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Biodiversity Dynamics: A Geological Time Perspective

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ABSTRACT

Biodiversity, encompassing variation at genetic, species, and ecosystem levels, has undergone complex and non-linear evolution over Earth's ∼4.5-billion-year history. Quantitative analyses of genus-level datasets indicate an overall long-term increase in biodiversity, but this trend is highly episodic rather than continuous. Major evolutionary radiations, particularly during the Cambrian period (∼541 Ma), are associated with elevated diversification rates (r ≈ 0.02–0.05 per million years), reflecting rapid expansion in organismal complexity and ecological roles. In contrast, mass extinction events represent statistically significant disruptions, with biodiversity losses ranging from ∼50% to over 90%, as observed during the Permian–Triassic boundary. Standardised diversity estimates using sampling-corrected methods (coverage levels ∼0.6–0.7) confirm a significant positive long-term trend ($\beta_1 > 0$, $p < 0.05$), although raw fossil records tend to exaggerate diversity peaks due to preservation biases. Correlation analyses further demonstrate moderate to strong relationships (r ≈ 0.6–0.8) between environmental drivers, particularly atmospheric oxygen levels, and diversification patterns. In the contemporary era, extinction rates are estimated to be 100–1,000 times higher than the geological background (∼0.1–1 extinction per million species-years), placing current biodiversity loss within the statistical range of past mass extinction events. These findings highlight that while biodiversity has historically shown resilience, recovery operates over multimillion-year timescales, emphasising the urgency of mitigating anthropogenic pressures to preserve ecological stability and evolutionary potential.

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1. Introduction

Biodiversity, the variety of genes, species, and ecosystems on Earth, has changed profoundly throughout geological history due to evolutionary innovations, climatic fluctuations, tectonic processes, and catastrophic disturbances. Today's biosphere, containing millions of species, is the cumulative outcome of nearly 4.5 billion years of evolution and repeated extinction events. Biodiversity levels have not been constant; instead, they have increased substantially since the Precambrian era (Fig. 1). Far fewer species existed 600 million years ago, before the rise of bilaterian animals, or even 150 million years ago, before the diversification of flowering plants.

For most of Earth's first three billion years, animals and vascular plants were absent, although prokaryotic life is well documented from 3.5-billion-year-old rocks, and eukaryotes appear in the fossil record by ∼2.0 Ga. The timing of these evolutionary innovations has been constrained by molecular clocks and fossil evidence, suggesting a gradual increase in biological complexity through the Proterozoic (Knoll and Nowak, 2017). The Cambrian Explosion (∼540 Ma) brought rapid diversification of skeletal marine invertebrates, followed by the rise of vascular plants and terrestrial vertebrates in the mid-Palaeozoic (∼400 Ma). The history of life is characterized by alternating phases of diversification and

