ORIGINAL ARTICLE

A survey of modern pollen and vegetation along a south–north transect in Mongolia

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ABSTRACT

Aim This modern pollen-rain study documents the spatial and quantitative relationships between modern pollen and vegetation in Mongolia, and explores the potential for using this relationship in palaeoclimatic reconstructions.

Location East-central Mongolia.

Methods We collected 104 pollen surface samples along a south–north transect across five vegetation zones in Mongolia. Discriminant analysis was used to classify the modern pollen spectra into five pollen assemblages corresponding to the five vegetation zones. Hierarchical cluster analysis was used to divide the main pollen taxa into two major groups and seven subgroups representing the dry and moist vegetation types and the main vegetation communities within them.

Results Each vegetation zone along the transect can be characterized by a distinctive modern pollen assemblage as follows: (1) desert zone: Chenopodiaceae–Zygophyllaceae–*Nitraria*–Poaceae pollen assemblage; (2) desert-steppe zone: Poaceae–Chenopodiaceae pollen assemblage; (3) steppe zone: *Artemisia–Aster*-type–Poaceae–*Pinus* Haploxylon-type pollen assemblage; (4) forest-steppe zone: *Pinus* Haploxylon-type–*Picea–Artemisia–Betula*, montane forb/shrub and pteridophyte pollen assemblage; and (5) mountain taiga zone: *Pinus* Haploxylon-type–*Picea*–Poaceae–Cyperaceae, montane forb/shrub and Pteridophyte pollen assemblage.

Main conclusions Based on the ratio between the major pollen taxon groups and subgroups, we propose two pollen–climate indices that represent the precipitation and temperature conditions in the study region. When plotted along our south–north transect, the moisture indices (M) and temperature indices (T) mimic the regional gradients of precipitation and temperature across Mongolia very closely. These pollen–climate indices can be used for palaeoclimatic reconstruction based on fossil pollen data.

Keywords
Cluster analysis, discriminant analysis, environmental gradient, modern pollen rain, Mongolia, ordination, palynology, pollen surface samples, pollen–climate indices, vegetation.

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INTRODUCTION

In order for palynologists to reconstruct past environments accurately with fossil pollen evidence, it is first necessary to understand how the current vegetation is represented in the modern pollen rain of the study area (Webb, 1987; Webb *et al.*, 1993). In Mongolia, however, no comprehensive study of the relationship between modern pollen and vegetation exists. With few exceptions (e.g. Tarasov *et al.*, 2000a), the Holocene pollen records from Mongolia are poorly dated (Dorofeyuk & Tarasov, 1998; Gunin *et al.*, 1999), and few studies have incorporated a modern pollen-rain analysis into their work.

Important generalizations and reconstructions of modern and mid-Holocene biomes have been produced by Tarasov

et al. (1998, 1999a) for the territory of the former Soviet Union and Mongolia based on pollen and plant macrofossil data. Based on the scores of the plant functional types (PFTs) calculated for 1245 surface pollen spectra (644 of which were from the Former Soviet Union and Mongolia, but few from the latter) covering northern Eurasia and western North America, the climate at 6 kyr BP and the Last Glacial Maximum has been reconstructed for this region (Tarasov *et al.*, 1999a,b, 2000b). At the same time, a parallel study based on a set of 102 modern pollen spectra from Mongolia concluded that the spatial patterns in modern pollen data reflect the current vegetation, and that *Larix* has low pollen productivity and poor pollen dispersal, which results in low pollen representation (Gunin *et al.*, 1999). Tarasov *et al.* (2000a) interpreted the pollen record from the Hoton-Nur basin in north-western Mongolia based on this conclusion and the quantitative method of pollen-based biome reconstruction. However, despite all the works cited above that utilize a modern pollen data set from northern Eurasia, including Mongolia, no data set or intensive study focusing on the modern pollen rain in Mongolia has been published to date, and the detailed relationships (both quantitative and qualitative) between pollen and vegetation and/or climate remain poorly known. The paucity of such knowledge is even more acute for the desert and desert-steppe regions of southern Mongolia, where pollen surface samples are completely lacking in the existing data network (Tarasov *et al.*, 1999b, 2000b).

