Magnitude of biome shifts over the last 21,000 years reveals the impact of seasonality and intense warming on future vegetation

Supplementary information

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Supplementary Tables:

Supplementary Table 1: Mean magnitude of biome shifts at 2,250 C.E. relative to pre-industrial (0.1 cal. ka BP) in the Northern Hemisphere. Group means represent the average values across all biomes within each biome group.

Biome group	Biome	Number of grid-cells	Mean magnitude
Forest	Tropical forest	62	0.00
	Subtropical forest	26	0.46
	Temperate forest	148	1.55
	Boreal forest	173	1.31
	Group mean		0.83
Non-forest	Warm savanna and dry woodland	13	1.69
	Grassland and dry shrubland	136	0.97
	Warm desert	128	1.40
	Tundra and polar desert	145	1.96
	Group mean		1.50

Supplementary Table 2: Proportion and magnitude of biome shifts at 2,250 C.E. relative to pre-industrial (0.1 cal. ka BP) in the Northern Hemisphere, by contingency class. Contingency classes are defined based on combinations of bioclimatic seasonality and the rate of change in growing season temperature (see Fig. 4). The proportion of biome shifts is calculated as the number of grid-cells that undergo biome shifts divided by the total number of grid-cells in that class in the MPI-ESM simulation. The mean magnitude of biome shifts is the average shift magnitude (scale 0–4) for all grid-cells within each class.

Contingency class	Number of grid-cells	Proportion of biome shifts	Mean magnitude of biome shift
1	–	–	–
2	55	0.35	0.49
3	66	0.70	0.91
4	98	0.94	1.58
5	–	–	–
6	33	0.64	1.09
7	56	0.80	1.18
8	128	0.95	1.44
9	–	–	–
10	27	0.81	2.00
11	45	0.62	1.02
12	124	0.93	1.66
13	NA	NA	NA
14	40	0.92	2.45
15	64	0.64	0.95

Supplementary Table 3: Agreement of modern potential natural biomes with the pollen-based reconstructions and ESM-based simulations at 0 cal. ka BP globally. The spatial resolution of the modern potential natural biomes is 5 arc minutes for the reconstruction and 3.75 degrees for the simulation (Supplementary Data 7).

Biome	**Pollen-based reconstruction**		**ESM-based simulation**	
	Number of records (5 arc minutes)	Agreement (%)	Number of records (3.75 degrees)	Agreement (%)
Tropical forest	112	83.04	105	72.38
Subtropical forest	61	77.05	1	0.00
Temperate forest	1,254	86.76	1,332	77.33
Boreal forest	454	79.30	354	53.67
Warm savanna and dry woodland	54	75.93	62	6.45
Grassland and dry shrubland	163	52.76	276	38.04
Warm desert	22	72.73	24	62.50
Tundra and polar desert	117	52.99	83	59.04
Total	2,237	80.15	2,237	65.67