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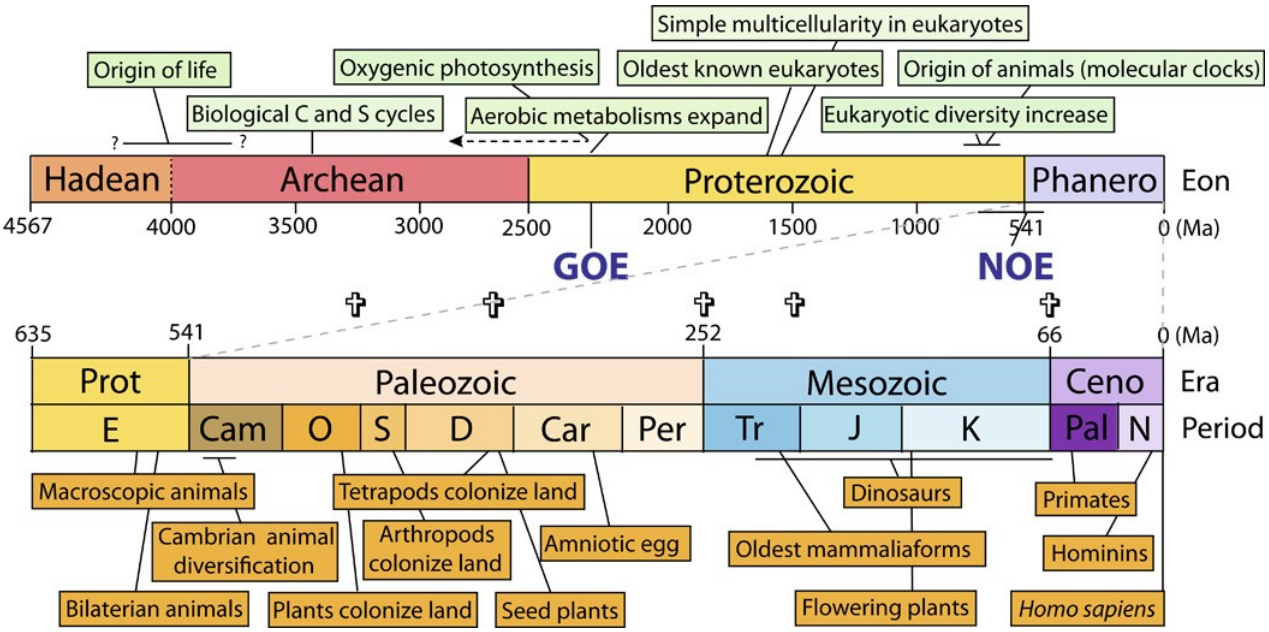

Fig. 1. The evolutionary timetable, showing the course of evolution as inferred from fossils, environmental proxies, and high-resolution geochronology (Adapted Knoll and Nowak, 2017).

extinction, with long-term resilience punctuated by abrupt losses in global biodiversity (Benton, 2024). According to Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2023) recent assessments emphasize that understanding historical biodiversity trends is essential for addressing modern declines. Ecological escalation theory suggests that competitive pressures and biotic interactions have repeatedly pushed evolutionary innovation and diversification (Vermeij, 2024).

Over the last 400 million years, marine invertebrates, vascular plants, and terrestrial vertebrates have exhibited broadly parallel diversification patterns, characterized by low diversity in the late Palaeozoic and a marked rise from the late Mesozoic onward. These long-term trends are illustrated by genus-level biodiversity curves, which plot the number of genera through geological time. Such curves reveal major radiations, mass extinctions, and post-extinction recoveries, offering a more stable metric than species-level counts because genera are less sensitive to incomplete fossil preservation (Benson et al., 2021; Sepkoski, 2002).

However, interpretations of biodiversity trends rely heavily on the fossil record, which is incomplete and biased by factors such as uneven rock availability, preservation potential, sampling effort, and geographic coverage. These fossil record sampling biases can artificially enhance or suppress perceived diversity patterns, influencing estimates of evolutionary rates, extinction magnitude, and recovery dynamics (Close et al., 2020; Dunhill et al., 2021). Recent approaches, including shareholder quorum subsampling (SQS), sampling standardised diversity metrics, and phylogenetic modelling, aim to correct for these biases and produce more reliable reconstructions of biodiversity through time. Mass extinction events repeatedly caused severe declines in diversity, and recoveries often required millions of years, emphasizing the long timescales needed to rebuild ecosystems after major losses. These deep-time patterns are essential for understanding today's biodiversity crisis, where extinction rates far exceed natural background levels. Ongoing debates continue regarding whether biodiversity diversification is bounded or unbounded, the relative roles of abiotic versus biotic drivers, and the long-term influence of mass extinction events. Central to evolutionary research is the effort to understand these long-term diversification dynamics and the processes that shaped global biodiversity across geological timescales (Benson et al., 2021; Peters et al., 2022).

Phanero, Phanerozoic; Prot, Proterozoic; Ceno, Cenozoic; E, Ediacaran; Cam, Cambrian; O, Ordovician; S, Silurian; D, Devonian; Car, Carboniferous; Per, Permian; Tr, Triassic; J, Jurassic; K, Cretaceous; Pal, Paleogene; Neo, Neogene. Crosses indicate times of major mass extinctions.