To establish the spatial and statistical relationships between modern pollen and vegetation, we collected modern pollen samples from 104 sites along a transect from south to north in Mongolia in July and August of 2002. This study is a systematic analysis of the modern pollen rain along this transect. These data will help to broaden our understanding of the modern relationships between pollen and vegetation in the region, and fill a large gap in the pollen data network for Mongolia.

STUDY AREA

The study area, encompassing 104 surface soil samples, lies roughly between 42°45′55″ and 51°35′08″ N latitude, and between 99°57′56″ and 110°07′35″ E longitude. It includes the Hovsgol nuur area, the Hangay–Hentiy mountain area, the drainage area of the Selenge and Orhon rivers, and the Tov and East Gobi area in east-central Mongolia. It is situated in the northern part of Central Asia, far from the ocean (Fig. 1).

The climate of the study area is distinctly continental (Tuvdendorzh & Myagmarzhav, 1985; Orshikh *et al.*, 1990) (Fig. 2). The mean annual precipitation decreases steadily from north-west to south-east, which is an important factor in the distribution of vegetation formations. The highest precipitation values, exceeding 600 mm, occur locally in the mountains of the Hovsgol region. The East Gobi has the lowest values, roughly 50 mm, and has periods without any precipitation lasting several years.

The winter (November to March) is very cold. The lowest temperatures are recorded in January, with monthly averages

below −16°C and minimum temperatures as low as −24°C. The winter is also dry, with less than 5% to 10% of the annual precipitation. Snow may fall in the north and in the mountains. There are long periods with clear skies and without wind.

The summer (June–August) is the wettest season, with about 70% of the annual precipitation. The highest rainfall is usually in July, which is also the warmest month, with mean temperatures between 12°C in the north and in the mountains and 24°C in the East Gobi. From the north-west to the south-east the climate becomes drier and warmer.

The spring (April, May) is characterized by a combination of strong winds, low relative air humidity, and very low precipitation. Fierce dust and sand storms develop in the early afternoon hours (Tuvdendorzh & Myagmarzhav, 1985; Orshikh *et al.*, 1990).

VEGETATION AND CLIMATE

Figure 1 gives the distribution of the main vegetation zones in Mongolia (Lavrenko *et al.*, 1979; Lavrenko & Karamisheva, 1990). Biogeographically, Mongolia is a transitional zone from Siberian taiga to dry steppe, steppe-desert, and desert in Central Asia, and the major portion of its territory is in the steppe and forest-steppe zones. From south to north our transect traverses five vegetation zones. Botanical nomenclature follows Hilbig (1995).

Desert vegetation

The vegetation in the East Gobi occurs in an elevation belt between 1200 and 750 m, with a mean annual temperature of 4–6°C, a July temperature > 24°C, and a January temperature < −16°C. Precipitation occurs almost exclusively in the summer. It amounts to 50–150 mm annually, but less than 40 mm year^{-1} is not uncommon (Fig. 2). Winters are cold and cloudless. Important vegetation components of the desert include low shrubs and semi-shrubs, most of them belonging to the families Chenopodiaceae (*Anabasis, Haloxylon, Kalidium, Kochia, Iljinia, Salsola, Sympegma, Nanophyton*); Asteraceae (*Ajania, Artemisia, Asterothamnus, Brachanthemum*); Polygonaceae (*Atraphaxis, Calligonum*); Zygophyllaceae (*Nitraria, Zygophyllum*); Tamarucaceae (*Reaumuria, Tamarix*); Fabaceae (*Caragana, Oxytropis*); Rosaceae (*Potaninia*); and Convolvulaceae (*Convolvulus*).

