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Supplementary Materials for

Cenozoic evolution of the steppe-desert biome in Central Asia

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The PDF file includes:

Other Supplementary Material for this manuscript includes the following:

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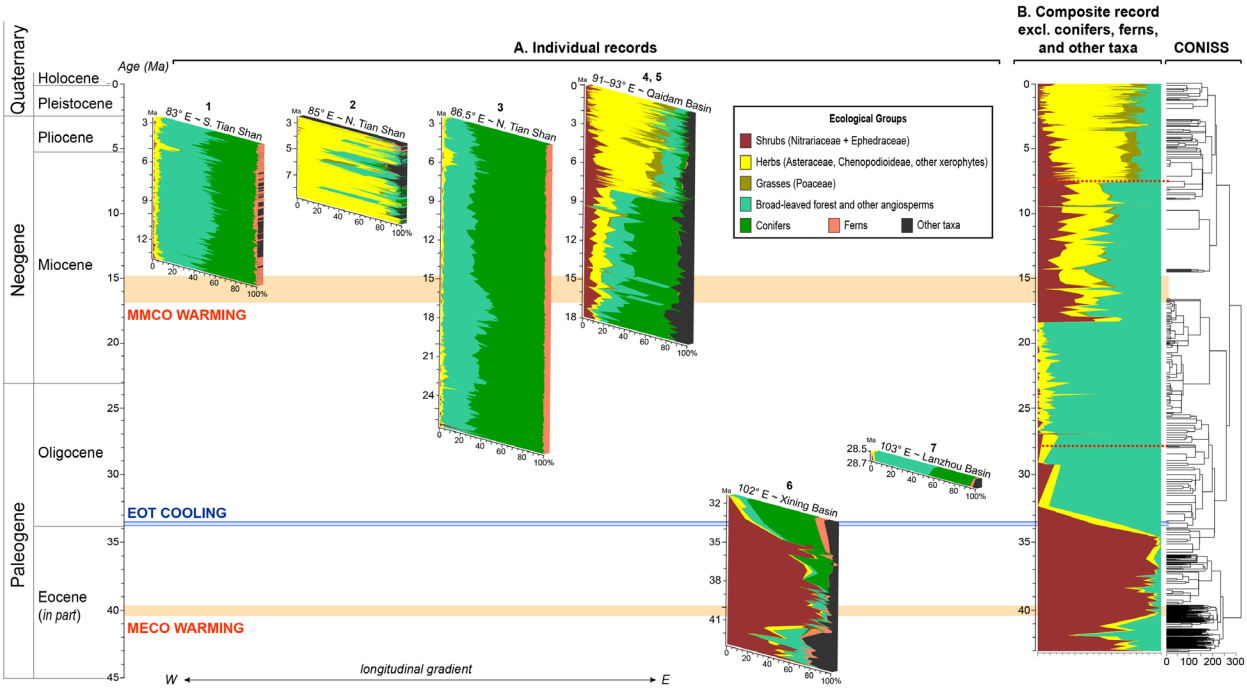

Fig. S1. Central Asian palynological records used for Fig. 5, and sources of the data. (**A)** Individual records with independent age control across a restricted longitudinal gradient in Central Asia, used to build the composite pollen section shown in Fig. 5b. (**B)** An additional composite pollen section excluding bisaccate pollen, fern spores and "other taxa" (see Table S1) is shown to the right, illustrating the same pattern and timing of shrub- to herb-dominated steppe as in Fig. 5, and supported by a CONISS (Constrained Incremental Sums of Squares cluster analysis) ordination. MECO = Middle Eocene Climatic Optimum; EOT = Eocene–Oligocene Transition; MMCO = Mid-Miocene Climatic Optimum. References for pollen data: 1) Zhang & Sun (*108*)*; 2) Sun et al. (*97*)[#]; 3) Sun & Zhang (*103*); 4, 5) Miao et al. (*107*); Cai et al. (*109*); Koutsodendris et al. (*6*); this study (Table S6); 6) Hoorn et al. (*5*); Page et al. (*39*); this study (Table S6); 7) Miao et al. (*13*). For an explanation of ecological groups shown, refer to Table S1.