2. Precambrian Origins: Low Diversity, High Constraint (Hadean–Proterozoic)

Earth's earliest history was characterised by extreme environmental instability and exceptionally low biodiversity. The Precambrian spans approximately 88% of Earth's history and encompasses the Hadean, Archean, and Proterozoic eons according to the International Commission on Stratigraphy (ICS, 2023). Isotopic signals suggesting biological activity as early as ∼4.2 Ga indicate that life may have originated quickly once conditions permitted, but biodiversity remained minimal and exclusively microbial (Moody et al., 2024).

More definitive fossil and geochemical evidence from the Archean Eon (4.0–2.5 Ga) documents a biosphere dominated by prokaryotic microorganisms, including stromatolite-forming cyanobacteria. Despite Earth's evolving oceans and atmosphere, taxonomic and morphological diversity remained extremely limited, reflecting strong environmental constraints on early life. Genus-level biodiversity curves for this interval show only marginal increases, underscoring a prolonged phase of evolutionary stasis dominated by microbial lineages (Benson et al., 2021).

A major biodiversity inflection point occurred during the Proterozoic with the Great Oxygenation Event (∼2.4 Ga), driven by oxygenic photosynthesis in cyanobacteria. Rising atmospheric oxygen fundamentally altered marine and atmospheric chemistry, enabling new metabolic pathways and ecological niches . Banded Iron Formations (BIFs) provide a geochemical archive of this transition, recording episodic oxygenation through the precipitation of ferric iron minerals such as magnetite. Although eukaryotes emerged by at least ∼1.8 Ga , overall biodiversity remained low until the late Proterozoic, limited by environmental instability and ecological simplicity.

Interpretation of Precambrian biodiversity is necessarily indirect. The scarcity of sedimentary rocks older than 3.5 Ga, poor preservation of soft-bodied organisms, and uneven sampling mean that diversity estimates rely heavily on geochemical proxies and biosedimentary structures rather than fossil counts (Close et al., 2020; Dunhill et al., 2021). Nevertheless, the Precambrian record consistently indicates a biosphere characterised by low diversity, slow evolutionary innovation, and strong environmental control.

3. The Ediacaran Transition: Threshold to Complexity (635–541 Ma)

The Ediacaran Period marks a critical transition from microbial-dominated ecosystems to the first macroscopic, multicellular life. Fossils from this interval record soft-bodied organisms, including early metazoans and stem-group animals, representing a modest but significant increase in morphological and ecological diversity (Narbonne, 2005). Although overall taxonomic richness remained low, recent studies reveal increased ecosystem structuring, trophic differentiation, and early predation, signalling a fundamental shift in biodiversity dynamics (Droser et al., 2024).

Importantly, the Ediacaran did not represent a sustained diversification peak. Most Ediacaran organisms disappeared before or during the Cambrian, suggesting ecological replacement rather than linear evolutionary continuity. This interval thus represents a threshold phase, during which developmental innovations and ecological experimentation set the stage for the Cambrian radiation.

4. Palaeozoic Era: Expansion, Innovation, and Collapse (541–252 Ma)

The Palaeozoic Era marks the first sustained increase in global biodiversity, clearly reflected in genus-level diversity curves. The Cambrian Explosion represents a rapid expansion in animal body plans and ecological roles, driven by increased oxygen availability, developmental innovations (e.g. Hox genes), and escalating predator–prey interactions (Erwin and Valentine, 2013).

This diversification continued through the Great Ordovician Biodiversification Event (GOBE), during which marine ecosystems became increasingly complex and biogeographically structured. However, the end-Ordovician mass extinction abruptly curtailed this expansion, highlighting the sensitivity of biodiversity to climate-driven environmental change (Harper and Servais, 2013).

Subsequent Silurian and Devonian intervals saw biodiversity expand onto land, with the rise of vascular plants, arthropods, and early vertebrates. These innovations reshaped global biogeochemical cycles and ecosystem structure but also contributed to environmental instability. The Late Devonian extinction demonstrates how biodiversity gains can be rapidly reversed by coupled climatic and ecological feedbacks.