Two major desert communities can be recognized based on their characteristic vegetation composition (Hilbig, 1995). The Chenopodiaceae community (Fig. 1; type 1) is a very important and widespread community in the desert zone. Characteristic dominants include *Anabasis brevifolia, Salsola passerine, Nanophyton erinaceum, Haloxylon ammodendron, Kalidium gracile, Kochia prostrata, Nitraria sibirica, Nitraria sphaerocarpa, Zygophyllum xanthoxylon, Peganum nigellastrum, Reaumuria soogorica*, and *Ephedra przewalskii*. Accompanying components include *Stipa gobica, Cleistogenes sinensis, Aristida adscenesionis, Caragana leucaphloea, Artemisia scoparia,*
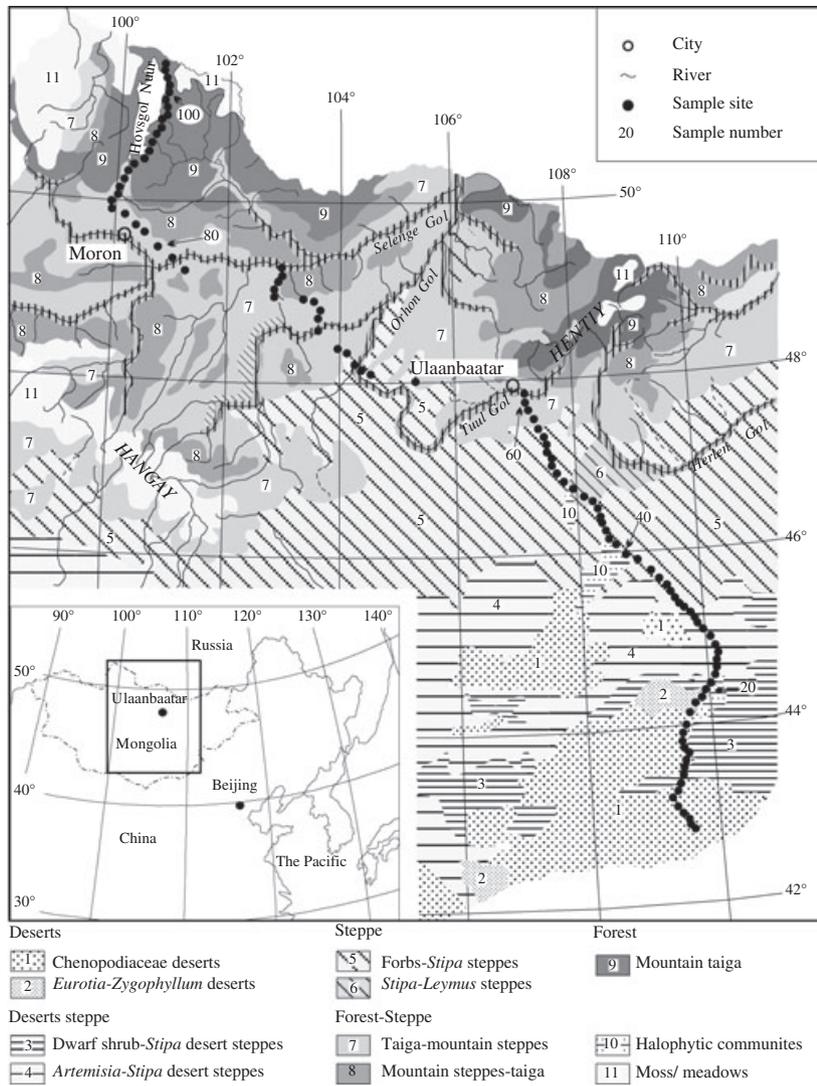
Figure 1 Vegetation map of Mongolia (based on Lavrenko *et al.*, 1979; Lavrenko & Karamisheva, 1990) and the locations of the 104 sample sites.

Tanacetum achillaeoides, Ajania spp., *Oxytropis aciphylla, Calligonum mongolicum, Asterothamnus, Allium* spp., *Brachanthemum gobicum, Halimodendron, Dodartia, Convolvulus, Scorzonera capito,* and *Potaninia mongolica* (Hilbig, 1995).

The *Eurotia–Zygophyllum* community (Fig. 1; type 2) is present in the desert zone, where the climate becomes slightly more humid, and there is a vegetation cover of 10–20%. The shrub layer is dominated by *Eurotia ceratoides, Zygophyllum xanthoxylon, Caragana leucophloea, Artemisia xerophytica, Atraphaxis frutescens, Calligonum mongolicum,* and *Ephedra* sp. The herb layer is composed mainly of *Stipa glareosa, Allium mongolicum, Convolvulus ammanii, Echinops gmelinii, Scorzonera pseudodivaricata, Lagochilus ilicifolius, Ptilotrichum canescens, Asparagus gobicus, Ajania achilleoides, Cleistogenes songorica, Anabasis brevifolia,* and *Iris tenuifolia*.

