Confidence Intervals For the Duration of a Mass Extinction

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Abstract

There are several statistical methods for distinguishing whether a mass extinction is sudden or gradual, based on the stratigraphic positions of fossil taxa. This distinction, however, is in some sense a false dichotomy. A "gradual" mass extinction can encompass a wide range of scenarios, from nearly simultaneous to very protracted. Here, instead of asking whether an extinction event was sudden or gradual, we reframe the question as "how gradual was it?" To do so, we calculate a confidence interval for the duration of the extinction, defined as the difference between the ages or stratigraphic positions of the first and last taxa to go extinct.

Introduction

Current hypotheses regarding the causes of mass extinctions vary from catastrophic events, where extinctions can be sudden, to inability to adapt to environmental change, where extinctions are relatively gradual. Here, we ask "how gradual was the extinction?" by estimating the duration of the mass extinction, while accounting for the incompleteness of the fossil record. Knowing the duration of a mass extinction may help in inferring its cause.

In this framework, an interval that includes zero indicates that the data are consistent with a simultaneous extinction (although they may also be consistent with a range of gradual scenarios). We describe a Monte Carlo (simulation-based) methodology to compute confidence intervals, which relies on inverting a series of hypothesis tests, and demonstrate the method on an illustrative dataset.

Notation

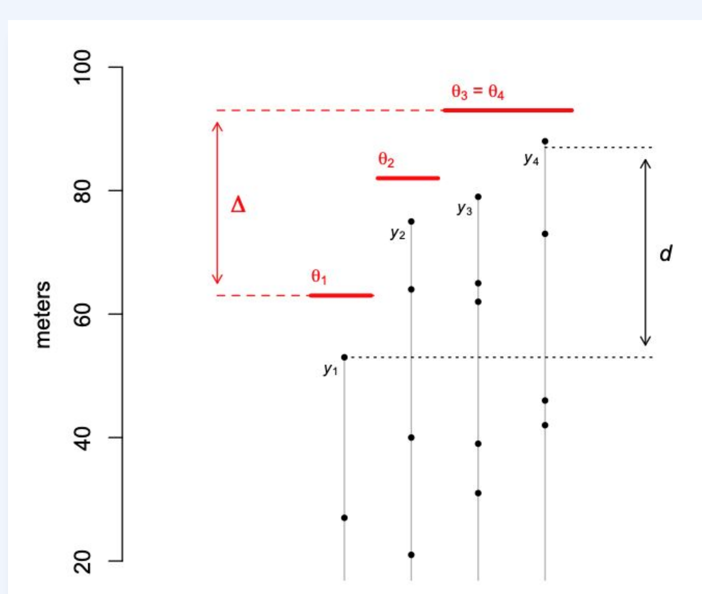
Duration: The time or stratigraphic thickness between the first and last species to go extinct (Δ).