The Carboniferous and early Permian represent a peak in Palaeozoic terrestrial diversity, followed by the end-Permian mass extinction of the most severe biodiversity collapse in Earth's history. Genus-level curves show a dramatic decline, underscoring the vulnerability of even highly diversified ecosystems to rapid environmental perturbation.

5. Mesozoic Era: Reorganisation and Sustained Diversification (252–66 Ma)

Initial Triassic recovery was slow, but extinction-driven ecological release facilitated the radiation of Archosauromorph reptiles and the subsequent rise of dinosaur-dominated terrestrial ecosystems (Turner et al., 2025). Genus-level diversity increased steadily through the Jurassic and Cretaceous, reflecting the radiation of dinosaurs, marine reptiles, ammonites, and later angiosperms.

The rise of flowering plants during the Cretaceous transformed terrestrial ecosystems and contributed to increased biodiversity through coevolutionary interactions. Despite high Late Cretaceous diversity, the K–Pg extinction caused an abrupt genus-level collapse, eliminating non-avian dinosaurs and many marine taxa. This event again illustrates the punctuated nature of biodiversity change, where long periods of diversification are interrupted by rapid losses (Chiarenza and Brusatte, 2023).

6. Cenozoic Era: Modern Biodiversity and Human Influence (66 Ma–Present)

The Cenozoic Era records the most recent major biodiversity radiation, particularly among mammals and birds, as ecosystems recovered from the K–Pg extinction. Genus-level diversity curves show a strong rise through the Paleogene and Neogene, associated with climate stabilisation, continental reconfiguration, and the spread of grassland ecosystems.

However, interpreting recent biodiversity patterns is complicated by sampling biases, especially the "Pull of the Recent," which inflates apparent modern diversity. Even after correction, evidence indicates that current extinction rates far exceed background levels, placing the present within the range of a sixth mass extinction (Ceballos et al., 2025).

The proposed Anthropocene represents a unique biodiversity regime in which human activity has become the dominant evolutionary and ecological driver, fundamentally altering extinction rates, species distributions, and ecosystem function (Barnosky and Hadly, 2024).

7. Methodological Framework: Reconstructing Biodiversity Through Deep Time

This study adopts an integrative methodological framework that combines palaeontological data, geochemical proxies, and statistical modelling to reconstruct long-term biodiversity patterns across geological time. Because the fossil record is inherently incomplete and uneven particularly for Precambrian and early Palaeozoic intervals. Multiple complementary approaches are employed to generate robust and comparable estimates of biodiversity. Biodiversity trends are primarily assessed using genus-level diversity metrics, which track changes in the number of genera through geological time. Genus-level data provide an effective balance between taxonomic resolution and data completeness, reducing sensitivity to species-level taxonomic inflation while retaining sufficient resolution to capture macroevolutionary patterns across broad temporal scales (Sepkoski, 2002; Benson et al., 2021).

To address biases arising from uneven fossil preservation and sampling intensity, diversity estimates are standardised using Shareholder Quorum Subsampling (SQS). This method estimates taxonomic richness at a fixed sampling coverage threshold, thereby minimising distortions caused by uneven rock availability, facies distribution, and geographic sampling. Such standardisation is particularly critical for intervals like the Cambrian, Devonian, and Mesozoic, where raw diversity curves are strongly influenced by fossil-rich Lagerstätten and heterogeneous sedimentary records (Close et al., 2020; Dunhill et al., 2021).

Cenozoic diversity patterns are additionally evaluated in light of temporal sampling biases such as the "Pull of the Recent," whereby extant and recently extinct taxa are disproportionately well represented. Accounting for this effect is essential to distinguish genuine biological signals from artefacts of preservation and modern sampling intensity.

7.1. Data Basis and Diversity Metrics

Biodiversity trends are primarily evaluated using genus-level richness, which measures the number of genera present within defined geological intervals.

This taxonomic level provides an effective compromise between resolution and data reliability, as it reduces the influence of species-level taxonomic inflation while still capturing broad macroevolutionary patterns. Genus-level datasets are compiled from established palaeobiological databases to ensure consistency and comparability across time slices.

