Decoding 10,000 years of ecological persistence through causal networks

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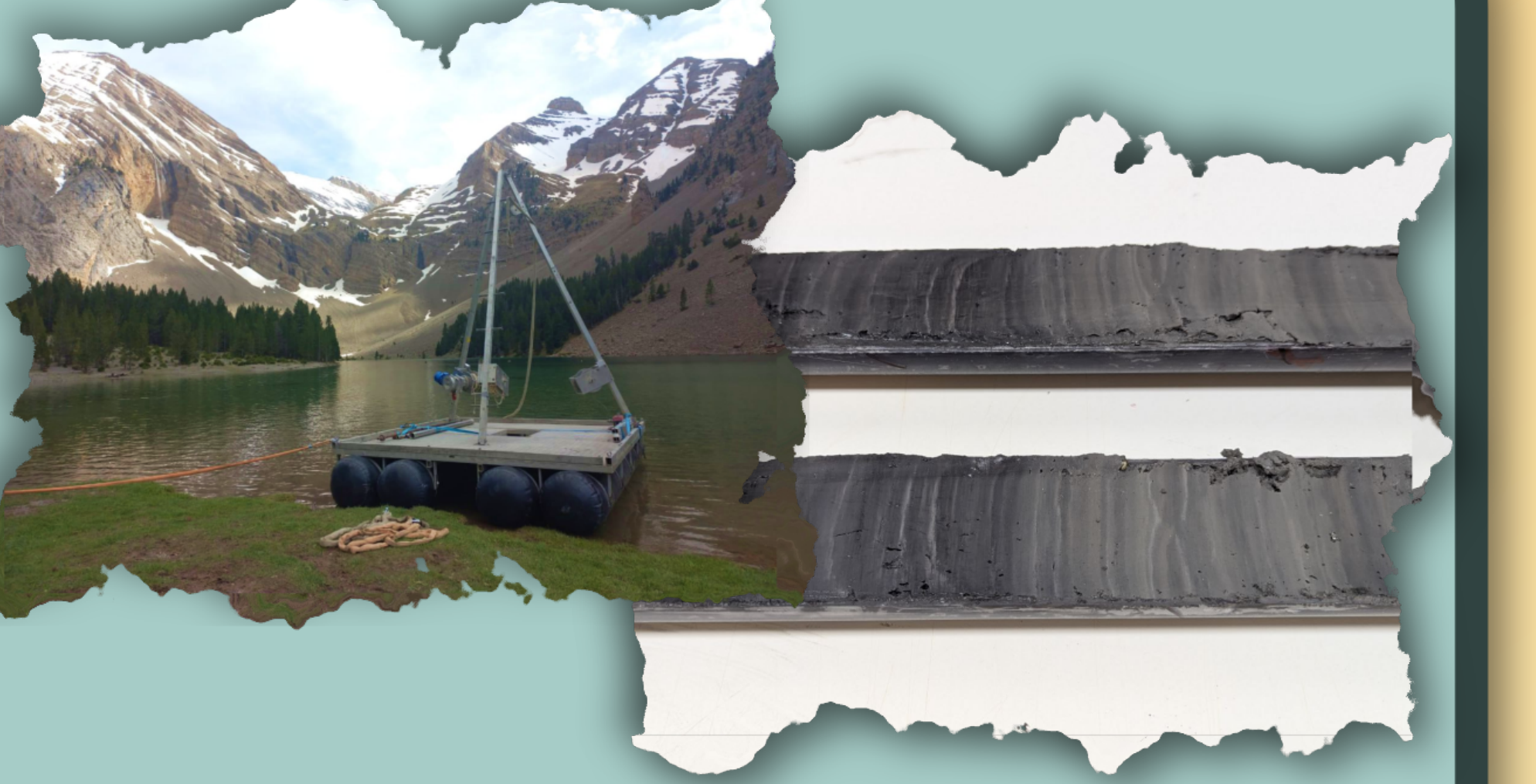
Foreword

The persistence and reorganization of ecological communities over long timescales represent a fundamental challenge in modern ecology. As anthropogenic pressures push the Earth system beyond its safe operating boundaries, identifying the mechanisms enabling to maintain functional integrity despite severe disturbances has become an urgent priority. To formulate robust ecological forecasts, it is essential to trace the baseline conditions of ecosystem complexity and stability through long-term paleoecological records.

