting dinosaurs: How many kinds were there? *Proc Natl Acad Sci USA* 87(19):7608–7612.
- Sarjeant WAS, Currie PJ (2001) The “Great Extinction” that never happened: The demise of the dinosaurs considered. *Can J Earth Sci* 38(2):239–247.
- Fastovsky DE, et al. (2004) Shape of Mesozoic dinosaur richness. *Geology* 32(10):877–880.
- Sullivan RM (2006) The shape of Mesozoic dinosaur richness: A reassessment. *N M Museum Natural Hist Sci Bull* 35:403–405.
- Wang SC, Dodson P (2006) Estimating the diversity of dinosaurs. *Proc Natl Acad Sci USA* 103(37):13601–13605.
- Taylor MP (2006) Dinosaur diversity analysed by clade, age, place and year of description. *Ninth International Symposium on Mesozoic Terrestrial Ecosystems and Biota*, eds Barrett PM, Evans SE (Cambridge Publications, Manchester, United Kingdom), pp 134–138.
- Lloyd GT, et al. (2008) Dinosaurs and the Cretaceous terrestrial revolution. *Proc Biol Sci* 275(1650):2483–2490.
- Barrett PM, McGowan AJ, Page V (2009) Dinosaur diversity and the rock record. *Proc R Soc Lond B Biol Sci* 276(1667):2667–2674.
- Upchurch P, Mannion PD, Benson RBJ, Butler RJ, Carrano MT (2011) Geological and anthropogenic controls on the sampling of the terrestrial fossil record: A case study from the Dinosauria. *Geol Soc Spec Publ* 358(1):209–240.
- Archibald JD (2012) Dinosaur extinction: Past and present perceptions. *The Complete Dinosaur*, eds Brett-Surman MK, Holtz TR, Farlow JO, Walter B (Indiana Press, Bloomington, IN), 2nd Ed, pp 1027–1038.
- Lloyd GT (2012) A refined modelling approach to assess the influence of sampling on palaeobiodiversity curves: New support for declining Cretaceous dinosaur richness. *Biol Lett* 8(1):123–126.
- Brusatte SL, et al. (2015) The extinction of the dinosaurs. *Biol Rev Camb Philos Soc* 90(2):628–642.
- Schulte P, et al. (2010) The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary. *Science* 327(5970):1214–1218.
- Hadfield JD (2010) MCMC methods for multi-response generalized linear mixed models: The MCMCglmm R Package. *J Stat Softw* 33(2):1–22.
- Benson RB, et al. (2014) Rates of dinosaur body mass evolution indicate 170 million years of sustained ecological innovation on the avian stem lineage. *PLoS Biol* 12(5):e1001853.
- Venditti C, Meade A, Pagel M (2011) Multiple routes to mammalian diversity. *Nature* 479(7373):393–396.
- Jetz W, Thomas GH, Joy JB, Hartmann K, Mooers AO (2012) The global diversity of birds in space and time. *Nature* 491(7424):444–448.
- Rabosky DL, et al. (2013) Rates of speciation and morphological evolution are correlated across the largest vertebrate radiation. *Nat Commun* 4:1958.
- Schluter D (2000) *The Ecology of Adaptive Radiation* (Oxford Univ Press, Oxford).
- Lee MSY, Cau A, Naish D, Dyke GJ (2014) Dinosaur evolution. Sustained miniaturization and anatomical innovation in the dinosaurian ancestors of birds. *Science* 345(6196):562–566.
- Brusatte SL, Lloyd GT, Wang SC, Norell MA (2014) Gradual assembly of avian body plan culminated in rapid rates of evolution across the dinosaur-bird transition. *Curr Biol* 24(20):2386–2392.
- Norman DB, Witmer LM, Weishampel DB (2004) Basal Thyreophoran. *The Dinosauria*, eds Weishampel DB, Dodson P, Osmolska H (Univ of California Press, Berkeley, CA), 2nd Ed, pp 335–342.
- Horner JR, Weishampel DB, Forster CA (2004) Hadrosauridae. *The Dinosauria*, eds Weishampel DB, Dodson P, Osmolska H (Univ of California Press, Berkeley, CA), 2nd Ed, pp 438–463.