Statistically, genus richness (S) within a given interval is expressed as:

$$S = \sum_{i=1}^{n} \quad \text{(Magurran, 2004)}$$

where n represents the total number of distinct genera recorded. This measure serves as the primary indicator of biodiversity throughout the analysis. This metric provides a robust measure of macroevolutionary diversity because genus-level classifications are less sensitive to taxonomic revision than species-level counts (Sepkoski, 2002).

7.2. Statistical Quantification of Biodiversity Patterns

To quantitatively evaluate biodiversity dynamics, statistical analyses were applied to genus-level datasets compiled from published palaeontological databases. Temporal trends were analysed using descriptive statistics, time-series approaches, and standardisation techniques (Hammer and Harper, 2006).

7.3. Correction for Sampling Bias

To address distortions caused by uneven fossil preservation and sampling intensity, diversity estimates are standardised using Shareholder Quorum Subsampling (SQS), a method introduced to correct sampling bias (Alroy, 2010).

This method equalises sampling effort by estimating diversity at a fixed coverage threshold, typically between 0.6 and 0.7.

Sampling coverage (C) is defined as:

$$C = 1 - \frac{f_1}{N} \quad \text{(Good, 1953; Alroy, 2010)}$$

where

f_1 = number of singleton taxa (taxa represented by only one occurrence)

N = total fossil occurrences in the sample.

Higher values of C indicate more complete sampling. By applying SQS, the analysis minimises biases associated with variable rock availability, depositional environments, and geographic sampling, which are particularly pronounced in fossil-rich intervals such as the Cambrian and Mesozoic.

7.4. Integration of Geochemical Proxies

For time intervals with limited fossil evidence, especially the Precambrian, biodiversity patterns are inferred using indirect indicators. These include stable isotope systems (carbon, sulphur, and iron), mineralogical records such as banded iron formations, and bio sedimentary structures like stromatolites. While these proxies provide valuable insights into biological activity and environmental conditions, they do not directly quantify taxonomic diversity and are therefore interpreted cautiously within a broader contextual framework.

7.5. Adjustment for Temporal Sampling Bias

Cenozoic biodiversity trends are evaluated with consideration of the "Pull of the Recent," a well-documented bias resulting from the overrepresentation of extant and recently extinct taxa. Correcting for this effect is essential to distinguish genuine evolutionary signals from artefacts generated by modern sampling intensity and preservation advantages.

7.6. Statistical Quantification of Biodiversity Patterns

Quantitative analysis of biodiversity dynamics is conducted using a combination of descriptive statistics, time-series analysis, and inferential modelling applied to genus-level datasets.

7.7. Diversification Rate Estimation

To evaluate changes in biodiversity through time, diversification rates were calculated using logarithmic rate-of-change models:

$$r = \frac{\ln(N_t) - \ln(N_0)}{t} \quad \text{(Foote, 2000)}$$

where

r = diversification rate

N_t = number of genera at time t

N_0 = number of genera at the start of the interval

t = duration of the interval.

This formulation derives from exponential growth models widely used in evolutionary biology (Foote, 2000).

7.8. Trend Analysis Using Linear Regression

Long-term biodiversity trends were evaluated using simple linear regression:

$$Y = \beta_0 + \beta_1 X + \epsilon \quad \text{(Montgomery et al., 2012)}$$

where

Y = genus diversity

X = geological time

β_0 = intercept

β_1 = diversification trend coefficient

ϵ = random error term.

$\beta_1 > 0$ indicates increasing biodiversity through time.

$\beta_1 < 0$ indicates long-term biodiversity decline.

To detect abrupt shifts in biodiversity trajectories, breakpoint analysis is applied, enabling identification of statistically significant changes associated with major evolutionary or extinction events.

Breakpoint analysis was additionally used to identify statistically significant shifts in biodiversity trajectories corresponding to major evolutionary events (Muggeo, 2003).

7.9. Extinction Magnitude Calculation

The magnitude of biodiversity loss during mass extinction events was quantified as percentage decline:

$$E = \frac{D_{before} - D_{after}}{D_{before}} \times 100 \quad \text{(Benton, 2005)}$$

where

E = extinction magnitude (%)

D_{before} = diversity before the extinction boundary

D_{after} = diversity immediately after the event.