Fire activity has proven to be a primary modulating force in ecological communities' assembly processes, functioning as a selective pressure which radically reorganizes causal dependencies between taxa and, thus, the predictability of relationships within a community. We move beyond individualistic species-response models to examine how whole-community (i.e., network) properties emerge and persist through time, providing a vital bridge between neo- and palaeo- ecological sciences. We focus on high-altitude subalpine and afroalpine ecosystems, as they are biodiversity hotspots acting as floral refugia during the Quaternary, but currently among the most endangered environments by global warming and land-use changes.

Data & Methods

We consider sedimentary (lakebed) samples extracted from two sites: **Basa de la Mora** [BSM, central Pyrenees (Spain), 1913 m a.s.l.] and **Garba Guracha** [GGU, Bale mountains (Ethiopia), 3950 m a.s.l.]. We slice those samples and analyze the **pollen spores contained within them**.



Step 1

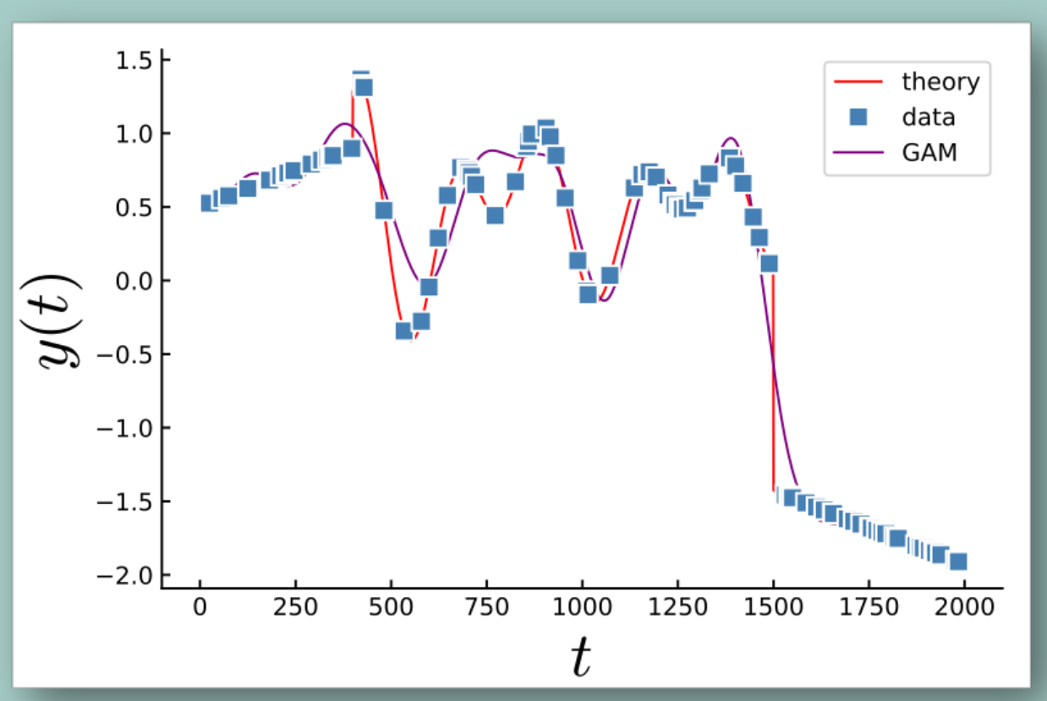
For each slice, we extract the **Pollen Accumulation Rates** (**PAR**) of taxa. PAR estimates the absolute rate at which pollen is deposited per unit area per year (grains · cm^{-2} · yr^{-1}).