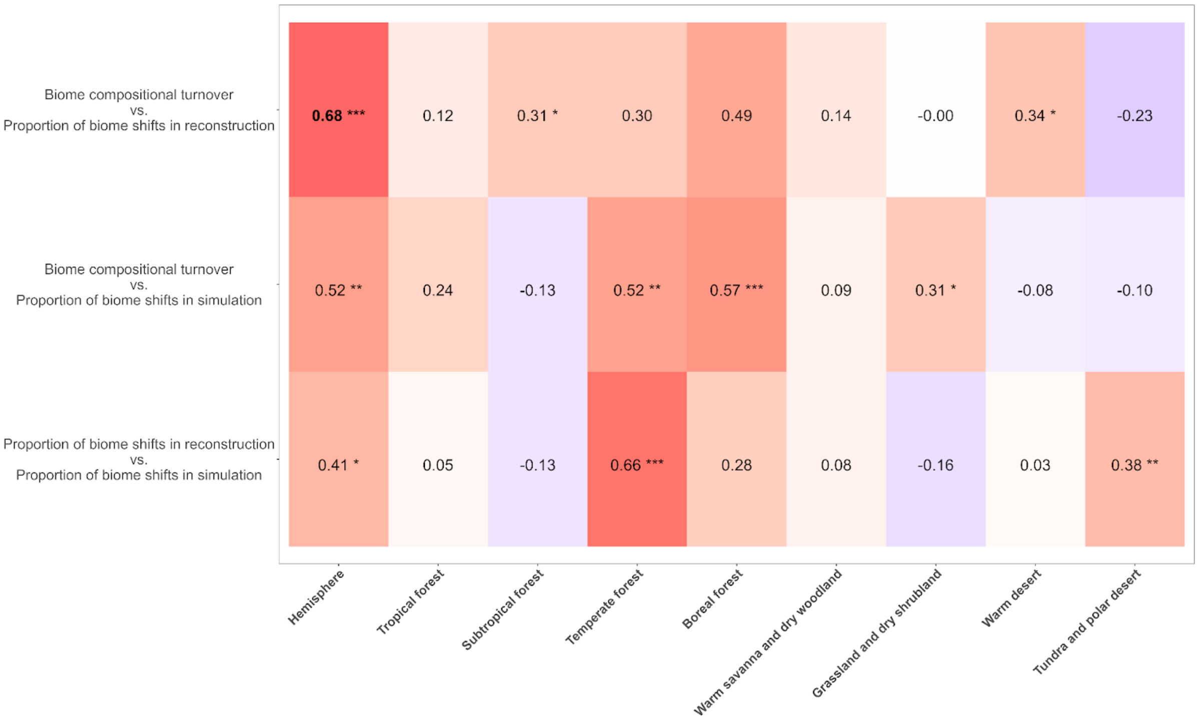
Supplementary Table 4: Number and proportion of grid-cells classified as modern potential natural biome in the Northern Hemisphere.

Biome	Number of grid-cells (5 arc minutes)	Proportion (%)
Tropical forest	125,724	7.84
Subtropical forest	25,317	1.58
Temperate forest	348,355	21.72
Boreal forest	364,014	22.69
Warm savanna and dry woodland	94,263	5.88
Grassland and dry shrubland	280,930	17.51
Warm desert	192,053	11.97
Tundra and polar desert	173,448	10.81
Total	1,604,104	100.00

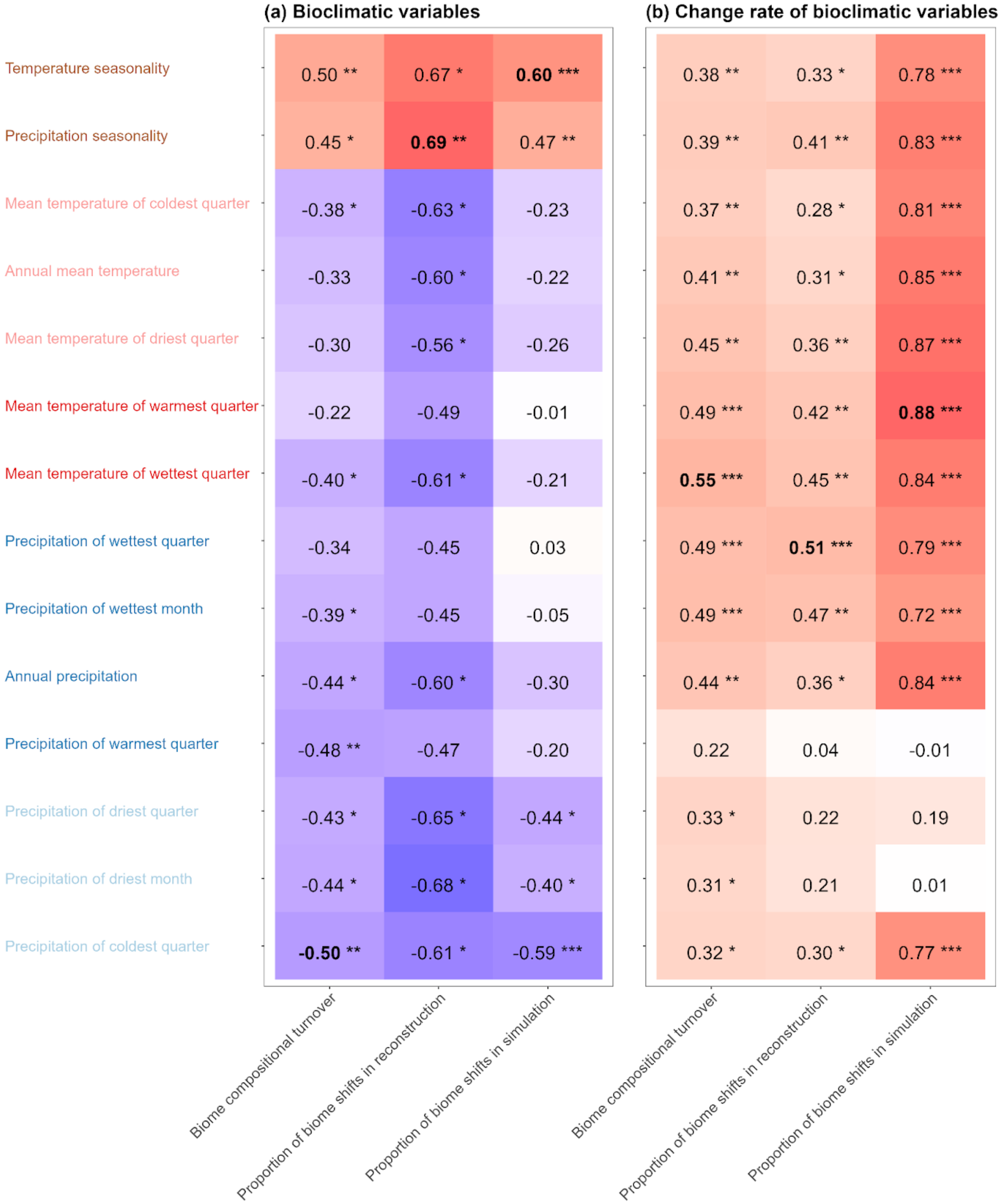
Supplementary Table 5: Distance matrix of biome shifts used in this study. Higher values indicate a greater magnitude of shift in vegetation structure or bioclimatic zone affinity between biome types.