y: last sighting of species

d: observed duration = $y_{max} - y_{min}$

θ: true extinction time of species

Δ: true duration = $\theta_{max} - \theta_{min}$

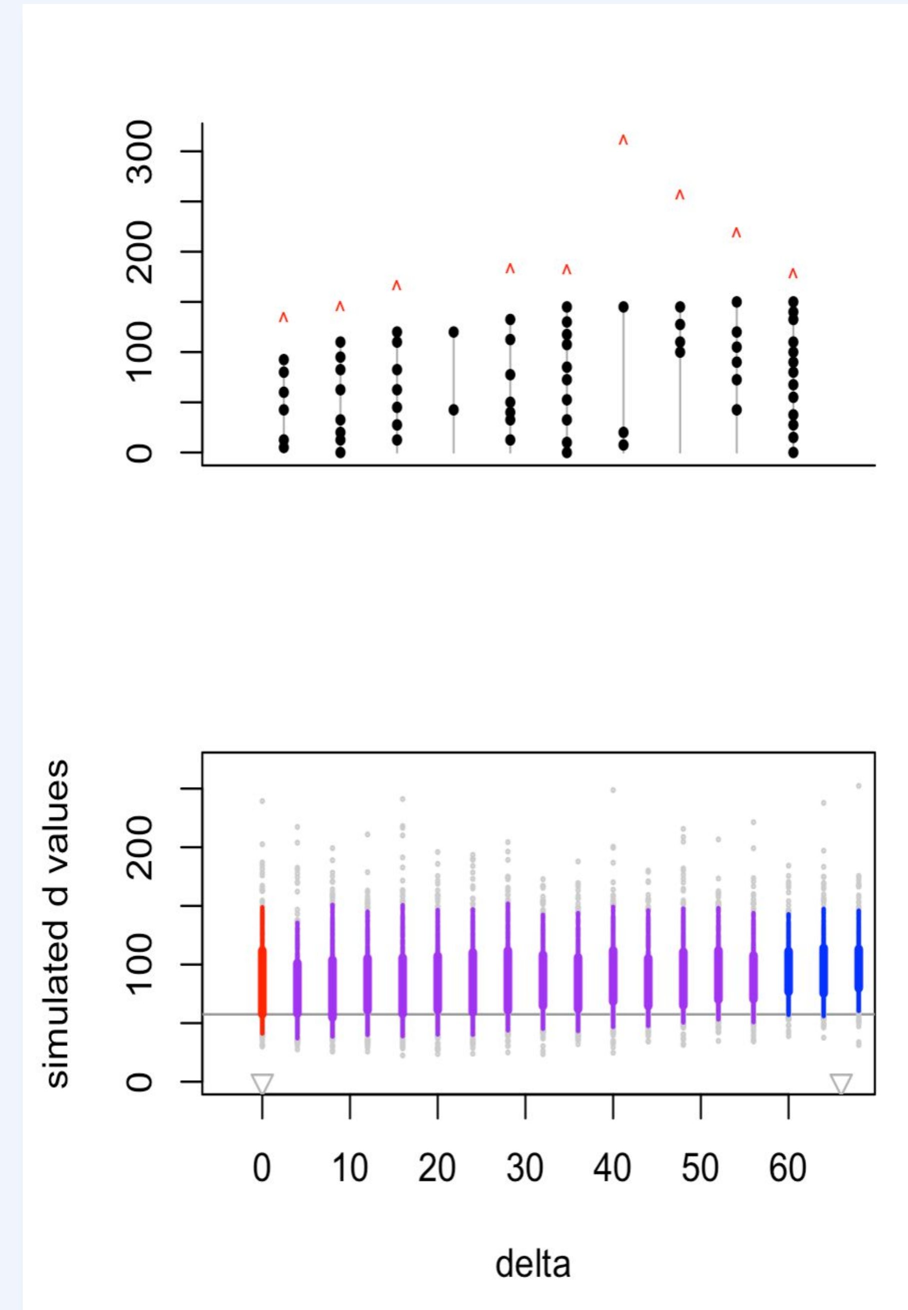


Monte Carlo Method

For every Δ value, we simulate datasets having that Δ but otherwise similar to the observed data. By comparing the observed d value with the distribution of d values from the simulated datasets, we conduct hypothesis tests on each Δ value. Values of Δ that are "accepted" are included in the confidence interval.

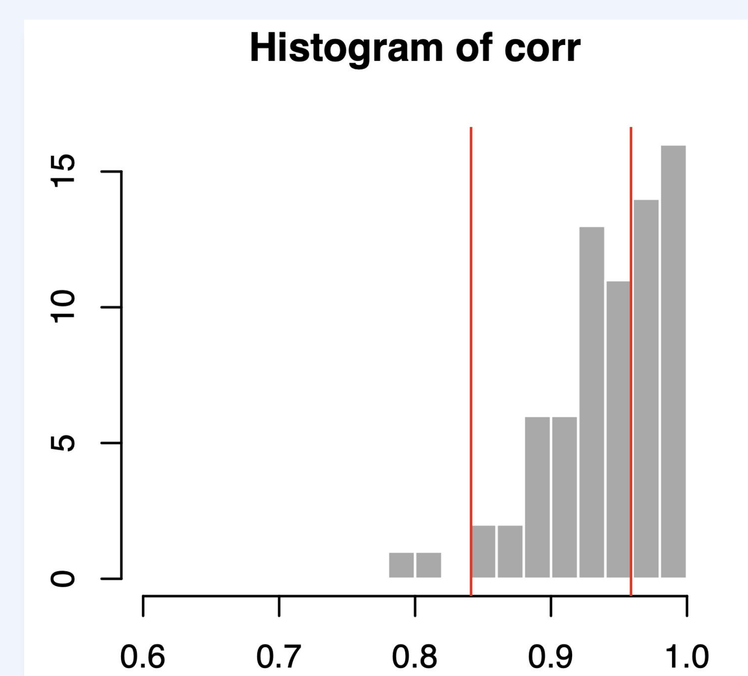
Null hypothesis	*p*-value	Outcome
H_0: $p < 48\%$	<0.0001	reject H_0
H_0: $p = 48\%$	0.0001	reject H_0
H_0: $p = 49\%$	0.002	reject H_0
H_0: $p = 50\%$	0.01	reject H_0
H_0: $p = 51\%$	0.06	do not reject H_0
H_0: $p = 52\%$	0.20	do not reject H_0
H_0: $p = 53\%$	0.53	do not reject H_0
H_0: $p = 54\%$	1.00	do not reject H_0
H_0: $p = 55\%$	0.53	do not reject H_0
H_0: $p = 56\%$	0.20	do not reject H_0
H_0: $p = 57\%$	0.06	do not reject H_0
H_0: $p = 58\%$	0.01	reject H_0
H_0: $p = 59\%$	0.002	reject H_0
H_0: $p = 60\%$	0.0001	reject H_0
H_0: $p > 60\%$	<0.0001	reject H_0

In the picture on the right, the colored bars indicate the middle 90% of d values at each value of Δ. The horizontal line indicates the observed d value. Values of Δ are accepted if their colored bar crosses the horizontal line, meaning that the observed d value is consistent with this value of Δ.