$$\mathrm{PAR}(i) = \text{grain count} \cdot \underbrace{\frac{\text{added lycopodium spores}}{\text{counted lycopodium spores}} \cdot \frac{\text{sedimentation rate}}{\text{sample volume}}}_{multiplier} \equiv PC(i)\ \lambda(i)$$

NOTE: PAR are available only for GGU

Step 2

As the original sedimentary samples are unevenly spaced in time, taxa abundances records have been converted into evenly spaced time series via a **Generalized Additive Model** (**GAM**). Then, we split the time series into a set of non overlapping snapshots (3 for BSM and 4 for GGU). Snapshots correspond to distinct **regimes of fire activity**.



Step 3

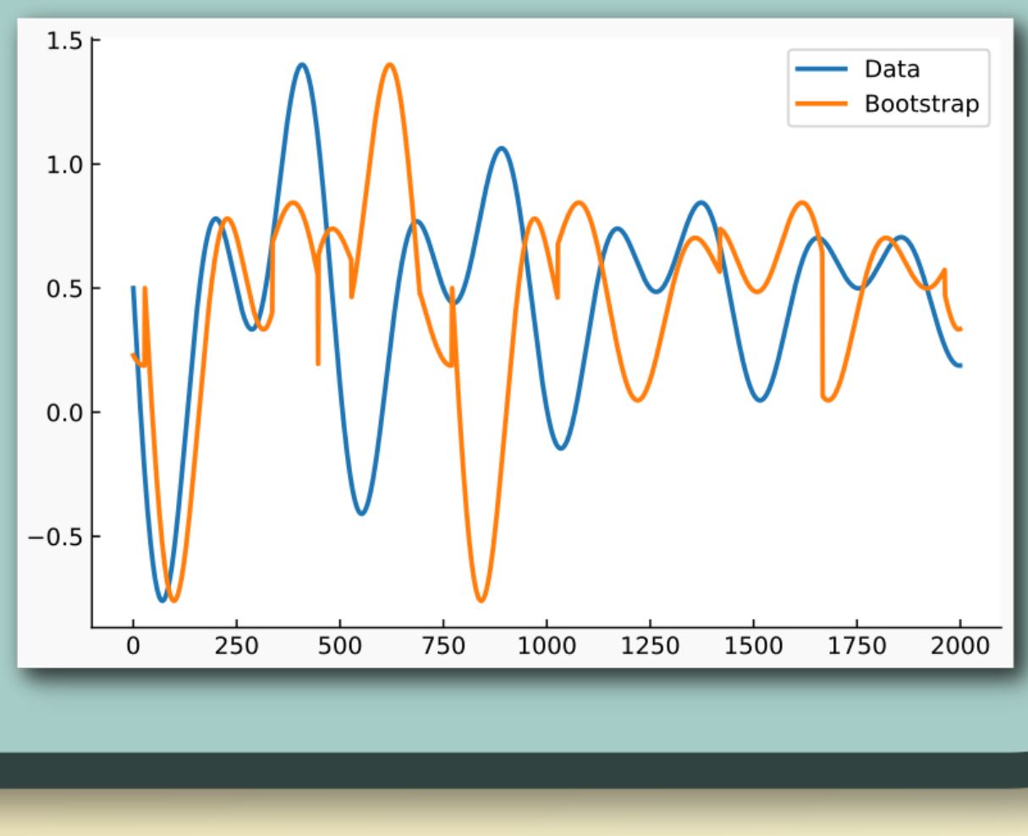
For each snapshot, we compute the **Granger Causality** (**GC**) $GC(X,Y)$ between the time series of taxa X and Y.

$$Y_t = c_0 + \sum_{i=1}^{h} \alpha_i\, X_{t-i} + \sum_{j=1}^{h} \beta_j\, Y_{t-j} + \sum_{p} \sum_{k=1}^{h} \gamma_k^p\, C_{t-k}^p + u_t\ ,$$

NOTE: We consider a *conditional* GC to include the PAR multipliers $\{\lambda\}$ and temperature as a covariates.