* https://figshare.com/articles/Pollen_data_of_Zhang_Sunl_2011_GPC/12101442

[#] https://figshare.com/articles/Pollen_data_JGR_2007_xls/12108507

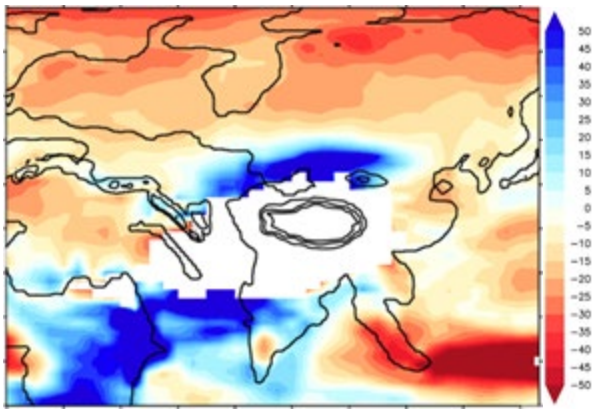

Fig. S2. Mean Annual Precipitation (MAP) anomaly (in %) obtained to test the effect of a halving of atmospheric *p*CO_2 concentration + Antarctic ice sheet without a sea retreat versus MAP from the Eocene simulation. The simulation shows that only cooling would trigger a significant decrease in precipitation at mid to high latitudes as well as in southern Myanmar, and increase precipitation in the Tarim and Xining regions. This highlights that the drying triggering the increased bare soil fraction along the 40°N westerlies path in our EOT experiment is actually initiated by lowered sea level (i.e., drying of the Tarim Basin) rather than by the cooling.

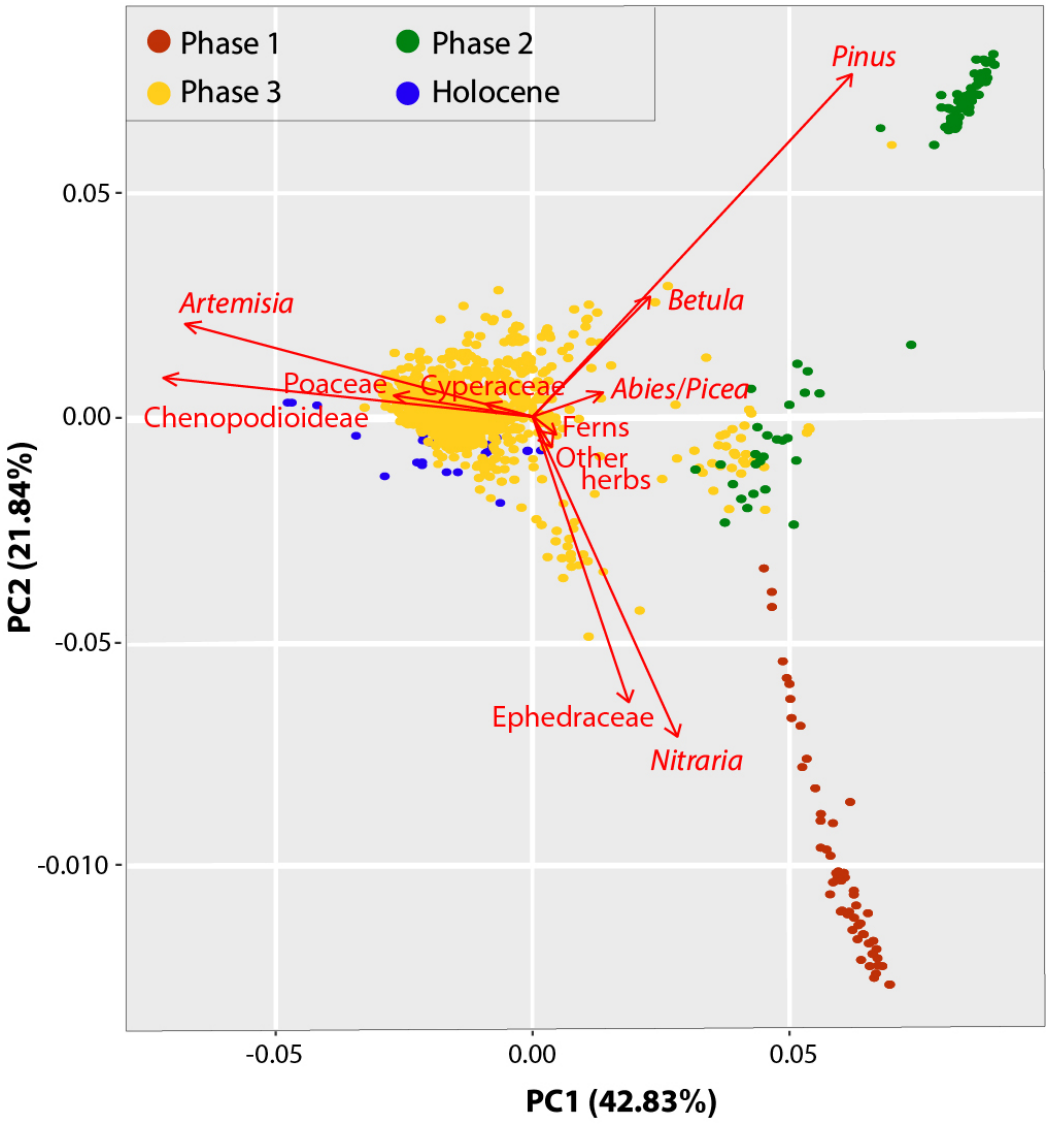

Fig. S3. Principal component analysis (PCA) of the palynological data used for Fig. 5, including a Holocene pollen dataset from Hurleg Lake, Qaidam Basin (*149*). Phases are similar to those defined in Fig. 5, with Holocene ranging from 0–13 ka, Phase 3 ranging from 0.12–17.91 Ma, Phase 2 from 17.96–33.10 Ma, and Phase 1 from 33.92–42.6 Ma. The statistical boundary of Phase 2/Phase 3 is predicted as slightly older than that shown in Fig. 5 because this is also the transition between two pollen datasets (northern Tian Shan to Qaidam Basin); to overcome this limitation we have adjusted the Phase 2/Phase 3 boundary based on documented

herb emergence for a wide range of basins across the Central Asian interior (Fig. 5; (*97–103*). In total, 95 palynological taxa are included in the analysis, but only taxa that clearly explain variance were plotted to increase visibility of the figure (see Table S5). For full percentage data of all individual taxa in the three phases, see Table S6.