From \ To	Tropical forest	Subtropical forest	Temperate forest	Boreal forest	Warm savanna and dry woodland	Grassland and dry shrubland	Warm desert	Tundra and polar desert
Tropical forest	0	1	2	3	1	2	3	4
Subtropical forest	1	0	1	2	2	2	3	3
Temperate forest	2	1	0	1	3	2	3	2
Boreal forest	3	2	1	0	4	3	2	1
Warm savanna and dry woodland	1	2	3	4	0	1	2	4
Grassland and dry shrubland	2	2	2	3	1	0	1	1
Warm desert	3	3	3	2	2	1	0	1
Tundra and polar desert	4	3	2	1	4	1	1	0

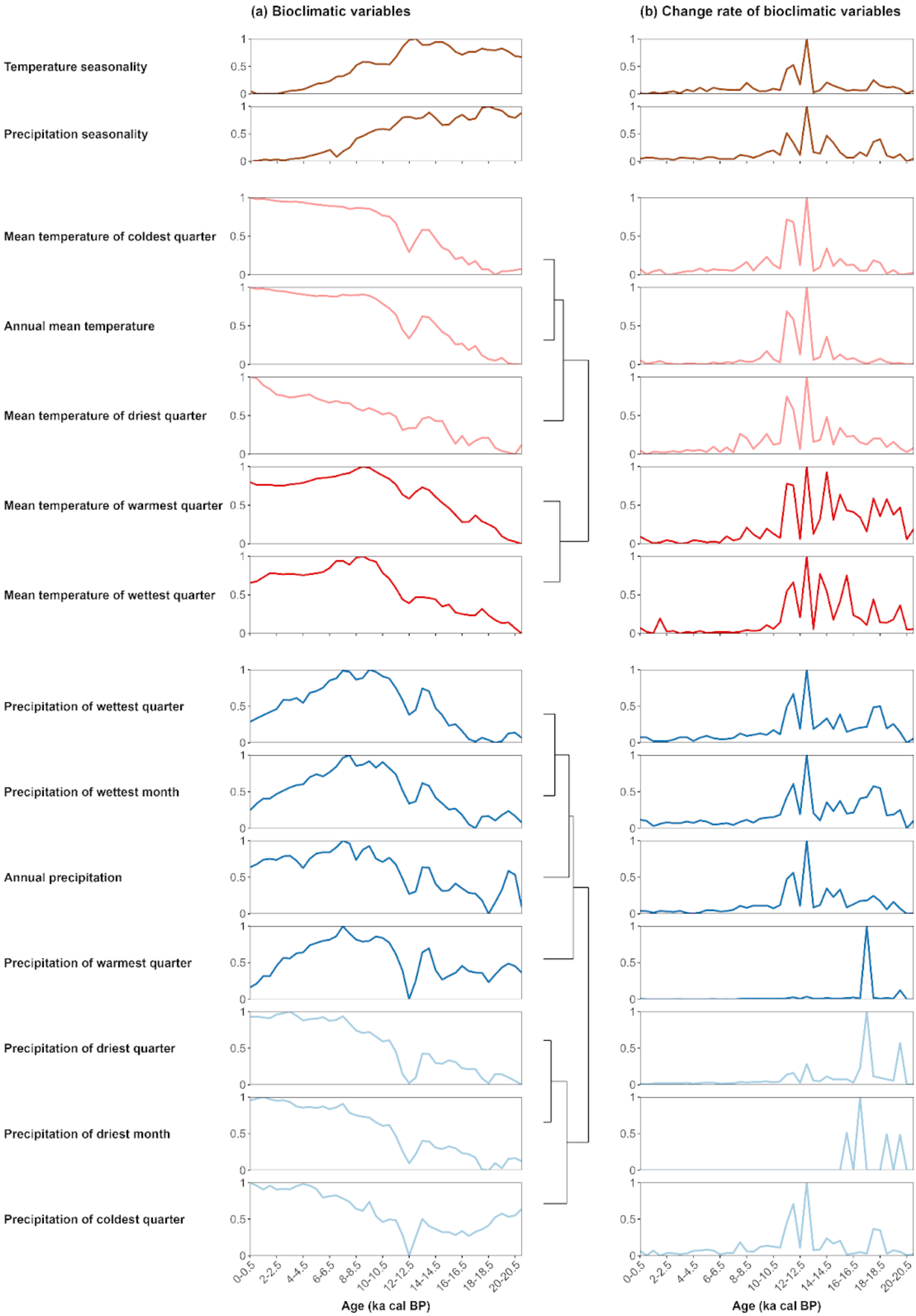
Supplementary Figures:



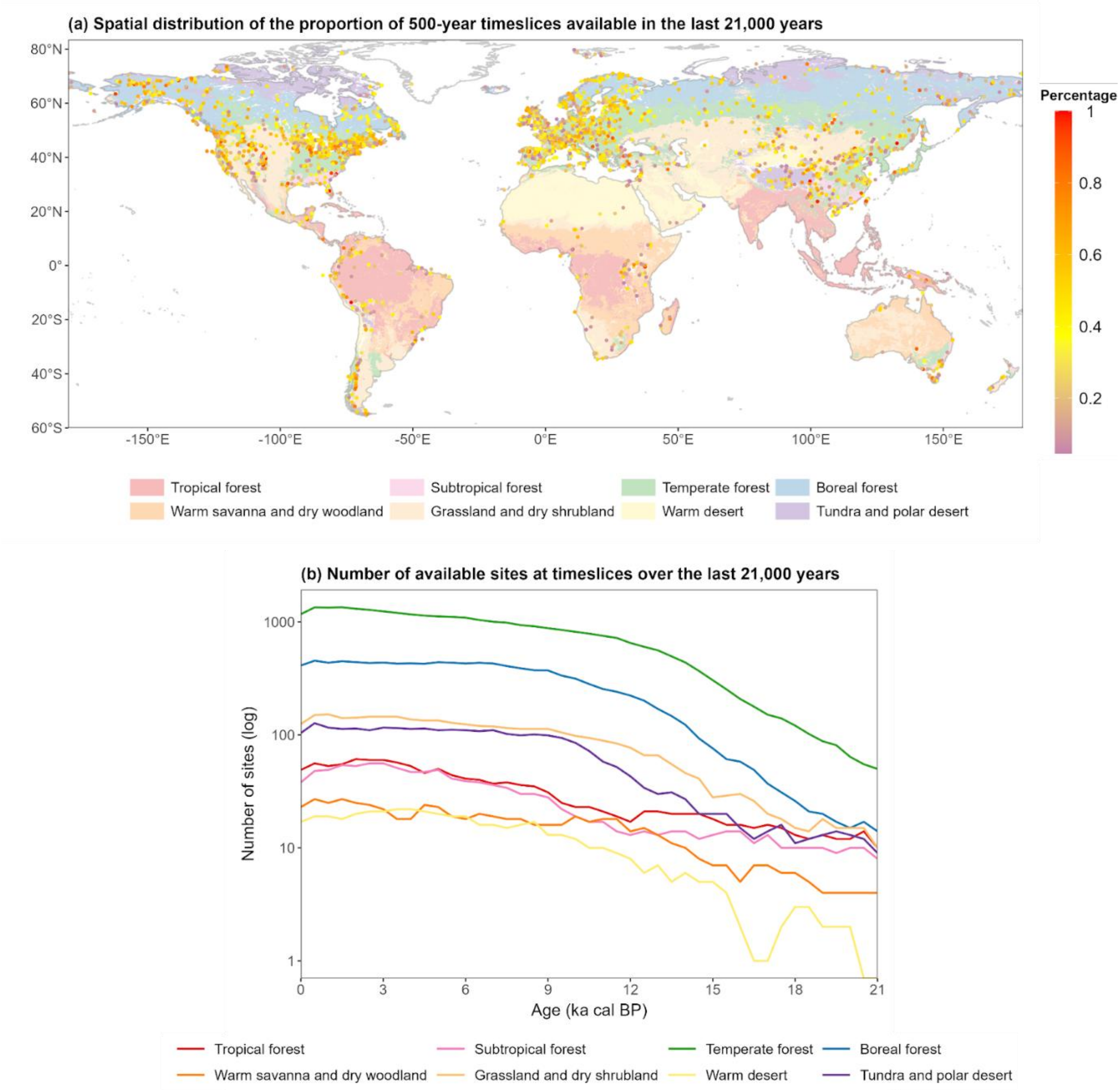
Supplementary Fig. 1: Gaussian kernel correlations between compositional turnover and the proportion of biome shifts over the last 21,000 years in the Northern Hemisphere, stratified by modern potential natural biome distributions. Statistically significant correlations are denoted by one ($p < 0.05$), two ($p < 0.01$), or three asterisks ($p < 0.001$).