- Jud NA (2015) Fossil evidence for a herbaceous diversification of early eudicot angiosperms during the Early Cretaceous. *Proc R Soc Lond B Biol Sci* 282(1814):20151045.
- Brusatte SL, Butler RJ, Prieto-Márquez A, Norell MA (2012) Dinosaur morphological diversity and the end-Cretaceous extinction. *Nat Commun* 3:804.
- Mallon JC, Anderson JS (2015) Jaw mechanics and evolutionary paleoecology of the megaherbivorous dinosaurs from the Dinosaur Park Formation (upper Campanian) of Alberta, Canada. *J Vertebr Paleontol* 35(2):e904323.
- Holtz TR, Chapman RE, Lamanna MC (2004) Mesozoic biogeography of Dinosauria. *The Dinosauria*, eds Weishampel DB, Dodson P, Osmolska H (Univ of California Press, Berkeley, CA), 2nd Ed, pp 627–642.
- Horner JR, Varricchio DJ, Goodwin MB (1992) Marine transgressions and the evolution of cretaceous dinosaurs. *Nature* 358(6381):59–61.
- Moen D, Morlon H (2014) Why does diversification slow down? *Trends Ecol Evol* 29(4):190–197.
- Rabosky DL (2013) Diversity-dependence, ecological speciation, and the role of competition in macroevolution. *Annu Rev Ecol Syst* 44:481–502.
- Darwin C (1859) *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* (John Murray, London), 1st Ed.
- Mayr E (1942) *Systematics and the Origin of Species, from the Viewpoint of a Zoologist* (Harvard Univ Press, Cambridge, MA).
- Haq BU, Hardenbol J, Vail PR (1987) Chronology of fluctuating sea levels since the triassic. *Science* 235(4793):1156–1167.
- Butler RJ, Benson RBJ, Carrano MT, Mannion PD, Upchurch P (2011) Sea level, dinosaur diversity and sampling biases: Investigating the ‘common cause’ hypothesis in the terrestrial realm. *Proc R Soc Lond B Biol Sci* 278(1709):1165–1170.
- Chenet AL, et al. (2009) Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: 2. Constraints from analysis of eight new sections and synthesis for a 3500-m-thick composite section. *J Geophys Res Solid Earth* 114(B6):B0610.
- Li LQ, Keller G (1998) Maastrichtian climate, productivity and faunal turnovers in planktic foraminifera in south Atlantic DSDP sites 525A and 21. *Mar Micropaleontol* 33(1–2):55–86.
- Li LQ, Keller G (1998) Abrupt deep-sea warming at the end of the Cretaceous. *Geology* 26(11):995–998.
- Naafs BDA, et al. (2016) Gradual and sustained carbon dioxide release during Aptian Oceanic Anoxic Event 1a. *Nat Geosci* 9(2):135–139.
- Miller KG, et al. (2005) The Phanerozoic record of global sea-level change. *Science* 310(5752):1293–1298.
- Wilson GP, et al. (2012) Adaptive radiation of multituberculate mammals before the extinction of dinosaurs. *Nature* 483(7390):457–460.
- Sheehan PM, Fastovsky DE, Barreto C, Hoffmann RG (2000) Dinosaur abundance was not declining in a “3 m gap” at the top of the Hell Creek Formation, Montana and North Dakota. *Geology* 28(6):523–526.
- Lyson TR, et al. (2011) Dinosaur extinction: Closing the ‘3 m gap.’ *Biol Lett* 7(6):925–928.
- Benson RBJ, Mannion PD (2012) Multi-variate models are essential for understanding vertebrate diversification in deep time. *Biol Lett* 8(1):127–130.
- Benson RBJ, et al. (2016) Near-stasis in the long-term diversification of mesozoic tetrapods. *PLoS Biol* 14(1):e1002359.
- Close RA, Friedman M, Lloyd GT, Benson RB (2015) Evidence for a Mid-Jurassic adaptive radiation in mammals. *Curr Biol* 25(16):2137–2142.