Desert-steppe vegetation

The *Artemisia–Stipa* desert-steppe (Fig. 1; type 4) is found in the northern part of the East Gobi between 750 and 1000 m

elevation, where there is a mean annual temperature of 3–4°C, a July temperature of 22–24°C, and a January temperature of −16 to −18°C. The mean annual precipitation is 100–150 mm (Fig. 2). The vegetation is dominated by species of Poaceae (such as *Stipa krylovii, S. gobica,* and *Cleistogenes soongorica*) mixed with subshrubs of *Artemisia frigida, A. xerophytica, A. caespition, Tanacetum sibiricum, T. achillaeoides,* and *T. trifidum*. Other common species include *Agropyrum sibiricum, Allium mongolium, Caragana pyhmaea, C. leucophloea, Convolvulus ammannii, Heteropappuss hispidus, Scorzonera divaricata, Anabasis brevifolia, Salsola passerine, Kochia prostrata, Eurotia cerataide Reaumuria soongorica, Oxytropis aciphylla, Peganum nigellastrum, Brachanthemum gobicum, Potaninia mongolica,* and *Zygophyllum xanthoxylon*.

The dwarf shrub–*Stipa glareosa* desert-steppe (Fig. 1; type 3), consisting mainly of *Convolvulus, Reaumuria, Zygophyllum, Tribulus, Artemisia, Peganum, Stipa, Eragrostis, Aristida, Eurotia, Calligonum, Caragana* and *Bassia*, is distributed mainly in the East Gobi (Hilbig, 1995).
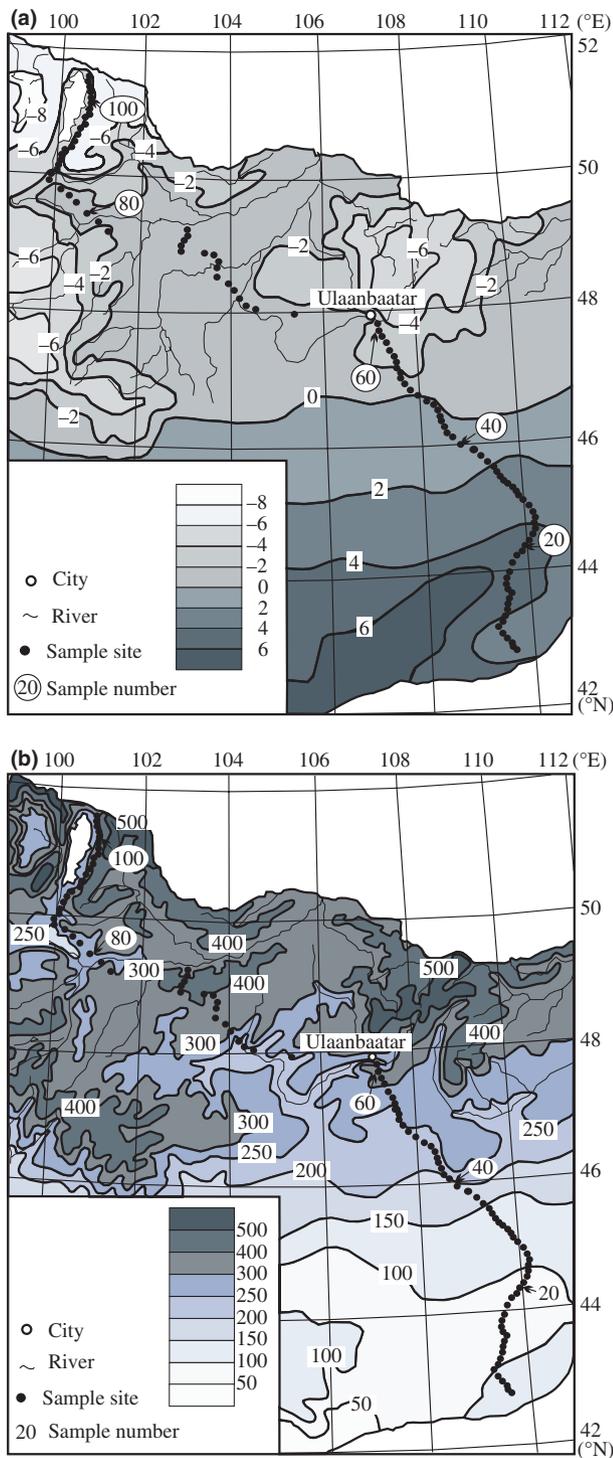
Figure 2 (a) Mean annual temperature (°C) and (b) mean annual precipitation (mm) for Mongolia (from Orshikh *et al.*, 1990).