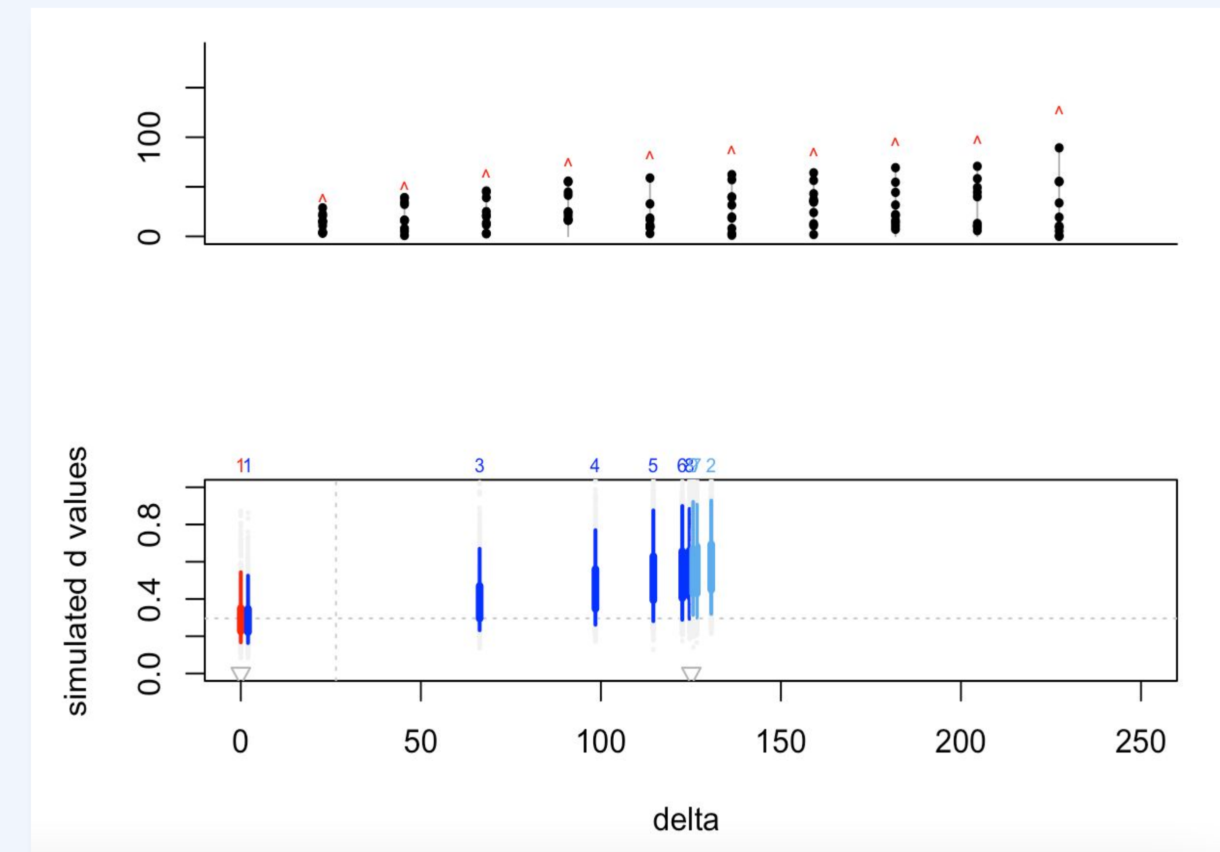
Evaluation Method

To confirm that the algorithm works correctly, we ran simulations with different combinations of parameters to estimate how often our confidence intervals contained the true value of Δ. The histogram on the right shows the results of simulations using 90% confidence intervals. In this case, we would expect that 90% of the confidence intervals indeed cover the correct value of Δ.



Speed Improvement using Binary Search

Rather than exhaustively searching the parameter space, we implemented a binary search to speed up the algorithm.



Further Work

- Improve the performance of the algorithm under different parameters for different confidence levels.
- Improve how we account for the incompleteness of the fossil record.
- Improve random generation of datasets in Monte Carlo algorithm

References

SC Wang, PJ Everson, HJ Zhou, D Park, and DJ Chudzicki (2016). Adaptive credible intervals on stratigraphic ranges when recovery potential is unknown. *Paleobiology* 42:2, 240-256.

SC Wang, AE Zimmerman, BS McVeigh, PJ Everson, H Wong (2012): Confidence intervals for the duration of a mass extinction. *Paleobiology* 38:2 265-277.