Step 4

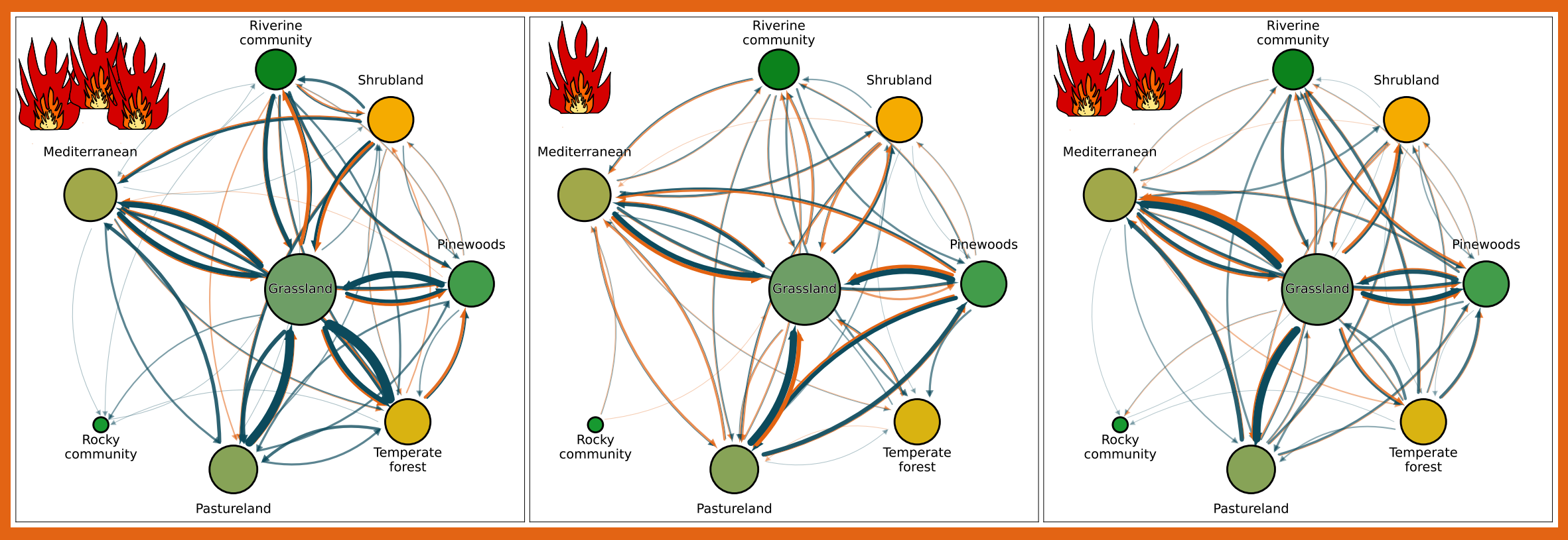
We create a causality network in which nodes are the taxa and a directed, weighted, signed edge denotes the causal relationship between their abundances. To validate the results, we perform a stationary bootstrapping on both time series and keep as "valid" only those edges whose GC can be accepted with a p-value less or equal to 0.05.