The forbs–*Stipa* grass steppe vegetation (Fig. 1; type 5; Hilbig, 1995), which is also known as the *Cymbario dahuricae–Stipetum krylovii* association (Hilbig, 1987), is the characteristic steppe community. This grass steppe is referred to as the dry steppe to distinguish it from the moister mountain steppe. It occurs in the hills east of the Hangay, and west, south, and south-east of the Hentiy. Geographically, these areas belong to the central Halha and the southern Mongolian–Daurian region. The mean annual temperature in this area varies from 3 to −2°C (Fig. 2), with a coldest temperature of −17 to −20°C and a warmest temperature of 16 to 22°C. The annual precipitation in these regions ranges from 150 to 300 mm (Fig. 2). Grass steppe contains a significant portion of tall and medium-sized grasses, particularly tussock grasses. Dominant species are *Stipa capillata* (*Stipa krylovii*), *Cleistogenes squarrosa*, and *Artemisia frigida*. Second dominant species are *Agropyrum cristatum*, *Elymus chinensis*, *Carex durinscula*, *Artemisia adamsii*, *A. scoparia*, *A. plusfria*, *A. peatinata* and *Achnatherum splendens*. Mixed in with these are forbs such as *Cymbaria dahurica*, *Goniolimion speciosum*, *Parmelia camtschadalis*, *Kochina prostrate*, *Saussurea salicifolia*, and *Peganum harmile*, as well as the subshrub *Caragana pygmaes* (Yunatov, 1959; Hilbig, 1995). In addition, where *Stipa* steppe is close to settlements of cattle farmers the land is degraded and dominated by other grasses and forbs (*Elymus chinensis*, *Cleistogenes squarrosa*, and *Artemisia frigida*).

The *Stipa–Leymus* steppe vegetation (Fig. 1; type 6) can be found in the moister areas. It is composed mainly of *Stipa krylovii* and *Leymus chinensis* (Hilbig, 1995).

Forest-steppe vegetation

This vegetation is widespread to the north and north-east of the Hangay, and to the north-west, west, and south of the Hentiy, generally between the Selenge and Orhon rivers. The forest-steppe vegetation borders the mountain taiga zone to the north and the steppe and desert-steppe zones to the south. Within the zone, patches of forest among steppe are well differentiated. Particularly in the lower mountain belt the north-facing slopes and higher elevations are often covered with needle-leaved forest, whereas steppe is nowadays concentrated on south-facing slopes and in and around valleys. In the east–west-oriented mountain ranges, the crest often marks the transition between forest and steppe (Yunatov, 1959; Hilbig, 1995). Furthermore, the steppe vegetation seems to have been expanding at the expense of forest (Hilbig, 1995).

The taiga mountain steppe vegetation (Fig. 1, type 7) is composed mainly of mountain and high-mountain herb–bunchgrass steppes locally mixed with *Larix sibirica* forests. This vegetation type typically occurs between 1000 and 1600 m elevation. The annual precipitation varies between 250 and 400 mm. The mean annual temperature is 0 to −2°C (Fig. 2), with a January mean temperature of −20 to −24°C and a July mean temperature of 12–17°C. A few companion species such as *Betula* and *Populus* grow in the higher mountain region.

Steppe vegetation

This vegetation type, consisting mainly of *Artemisia–Stipa* grass steppe and *Stipa–Leymus* steppe communities, occupies a vast region of central and eastern Mongolia, at elevations between 950 and 1400 m.

Mountain steppe vegetation is fairly sparse, covering 60–70% of the ground surface, and is dominated by bunchgrasses such as *Festuca lenensis*, *Koeleria macrantha*, *K. gracilis*, *Poa attenuate*, *Agropyrum cristatum*, and *Stipa krylovii*. Several *Artemisia* species may be present: *Artemisia frigida*, *A. argyrophylla*, and *A. borealis*. Other common herbaceous species include *Aster alpinus*, *Saussurea salicifalre*, *Thalictrum foetidum*, *Astragalus brevifolius*, *Oxytropis pumila*, *Pulsatilla*, *Thymus serpyllum*, *Allium bidentatum*, *Arenaria capillaris*, *Bupleurum bicaule*, *Hedysarum pumilum*, *Iris potaninii*, *Pedicularis flava*, *Ptilotrichum canescens*, *Potentilla sericea*, *P. acaulis*, *Stellaria petraea*, *Stellaria chamaejasme*, and *Sibbaldianthe adpressa* (Yunatov, 1959; Hilbig, 1995).

