

**Supplementary Information for:
Delayed biological recovery from extinctions throughout the fossil record**

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1. Statistical significance of cross-correlations between extinctions and originations

The statistical significance of the cross-correlations that we observed can be quantified most straightforwardly using randomization methods. Here we explain our calculations and summarize their results.

Estimates of statistical significance answer the question, "What is the likelihood that we could observe a relationship -- as strong as the one that we have observed -- simply by chance, without any pattern in the underlying data?" This query leads directly to a general procedure for estimating statistical significance by randomization methods:

1. Calculate the strength of the observed relationship in the real-world data.
2. Repeat the same calculation procedure for a large number of appropriately randomized data sets (each of which therefore has no pattern or structure, except for that which arises by chance). This simulates the expected distribution of outcomes under the null hypothesis.
3. Tally the fraction of cases in which the randomized data sets (in step 2) yield a relationship at least as strong as that which was calculated (in step 1) for the real-world data. This yields an estimate of the chances that an equally strong relationship could arise at random.

Randomization methods offer two important advantages over classical estimates of statistical significance. First, one need not be able to mathematically derive the distribution of possible outcomes under the null hypothesis, since one can construct it by simulation instead. Second, the original data need not obey any particular distribution, since any of their potentially troublesome features (skew, outliers, etc.) can be incorporated in the randomized data sets as well. In our case, this is easily accomplished by generating the randomized data sets by re-shuffling the time-series sequence of the original data values themselves. This has the effect of eliminating any cross-correlation between extinctions and originations (except that which arises by chance) in the randomized data, while retaining the original distributions of the extinction and origination data themselves.

We implemented the approach outlined above using the following procedures. First, we calculated cross-correlations between extinctions and originations, for lags from -15 to 35 Myr, using both geostatistical and Fourier transform methods. We measured the strength of the cross-correlation in two separate ways: the peak cross-correlation, (the strongest positive correlation occurring at any lag between -15 and 35 Myr),

$$\text{peak cross-correlation} = \max\{r_{EO}(\tau_i)\} \quad (1)$$

and the root-mean-square cross-correlation (which expresses the overall degree of both positive and negative correlation in the data)

$$RMS \text{ cross-correlation} = \sqrt{\frac{1}{n} \sum r_{EO}(\tau_i)^2} \quad (2)$$

Next, we randomized the extinction and origination data by randomly re-shuffling their sequence in time (we kept the same stratigraphic boundaries as in the real fossil record, but randomly reassigned the extinction and origination data among those boundaries). We then recalculated the cross-correlations between these randomized data sets, just as we did for the real data. We repeated this procedure for 1000 random re-shuffles of each original data set, and compiled the peak and RMS cross-correlations for each. We then tallied the fraction of cases in which the peak or RMS cross-correlations in the randomized data exceeded those we obtained for the real data. Note that our approach measures the likelihood of a strong cross-correlation occurring at random for *any* lag between -15 and 35 Myr; this is a much stricter test than one which examines only correlations at the 10 Myr lag observed in the real data.

Results from this analysis (see Supplementary Table 1 below) indicate that cross-correlations as strong as those observed in the real data are unlikely to arise by chance. Among the 16 cross-correlations plotted in our Figure 2, in only two cases are either peak or RMS cross-correlations comparable to those that arise in >1 percent of the randomized samples, and only a single case has both peak and RMS cross-correlations that are not statistically significant at the 1-percent level.

Supplementary Table 1. Significance levels for cross-correlations between extinctions and originations