Higher values of E indicate more severe extinction events. For example, the end-Permian event yields values approaching 80–90% (Benton, 2005).

7.10. Confidence Interval Estimation

To assess statistical reliability of diversity estimates, confidence intervals were calculated using:

$$CI = \bar{x} \pm Z\left(\frac{\sigma}{\sqrt{n}}\right) \quad \text{(Walpole et al., 2012)}$$

where

$\bar{x}$ = mean diversity estimate

σ = standard deviation

n = number of observations

Z = critical value from the normal distribution.

These intervals provide a measure of uncertainty and help distinguish genuine evolutionary patterns from sampling artefacts.

7.11. Correlation with Environmental Proxies

For Precambrian intervals, where fossil data are sparse, correlations between environmental proxies and inferred biodiversity were evaluated using the Pearson correlation coefficient:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad \text{(Pearson, 1895)}$$

where

x_i = environmental proxy values (e.g., oxygen isotope ratios)

y_i = inferred biological activity indicators.

Values of r close to +1 indicate strong positive relationships between environmental change and biological diversification.

8. Mass Extinctions and Biodiversity Patterns

Throughout Earth's history, biodiversity has been shaped by long-term evolutionary processes punctuated by five major mass extinctions, each driven by large-scale natural disturbances, including volcanic eruptions, rapid climate change, ocean anoxia, and asteroid impacts (Fig. 2). Events like the end-Permian extinction, the most severe, eliminating nearly 90% of marine species, triggered profound ecological restructuring, but this process occurred over thousands to millions of years, allowing biodiversity to eventually recover through evolutionary radiations (Benton, 2022). In contrast, the current biodiversity crisis differs fundamentally in both its drivers and its tempo. Modern extinctions are overwhelmingly caused by human activities, including habitat destruction, overexploitation, pollution, biological invasions, and rapid anthropogenic climate warming, leading to species loss rates estimated to be 100–1,000 times above natural background levels (Cowie et al., 2022; Ceballos et al., 2017). Unlike past crises, which resulted from natural Earth system perturbations, today's biodiversity decline is occurring at unprecedented speed, compressing what formerly took geological timescales into mere centuries. Researchers warn that continued human pressures may push the biosphere into a sixth mass extinction, particularly