Table S1. Ecological groups represented by palynological assemblages across Central Asia shown in Fig. 3, Fig. 5, and Fig. S1.

Ecological Group	Plant composition
*Shrubs (Nitrariaceae and Ephedraceae)	Nitrariaceae and Ephedraceae (numerous morphotaxa). **We represent these unrelated families as a single ecological group because they coexisted as the dominant steppe-desert shrubs for millions of years, and constitute a distinctive marker of arid environments in Central Asia in the present and geological past.*
^Herbs (Asteraceae, Chenopodioideae, other xerophytes)	*Artemisia* (Asteraceae), Chenopodioideae (former goosefoot family Chenopodiaceae), Compositae, Caryophyllaceae. *^Asian xerophytic herbaceous taxa*
$Grasses (Poaceae)	Poaceae / Gramineae. *$Asian xerophytic graminoids (also herbaceous); graphed separately to illustrate fluctuations of grasses.*
Broad-leaved forest	Deciduous angiosperm trees
Other angiosperms	Cruciferae, Cyperaceae, Elaeagnaceae, Labiatae, Liliaceae, Leguminosae, Ranunculaceae, Rosaceae, Sapindaceae, Urticaceae
Conifers	Pinaceae, Podocarpaceae
Ferns	Pteridophytes (undifferentiated)
Other taxa	*Potamogeton* and *Typha* plus other aquatics, palms, and taxa with unidentified or multiple botanical affiliations

Table S2. Climate simulation results for the late Eocene and early Oligocene Xining Basin, northeastern (NE) Tibet. These indicate Mean Annual Temperature (MAT), Cold Month Mean Temperature (CMMT), Warm Month Mean Temperature (WMMT), Mean Annual Precipitation (MAP), and Bare soil proportion.

	MAT	**CMMT**	**WMMT**	**MAP**	**Bare soil proportion**
Eocene	**20.9**	**5.9**	**37.2**	**450**	**24%**
Oligocene	**12.5**	**-1.3**	**28.7**	**280**	**56%**

Table S3. Normalized difference vegetation index (NDVI) model collection data.

Region	**Landsat ID**	**Acquire Date**	**Cloud %**
Gurbantunggut	LC81430292015198LGN00	2015-07-17	2.03
Taklimakan	LC81430322015198LGN00	2015-07-17	2.44
Jinghe	LC81460292015203LGN00	2015-07-22	6.1

Table S4. Modern Asian desert climatic parameters. These indicate Cold Month Mean Temperature (CMMT), Warm Month Mean Temperature (WMMT), and Mean Annual Precipitation (MAP), together with normalized difference vegetation index (NDVI) values and steppe-desert ecosystem phases illustrated in Fig. 5.

Modern desert	**Desert type**	**MAP**	**CMMT**	**WMMT**	**NDVI value**	**Corresponding steppe-desert phase**
Gurbantunggut	wet desert	79.5 mm	-21.8 °C	32.6 °C	NDVI > 0.2	Phase 1: middle–latest Eocene
Taklimakan	dry desert	20–50 mm	-6 °C	26 °C	NDVI < 0.1	Phase 2: EOT–mid/late Miocene
Jinghe	mountain to desert	102 mm	-15.2 °C	25.5 °C	NDVI range 1–0	Phase 3: mid/late Miocene– Pleistocene

Table S5. List of 39 palynological taxa plotted in the Principal component analysis (PCA) for Fig. S3. All taxa have an abundance > 5% in at least 1 sample.

Abies/Picea	Chenopodiaceae	*Juglans*
Cedrus	Poaceae	Lamiaceae
Cupressaceae	*Acer*	*Quercus*
Conifers indet	*Alnus*	Sapindaceae
Pinus	*Betula*	Ranunculaceae
Podocarpus	*Calligonum*	*Salix*
Tsuga	*Cupuliferoipollenites*	*Senecio* type
Abietineaepollenites	*Carya*	Tamaricaceae
Ephedraceae	*Centaurea* type	*Tilia*
Nitraria	*Crepis* type	*Ulmus/Zelkova*
Artemisia	Cyperaceae	Other herbs
Asteraceae indet	Elaeagnaceae	Ferns
Caryophyllaceae (CAC)	*Fraxinus*	Varia

Table S6. Individual percentages of all palynological taxa plotted in Fig. 5 and Fig. S3.