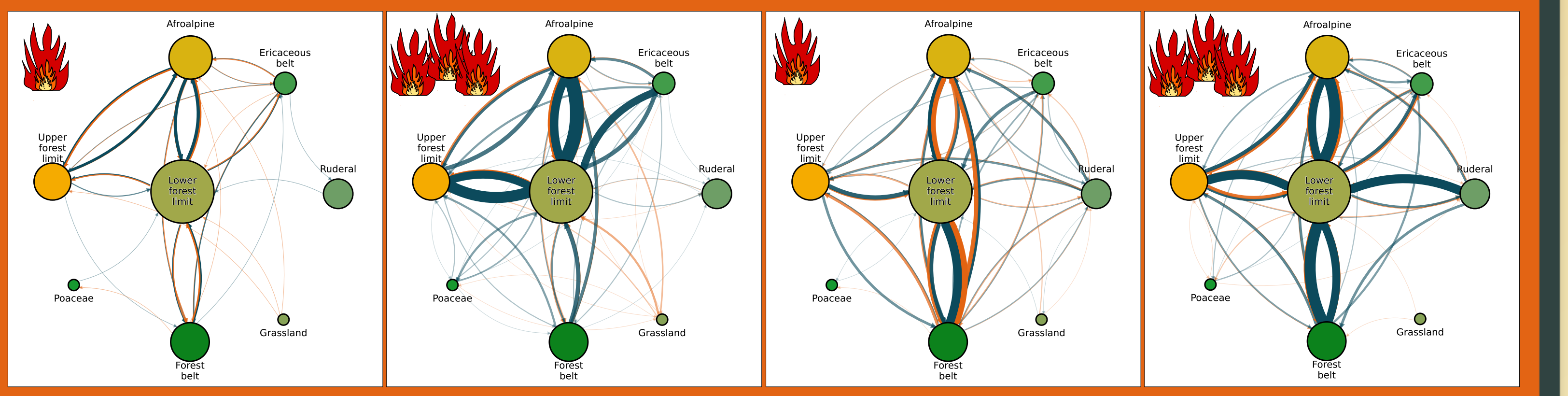
Results

We build networks for the pollen time series of the N=79 (N=83) taxa available in BSM (GGU). Then, we group species into 8 communities and coarse grain the causality networks. In the new network, a node is a community and an edge denote the abundance of edges of the same type (*e.g.*, same direction and sign) between taxa belonging to the two communities.

BSM Networks



GGU Networks



Networks' properties

Snapshot ID	Duration (ka BP)	Fire	N original	N coarse	E original	E coarse	$\langle k \rangle$ original	$\langle k \rangle$ coarse	GCC original	GCC coarse	f_-(%) original	f_-(%) coarse
Basa de la Mora (BSM)												
1	9.8 – 6.2	High	79	8	211	52	2.67	6.50	0.73	1.00	**26.5**	37.3
2	6.2 – 3.8	Low			92	33	1.16	4.12	0.57		41.3	43.8
3	3.8 – Pres.	Medium			111	44	1.41	5.50	0.72		34.2	38.7
Garba Guracha (GGU)												
1	13.6 – 11.1	Low	83	8	77	26	0.93	3.25	0.54	0.87	48.1	53.8
2	11.1 – 6.8	High			203	40	2.45	5.00	0.82	1.00	**22.2**	37.5
3	6.8 – 2.2	Low			158	35	1.90	4.38	0.84		39.9	48.1
4	2.2 – Pres.	High			182	43	2.19	5.38	0.98		**28.0**	43.3

Take home messages

The reconstruction of ecological dynamics over millennial timescales reveals that the persistence and reorganization of plant communities are not merely responses to individualistic environmental tolerances, but are governed by complex, time-varying interdependencies. The main take home messages are:

1) We have found an inverse relationship between fire intensity and the prevalence of negative causal links (f_-).

2) Periods of elevated fire activity show a prevalence of positive links, suggesting that taxa respond to severe disturbances as a synchronized whole.

3) Intense disturbance may have fostered emergent cooperation and self-organised regulation, where collective resilience becomes the primary mechanism for community persistence.

Perhaps the most thought-provoking result is the high volatility of community temporality. Our analysis of node turnover and interaction persistence suggests that even when the same taxa are present over millennia, the coexistence patterns are not static. This "persistence through reorganization" indicates that dynamic rewiring is a key mechanism for ecological resilience. Communities do not simply persist by remaining unchanged; they survive by constantly reorganizing their causal dependencies in response to shifting environmental filters.

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