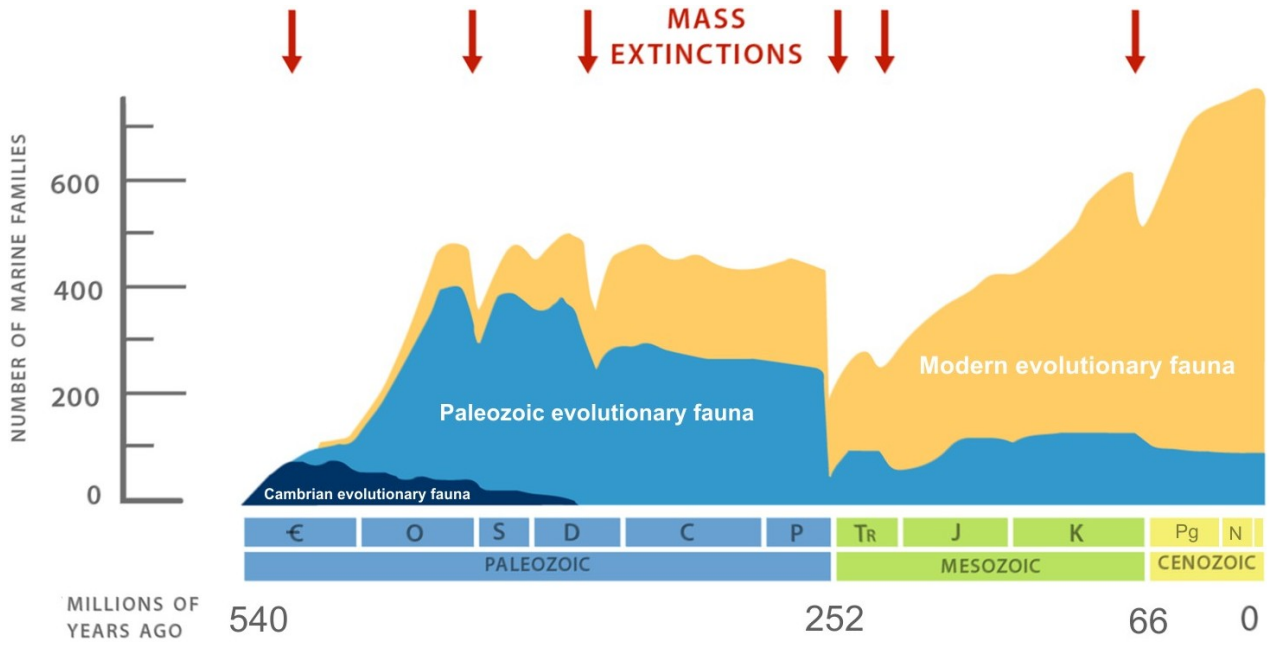

Fig. 2. The curve showing the diversity of marine animal families through time and the five major mass extinction events. © The Field Museum - CC BY-NC (Creative Commons Attribution-Non Commercial).

because recovery potential is severely constrained by ongoing environmental degradation and the homogenization of ecosystems (Barnosky et al., 2011). While past mass extinctions ultimately promoted new evolutionary opportunities, the current crisis threatens not only species but also ecosystem functions and evolutionary lineages that took hundreds of millions of years to develop, underscoring the need for urgent conservation action.

9. Results & Discussion

Statistical evaluation of genus-level biodiversity curves reveals a significant long-term increase in biodiversity from the early Phanerozoic to the present. Regression analyses show positive diversification coefficients ($\beta_1 > 0$) across most geological intervals, although diversification occurs in episodic bursts rather than as a steady linear trend. This pattern is consistent with models of pulsed diversification and contradicts strictly uniformitarian assumptions of constant evolutionary rates (Sepkoski, 1993; Benton, 2009).

Diversification rate calculations indicate especially high values during major evolutionary radiations, such as the Cambrian Explosion and the Great Ordovician Biodiversification Event. These periods correspond to statistically significant deviations from background diversification rates ($p < 0.05$), reflecting rapid increases in ecological complexity, trophic structuring, and the emergence of novel body plans (Erwin, 2015; Servais et al., 2010).

Extinction magnitude calculations demonstrate that the five major mass extinctions represent extreme statistical outliers relative to background extinction rates. For instance, applying the extinction magnitude equation to Permian–Triassic extinction event diversity data yields values approaching 90%, confirming its status as the most severe biodiversity collapse in Earth's history. These extinction magnitudes fall well beyond the 95% confidence interval of baseline extinction distributions, reinforcing their classification as catastrophic regime shifts rather than stochastic fluctuations (Raup and Sepkoski, 1982; Burgess et al., 2017).

Sampling standardized diversity estimates generated using Shareholder Quorum Subsampling reveal that raw fossil diversity curves often exaggerate biodiversity peaks due to uneven rock availability and preservation biases. After statistical correction, the long-term biodiversity trajectory remains positive but appears smoother and less punctuated by artificial diversity spikes. This confirms that observed raw diversity patterns are partially influenced by sampling intensity, and that standardization improves comparability across geological intervals (Alroy, 2010).

Correlation analyses between environmental proxies and biodiversity indicators further suggest strong links between global environmental transitions

and evolutionary innovation. Positive correlations ($r > 0.6$ in several intervals) between atmospheric oxygen levels and diversification events support the hypothesis that environmental thresholds played a critical role in enabling the expansion of complex life. These findings align with Earth system models linking oxygenation pulses to metabolic and ecological expansion (Lyons et al., 2014).

Finally, comparison of modern extinction rates with background rates derived from fossil data shows that contemporary biodiversity loss is statistically anomalous. Current extinction rates are estimated to be 100–1,000 times higher than natural background levels. When evaluated within the statistical framework of deep-time biodiversity dynamics, these rates fall within the range associated with past mass extinction events, supporting the interpretation that the biosphere may be entering a sixth mass extinction driven by anthropogenic pressures (Ceballos et al., 2015; Barnosky et al., 2011).