On severely overgrazed spots the mountain steppe has degraded into a kind of short-turf mat dominated by *Carex duriuscula*. Such impoverished steppes also contain *Artemisia frigida*, and grasses become less important, with the exception of *Agropyron cristatum*. With an increase in elevation, the type changes to the mountain steppe-taiga vegetation (Fig. 1, type 8), consisting mainly of *Larix sibirica* forests, *Pinus sylvestris* forests, and mixed *Betula–Larix sibirica* forests combined with mountain steppe (Yunatov, 1959; Hilbig, 1995).

Mountain taiga vegetation

The mountain taiga vegetation (Fig. 1, type 9) is distributed mainly in the Hovsgol Nuur area at elevations of 1700–1950 m, with an annual mean temperature of −2 to −6°C, a January mean temperature of −24°C, and a July mean temperature of 12°C. The annual precipitation varies between 300 mm and 500 mm (Fig. 2). Mountain taiga is dominated by *Larix sibirica* and *Pinus sibirica*. Characteristic species of the shrub layer are *Rosa acicularis*, *Betula rotundifolia*, and, at higher altitudes, *Spiraea alpina*, *Lonicera altaica*, *Juniperus sibirica*, *Ledum palustre*, and *Rhododendron* spp. Hygrophilous grasses and perennial forbs occur here as well: *Calamagrostis obtusata*, *C. purpurea*, *Aegopodium alpestre*, *Polygonum viviparum*, *Trisetum*, *Elymus*, and members of the Caryophyllaceae, Cyperaceae, Ranunculaceae, Saxifragaceae, and Apiaceae (Yunatov, 1959; Hilbig, 1995).

FIELD AND LABORATORY METHODS

Field methods

Our sampling transect starts from south-eastern Mongolia, heads northwards, and then cuts across northern Mongolia in an east-to-west direction. We collected 104 samples from lowland desert to mountain taiga at an interval of 4 min (4′) latitude per sample (Fig. 1). Among these samples, numbers 1–25 and 90–104 were collected from nature reserves. Each sample was a composite of 10–20 subsamples of surface soil that were obtained randomly from an area of 20 m² to ensure even representation (Fig. 1; Table. 1). Some samples contained a small amount of moss and litter material at the top (1 cm).

Laboratory methods

Individual surface samples were homogenized before processing for pollen. One *Lycopodium* spore tablet (containing 12,542 ± 3.3% exotic *Lycopodium* spores, manufactured by Lund University, Batch No. 124961) was added to each sample prior to processing in order to allow total pollen and spore concentrations to be calculated. The samples were processed using 10–15% HCl (2 h), 5% KOH (boiling 3–5 min), and acetolysis solution consisting of a 9 : 1 mixture of acetic anhydride and sulphuric acid (Moore *et al.*, 1991). Furthermore, the pollen in the residue was concentrated with a 7-µm mesh sieve in conjunction with ultrasonic vibration. Finally, water-free glycerol was used for storage and preparation of microscopic slides.

Pollen identification was aided by the use of published pollen books and papers (Moore *et al.*, 1991; Wang *et al.*, 1995; Wan & Wei, 1999). We also consulted an extensive pollen reference-slide collection of more than 500 taxa from this and other regions.

A Leica light-microscope (Wetzler, Germany) was used to identify and count pollen. Routine counting was carried out at 400× magnification, and critical identifications were made under oil immersion at 1000×. A minimum of 500 pollen grains were counted from each sample. Pollen percentages were calculated using a total pollen sum excluding spores, and presented as curves in a pollen percentage diagram (Fig. 3). Pollen and spore concentrations were calculated on the basis of exotic *Lycopodium* spore counts and were expressed as the number of grains per gram of sediment (Fig. 4). Taxa with pollen percentages consistently below 2% or pollen concentration values consistently below 100 grains g^{-1} were excluded from the pollen diagrams. Graph and CorelDraw software were used to plot the pollen diagrams.