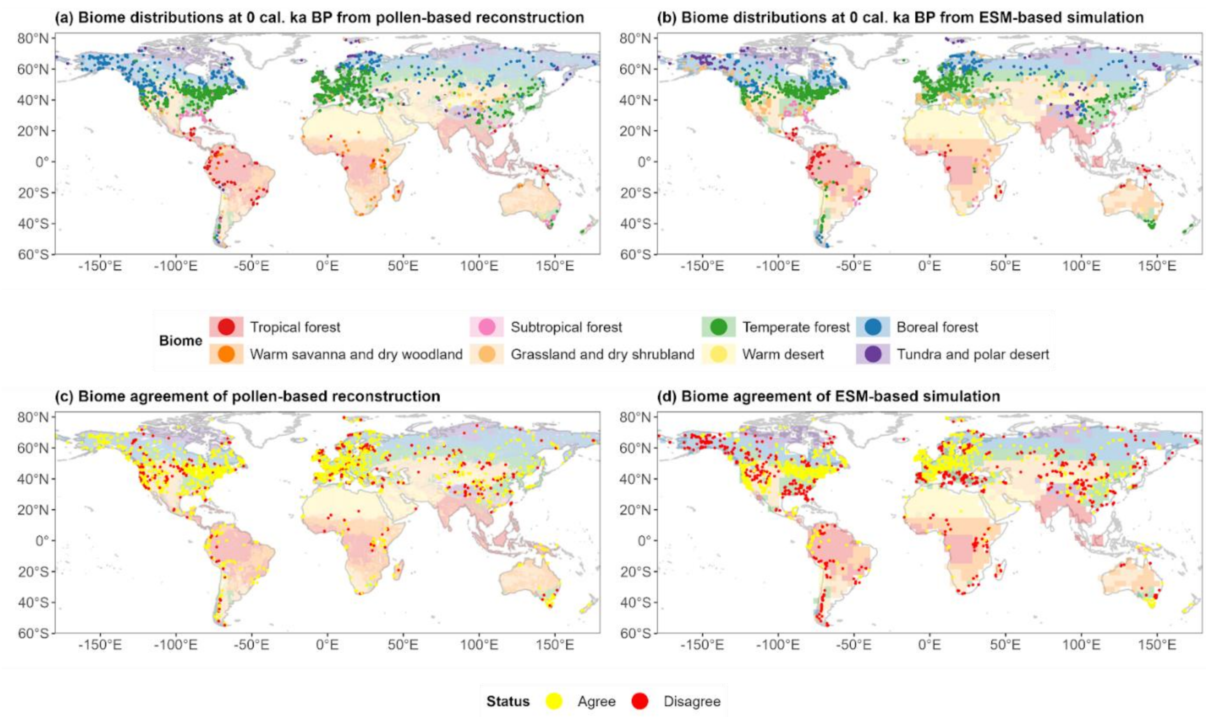
Supplementary Fig. 2: Gaussian kernel correlation coefficients between compositional turnover and the proportion of biome shifts with simulated bioclimatic variables and their rates of change over the last 21,000 years in the Northern Hemisphere. Statistical significance is indicated by one ($p < 0.05$), two ($p < 0.01$), or three asterisks ($p < 0.001$).