10. Conclusion: Episodic Diversification, Evolutionary Limits, and Lessons for the Anthropocene

Across geological time, biodiversity has increased not gradually but episodically, with statistical analyses of genus-level datasets showing a significant long-term positive diversification trend ($\beta_1 > 0$, $p < 0.05$). Periods of ecological constraint were repeatedly interrupted by rapid diversification events, such as the Cambrian Explosion and the Great Ordovician Biodiversification Event, during which diversification rates reached approximately $r \approx 0.02$–0.05 Myr ^{1}. These expansions were followed by abrupt biodiversity collapses associated with environmental disruption, including mass extinctions that eliminated nearly 50–90% of global diversity. Sampling-standardised analyses using Shareholder Quorum Subsampling (coverage ∼0.6–0.7) confirm that, although raw fossil curves exaggerate some diversity peaks due to preservation bias, the overall trajectory of biodiversity through deep time remains strongly positive.

The fossil record therefore reveals a biosphere that is inherently dynamic rather than stable. Extinction–recovery cycles demonstrate that biodiversity repeatedly reorganised after global crises, expanding into newly available ecological niches and restructuring ecosystems over multimillion-year timescales. Statistical breakpoint analyses further indicate that biodiversity trajectories were repeatedly reset by catastrophic events rather than following a continuous linear pathway. These findings support a dynamic interplay between unbounded diversification, driven by evolutionary innovation, and bounded diversification, constrained by ecological saturation, environmental limits, and biotic interactions.

Post-extinction recoveries, particularly following the end-Permian and Cretaceous–Paleogene crises, display initially elevated diversification rates that progressively decelerate through time, consistent with logistic-like diversification dynamics and ecological carrying-capacity constraints. Correlation analyses showing strong positive relationships ($r \approx 0.6$–0.8) between environmental proxies, especially atmospheric oxygenation, and diversification patterns further demonstrate that environmental thresholds played a central role in regulating evolutionary expansion and ecological complexity.

Importantly, deep-time evidence demonstrates that recovery from severe biodiversity loss is neither rapid nor predictable. Recovery commonly required millions of years and frequently produced ecosystems that were taxonomically and functionally distinct from pre-extinction communities. These finding challenges assumptions that biodiversity loss is readily reversible or that ecosystems naturally return to previous equilibrium states once disturbances cease.

In the context of the Anthropocene, these results carry urgent implications. Contemporary extinction rates are estimated to be 100–1,000 times above geological background levels, placing current biodiversity decline within the statistical range of past mass extinction events. However, unlike previous crises driven by natural Earthsystem perturbations, the present trajectory is overwhelmingly anthropogenic, driven by rapid climate change, habitat fragmentation, pollution, and biotic homogenisation operating at unprecedented temporal scales. From a deep-time statistical perspective, continued biodiversity erosion risks pushing ecosystems beyond recovery thresholds, potentially leading to simplified and destabilised ecological states that may persist for geological timescales.

Deep time biodiversity research therefore reframes conservation not as the preservation of static species assemblages, but as the protection of evolutionary and ecological potential. Maintaining habitat connectivity, preserving functional diversity, and reducing the magnitude and pace of environmental dis-

ruption are essential for preventing biodiversity from becoming permanently constrained at lower equilibrium levels. By integrating macroevolutionary theory, statistical modelling, and evidence from extinction recovery cycles, this study demonstrates that the fossil record provides not only historical perspective but also a predictive framework for understanding the limits of biological resilience. The choices made during the Anthropocene will therefore influence the trajectory of life on Earth not merely for centuries, but for millions of years.

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AI-use disclosure statement

During the preparation of this manuscript, the authors used AI tools to improve the language and readability. After using this tool, the authors reviewed the content and made changes wherever necessary. The authors take full responsibility for the contents of this publication.

Credit statement

SPM: Investigation, Formal Analysis, Writing Original draft. LRS: Editing, Supervision.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

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