Numerical analyses

Twenty-four pollen taxa were selected for the numerical analyses. These included *Pinus* Haploxylon-type, *Pinus* Diploxylon-type, *Picea*, *Abies*, *Larix*, *Betula*, *Alnus*, Rosaceae, *Artemisia*, *Aster*-type, *Anthemis*-type, *Taraxacum*-type, Poaceae, Ranunculaceae, Polemoniaceae, Liliaceae, Caryophyllaceae, *Convolvulus*, Polygonaceae, Chenopodiaceae, Zygophyllaceae, *Nitraria*, *Ephedra* and Cyperaceae. The selection of these pollen taxa was based on their importance in characterizing the major vegetation regions in Mongolia and the pollen assemblages as presented above. All samples (104) were used in the numerical analyses.

Discriminant analysis

Understanding the quantitative relationships between modern pollen rain and contemporary vegetation is vital for the interpretation of vegetation history based on fossil data. Discriminant analysis has been used in palynological research for deriving a predictive model of group membership based on

Table 1 Site information for the 104 modern pollen surface samples from Mongolia.

No.	Lat. (N)	Long. (E)	Alt. (m)	Material	Vegetation type	Main taxa
1	42°45′55″	109°37′04″	1031	Sand + litter	Chenopodiaceae desert	Chenopodiaceae, *Nitraria*, *Ephedra* and
2	42°50′21″	109°36′02″	1104	Sand + litter		Zygophyllaceae
3	42°54′49″	109°31′11″	1147	Sand + litter		
4	43°00′05″	109°24′49″	1195	Sand + litter		
5	43°06′11″	109°12′41″	1217	Sand + soil		
6	43°10′15″	109°08′51″	1100	Sand + litter		
7	43°15′12″	109°13′05″	1070	Sand + soil		
8	43°19′57″	109°20′50″	1014	Sand + soil		
9	43°25′13″	109°29′20″	1000	Sand + soil	*Stipa* desert steppe	Poaceae
10	43°30′22″	109°35′57″	979	Sand + soil	Chenopodiaceae desert	Chenopodiaceae, *Nitraria Ephedra* and
11	43°35′03″	109°38′01″	950	Sand + soil		Zygophyllaceae
12	43°40′10″	109°37′43″	1011	Sand + soil	*Stipa* desert steppe	Poaceae
13	43°45′06″	109°36′43″	937	Sand + soil	Chenopodiaceae desert	Chenopodiaceae, *Nitraria*, *Ephedra*
14	43°49′34″	109°35′51″	887	Sand + soil		Zygophyllaceae and Poaceae
15	43°54′55″	109°36′59″	884	Sand + soil		
16	44°00′13″	109°38′22″	803	Soil + litter	*Eurota – Zygophyllum* desert	Chenopodiaceae, *Zygophyllum*, Poaceae,
17	44°06′11″	109°40′40″	773	Sand + soil		*Allium*, *Artemisia*, *Caragana*,
18	44°12′13″	109°43′22″	754	Soil + litter		*Calligonum* and *Ephedra*
19	44°16′39″	109°46′08″	751	Soil + litter		
20	44°20′19″	109°51′42″	782	Sand + soil		
21	44°25′03″	109°57′27″	810	Sand + soil	*Artemisia – Poaceae* desert steppe	Poaceae, *Artemisia*, *Ajania*, *Convolvulus*,
22	44°31′25″	110°03′46″	748	Sand + soil		Chenopodiaceae, *Zygophyllum* and
23	44°35′22″	110°05′47″	774	Soil + litter		*Caragana*
24	44°39′51″	110°07′20″	791	Sand + soil		
25	44°45′10″	110°07′35″	848	Soil + litter		
26	44°49′52″	110°07′34″	889	Soil		
27	44°55′50″	110°06′32″	985	Soil		
28	45°00′05″	110°02′41″	931	Sand + soil		
29	45°05′00″	109°58′54″	917	Soil + litter		
30	45°10′07″	109°54′50″	925	Sand + soil		
31	45°15′13″	109°48′18″	964	Soil + litter	Forb + *Stipa* steppe	Poaceae (*Stipa*, *Cleistogenes*, *Elymus*,
32	45°20′05″	109°42′00″	991	Soil + litter		*Agropyrum*), *Artemisia*, *Caragana*,
33	45°25′22″	109°36′29″	988	Soil + litter		*Cymbaria* and *Convolvulus*
34	45°30′06″	109°32′45″	988	Soil + litter		
35	45°35′27″	109°29′14″	1011	Soil + litter		
36	45°40′20″	109°26′13″	1012	Soil + litter		
37	45°45′26″	109°21′13″	1051	Soil + litter		
38	45°50′09″	109°09′57″	1066	Soil + litter		
39	45°55′05″	109°03′00″	1071	Soil + litter	Forb + *Stipa* steppe	Poaceae (*Stipa*, *Cleistogenes*, *Elymus*,
40	46°00′01″	108°46′48″	1218	Soil + litter		*Agropyrum*), *Artemisia*, *Caragana* and
41	46°05′19″	108°38′07″	1154	Soil		*Cymbaria*
42	46°10′06″	108°33′49″	1178	Soil		
43	46°15′03″	108°29′16″	1191	Soil		
44	46°19′49″	108°24′22″	1277	Soil		
45	46°21′10″	108°21′01″	1288	Soil		
46	46°30′26″	108°19′12″	1292	Soil	*Stipa – Elymus* steppe	*Elymus*, *Stipa*, *Heteropappus hispidus*,
47	46°34′50″	108°16′49″	1266	Soil		*Artemisia*, *Caragana* and *Allium*
48	46°40′02″	108°06′51″	1332	Soil + litter		
49	46°45′01″	107°56′13″	1240	Soil + litter	Forb + *Stipa* steppe	Poaceae (*Stipa*, *Cleistogenes*, *Elymus*,
50	46°50′08″	107°46′19″	1266	Soil		*Agropyrum*), *Artemisia*, *Caragana* and
51	46°55′07″	107°43′54″	1322	Soil + litter		*Cymbaria*
52	47°00′15″	107°38′20″	1312	Soil + litter		
53	47°05′09″	107°35′49″	1314	Soil + litter		
54	47°09′48″	107°34′09″	1358	Soil + litter		
55	47°15′07″	107°31′06″	1415	Soil + litter		