(a) Bioclimatic variables
(b) Change rate of bioclimatic variables
Temperature seasonality
Precipitation seasonality
Mean temperature of coldest quarter
Annual mean temperature
Mean temperature of driest quarter
Mean temperature of warmest quarter
Mean temperature of wettest quarter
Precipitation of wettest quarter
Precipitation of wettest month
Annual precipitation
Precipitation of warmest quarter
Precipitation of driest quarter
Precipitation of driest month
Precipitation of coldest quarter
0-0.5
2-2.5
4-4.5
6-6.5
8-8.5
10-10.5
12-12.5
14-14.5
16-16.5
18-18.5
20-20.5
Age (ka cal BP)

Supplementary Fig. 3: Temporal dynamics of simulated bioclimatic variables and their rates of change over the last 21,000 years in the Northern Hemisphere. Bioclimatic variables are defined following O'Donnell and Ignizio[1], and clustered hierarchically based on normalized time series. For each timeslice, hemispheric values are calculated as the weighted sum of biome-level values, with weights corresponding to the proportion of each biome in the modern potential natural biome distribution (see Supplementary Table 4). Variable values at each timeslice represent medians between adjacent timeslices, while rates of change represent relative changes between consecutive timeslices. All time series are normalized to a 0–1 scale.



Supplementary Fig. 4: Record density of pollen-based biome reconstructions over the last 21,000 years. **(a)** Spatial distribution of the proportion of 500-year timeslices available for each site globally. The background map shows modern potential natural biome distributions, aggregated from modern potential natural vegetation at 5-arcminute resolution[2,3]. (**b)** Number of available sites at each timeslice over the past 21,000 years in the Northern Hemisphere, grouped by modern potential natural biome. The y-axis is shown on a logarithmic scale.



Supplementary Fig. 5: Spatial distribution of biomes at 0 cal. ka BP and their agreement with modern potential natural biomes. Maps are derived from pollen-based biome reconstructions and ESM-based simulations. The background shows modern potential natural biomes aggregated from modern potential natural vegetation. Spatial resolution is 5 arc minutes for the pollen-based reconstruction and 3.75° for the simulation.

Supplementary References:

1. O'Donnell, M. S. & Ignizio, D. A. Bioclimatic predictors for supporting ecological applications in the conterminous United States. *U.S. Geological Survey Data Series* **691**, 1–10 (2012).
2. Ramankutty, N. *et al.* ISLSCP II Potential Natural Vegetation Cover. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/961 (2010).
3. Dallmeyer, A., Claussen, M. & Brovkin, V. Harmonising plant functional type distributions for evaluating Earth system models. *Clim. Past* **15**, 335–366 (2019).