- Brusatte SL, Benton MJ, Ruta M, Lloyd GT (2008) Superiority, competition, and opportunism in the evolutionary radiation of dinosaurs. *Science* 321(5895):1485–1488.
- Bapst DW (2012) paleotree: An R package for paleontological and phylogenetic analyses of evolution. *Methods Ecol Evol* 3(5):803–807.
- O’Hara RB, Kotze DJ (2010) Do not log-transform count data. *Methods Ecol Evol* 1(2):118–122.
- Alroy J (2010) Geographical, environmental and intrinsic biotic controls on phanerozoic marine diversification. *Palaeontology* 53(6):1211–1235.
- Smith AB, McGowan AJ (2007) The shape of the phanerozoic marine palaeodiversity curve: How much can be predicted from the sedimentary rock record of western Europe? *Palaeontology* 50(4):765–774.
- Peters SE, Foote M (2001) Biodiversity in the Phanerozoic: A reinterpretation. *Paleobiology* 27(4):583–601.
- Brocklehurst N, Upchurch P, Mannion PD, O’Connor J (2012) The completeness of the fossil record of mesozoic birds: Implications for early avian evolution. *PLoS One* 7(6):e39056.
- Benton MJ (2008) How to find a dinosaur, and the role of synonymy in biodiversity studies. *Paleobiology* 34(4):516–533.
- Benton MJ, Dunhill AM, Lloyd GT, Marx FG (2011) Assessing the quality of the fossil record: Insights from vertebrates. *Geol Soc Spec Publ* 358:63–94.
- Cleary TJ, Moon BC, Dunhill AM, Benton MJ (2015) The fossil record of ichthyosaurs, completeness metrics and sampling biases. *Palaeontology* 58(3):521–536.
- Prothero D (1999) Fossil record. *Encyclopedia of Paleontology*, ed Singer R (Fitzroy Dearbon Publishers, Chicago), pp 490–492.
- Raup DM (1991) *Extinction: Bad Genes or Bad Luck?* (W. W. Norton, New York).
- Raup DM (1972) Taxonomic diversity during the Phanerozoic. *Science* 177(4054):1065–1071.
- Ren L, et al. (2008) The movements of limb segments and joints during locomotion in African and Asian elephants. *J Exp Biol* 211(Pt 17):2735–2751.
- Benton MJ, Ruta M, Dunhill AM, Sakamoto M (2013) The first half of tetrapod evolution, sampling proxies, and fossil record quality. *Palaeogeogr Palaeoclimatol Palaeoecol* 372(1):18–41.
- Turner AH, Pol D, Clarke JA, Erickson GM, Norell MA (2007) A basal dromaeosaurid and size evolution preceding avian flight. *Science* 317(5843):1378–1381.
- Marsicano CA, Irmis RB, Mancuso AC, Mundil R, Chemle F (2016) The precise temporal calibration of dinosaur origins. *Proc Natl Acad Sci USA* 113(3):509–513.
- Revell LJ (2012) phytools: An R package for phylogenetic comparative biology (and other things). *Methods Ecol Evol* 3(2):217–223.
- Stadler T (2011) Simulating trees with a fixed number of extant species. *Syst Biol* 60(5):676–684.
- Mooers A, Gascuel O, Stadler T, Li H, Steel M (2012) Branch lengths on birth-death trees and the expected loss of phylogenetic diversity. *Syst Biol* 61(2):195–203.
- Pennell MW, Sarver BAJ, Harmon LJ (2012) Trees of unusual size: Biased inference of early bursts from large molecular phylogenies. *PLoS One* 7(9):e43348.
- Hartmann K, Wong D, Stadler T (2010) Sampling trees from evolutionary models. *Syst Biol* 59(4):465–476.
- Mallon JC, Anderson JS (2013) Skull ecomorphology of megaherbivorous dinosaurs from the dinosaur park formation (upper campanian) of Alberta, Canada. *PLoS One* 8(7):e67182.
- Mallon JC, Anderson JS (2014) Implications of beak morphology for the evolutionary paleoecology of the megaherbivorous dinosaurs from the Dinosaur Park Formation (upper Campanian) of Alberta, Canada. *Palaeogeogr Palaeoclimatol Palaeoecol* 394(1):29–41.