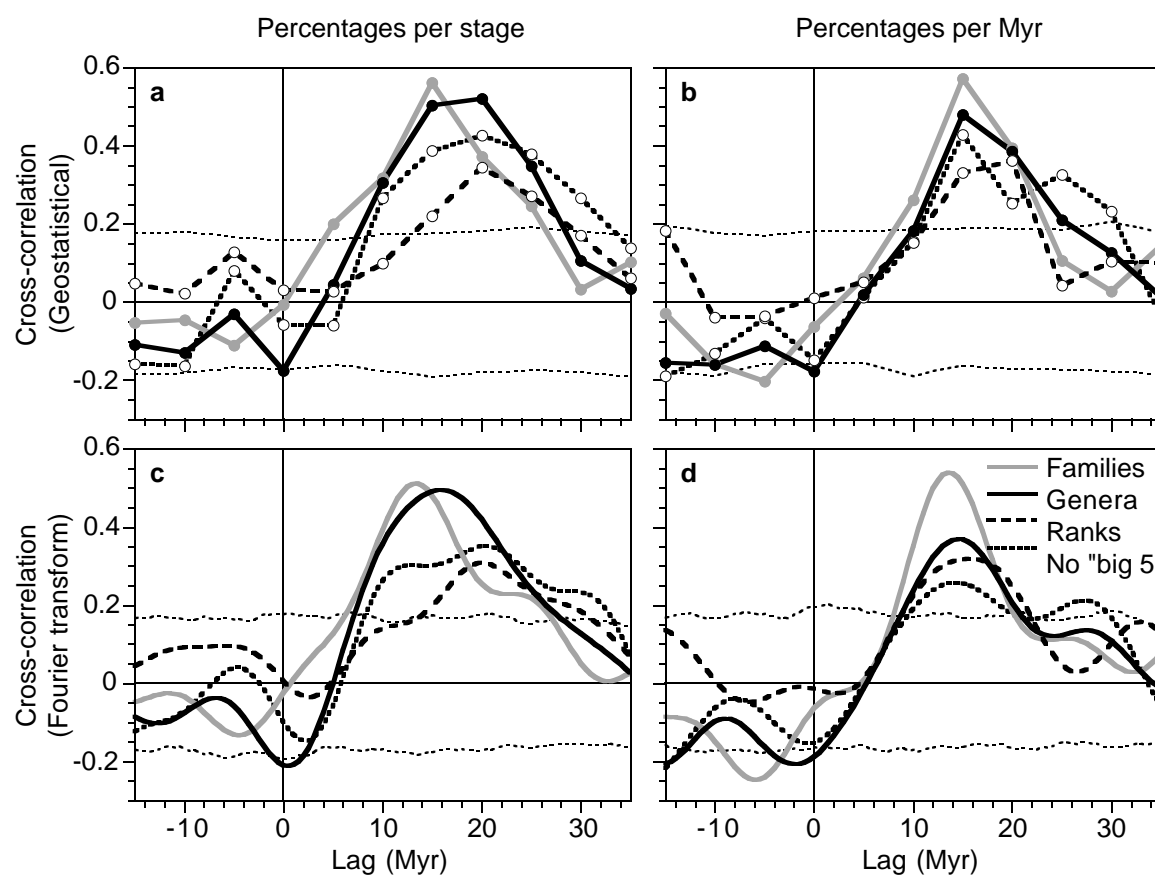
Taxonomic level	Extinction/origination metric	Method: Criterion:	<u>Geostatistical</u>		<u>Fourier transform</u>	
			peak	RMS	peak	RMS
Genera	%/stage		<0.001	<0.001	<0.001	<0.001
	%/Myr		<0.001	<0.001	0.005	0.003
Families	%/stage		0.002	<0.001	<0.001	<0.001
	%/Myr		0.002	<0.001	<0.001	<0.001
<u>Rank correlations (cross-correlation of rank-transformed data)</u>						
Genera	%/stage		0.005	0.001	0.014	0.001
	%/Myr		<0.001	0.003	0.009	0.009
<u>"Big Five" mass extinctions removed</u>						
Genera	%/stage		<0.001	<0.001	0.006	<0.001
	%/Myr		0.001	<0.001	0.118	0.032

Designation "<0.001" indicates that none of the 1000 randomized data sets had cross-correlations as strong as those observed in the real data.

2. Alternative assignments of extinctions and originations

For the calculations in the published paper, we assigned originations in each interval to the stratigraphic boundary that begins it, and extinctions to the stratigraphic boundary that ends it. This minimises the time by which originations lag extinctions, because it assumes that originations occur as early as possible in each interval, and extinctions occur as late as possible. This approach is appropriate if most faunal turnover occurs between stratigraphic intervals rather than within them.

If, instead, most faunal turnover occurs within stratigraphic intervals, this approach creates an artefactual *negative* lag (that is, extinctions lagging originations), approximately equal to the average duration of a stratigraphic interval (5 Myr). However, if most faunal turnover occurs within stratigraphic intervals, it is more appropriate to assign originations and extinctions to the middle of each interval, rather than to its boundaries. The resulting cross-correlation functions (see Supplementary Fig. 1, below) are similar to those in Fig. 2 of the published paper, and have similar levels of statistical significance (see Supplementary Table 2, below), but the strongest cross-correlations occur at lags that are approximately 5 Myr longer.



Supplementary Figure 1. Cross-correlation between extinctions and originations, with extinctions and originations assigned to midpoints of stratigraphic intervals. Cross-correlation functions calculated by geostatistical (a,b) and Fourier transform (c,d) methods, from percentage rates of extinction and origination per stratigraphic interval (a,c) and per million years (b,d). Cross-correlations are shown for genera (black lines), families (grey lines), rank-transformed genera (dashed lines), and genera with the "Big Five" major mass extinctions removed (heavy dotted lines). Fine dotted lines indicate upper and lower 5% confidence bounds for uncorrelated time series, calculated from cross-correlations of 1000 random shuffles of the original data. Positive lags indicate originations lagging extinctions.

Supplementary Table 2. Significance levels for cross-correlations between extinctions and originations (extinctions and originations assigned to midpoints of stratigraphic intervals)

Taxonomic level	Extinction/origination metric	Method: Criterion:	<u>Geostatistical</u>		<u>Fourier transform</u>	
			peak	RMS	peak	RMS
Genera	%/stage		<0.001	<0.001	<0.001	<0.001
	%/Myr		<0.001	<0.001	0.011	0.001
Families	%/stage		<0.001	<0.001	<0.001	<0.001
	%/Myr		<0.001	<0.001	<0.001	<0.001
<u>Rank correlations (cross-correlation of rank-transformed data)</u>						
Genera	%/stage		0.003	0.001	0.012	0.002
	%/Myr		0.001	0.002	0.008	0.002
<u>"Big Five" mass extinctions removed</u>						
Genera	%/stage		<0.001	<0.001	0.006	<0.001
	%/Myr		0.005	<0.001	0.149	0.018

Designation "<0.001" indicates that none of the 1000 randomized data sets had cross-correlations as strong as those observed in the real data.