Table 1 Continued

No.	Lat. (N)	Long. (E)	Alt. (m)	Material	Vegetation type	Main taxa
56	47°24′58″	107°25′50″	1415	Soil		
57	47°30′03″	107°22′50″	1504	Soil		
58	47°35′40″	107°16′29″	1581	Soil	Taiga forests – mountain forb/	*Artemisia*, *Aster*-type, Poaceae, *Potentilla*,
59	47°40′37″	107°14′18″	1678	Soil	bunchgrass steppes	*Stellera*, *Oxytropis*, *Pinus*, *Larix*, *Picea*
60	47°45′12″	107°14′33″	1568	Soil		and *Betula*
61	47°50′24″	107°09′20″	1570	Soil		
62	47°59′32″	105°26′06″	1231	Soil	*Stipa* steppe	Poaceae, *Artemisia*, *Caragana* and
						Cymbaria
63	48°05′54″	104°24′00″	1080	Soil + litter	*Stipa* steppe	Poaceae (*Stipa*, *Cleistogenes*, *Agropyrum*,
64	48°09′41″	104°20′43″	1042	Soil + litter		*Elymus*,), *Artemisia*, *Caragana* and
65	48°14′49″	104°13′32″	1022	Soil + litter		*Cymbaria*
66	48°20′18″	104°06′49″	1120	Soil + litter	Mountain steppes	Poaceae, *Artemisia* and *Betula*
67	48°24′57″	103°59′22″	1222	Soil	Forb + *Stipa* steppe	Poaceae, *Artemisia*, *Potentilla* and
						Stellera
68	48°29′42″	103°39′47″	1172	Soil + litter	*Stipa* steppe	Poaceae, *Artemisia*, *Caragana* and
69	48°34′00″	103°35′47″	1095	Soil + litter		*Cymbaria*
70	48°44′57″	103°34′29″	1170	Soil + litter	Taiga forest – mountain forb/	Poaceae, *Artemisia*, *Aster*-type, *Potentilla*,
71	48°49′47″	103°30′30″	1255	Soil	bunchgrass steppes	*Stellera*, *Carex*, *Larix*, *Pinus*,
72	48°55′00″	103°20′39″	1477	Soil + litter		*Picea* and *Betula*
73	49°00′35″	102°47′59″	1422	Soil + litter		
74	49°05′09″	102°47′23″	1289	Soil + litter		
75	49°10′09″	102°51′27″	1161	Soil + litter	Mountain steppes	Poaceae, *Artemisia*, *Caragana* and
76	49°15′02″	102°57′16″	1035	Soil + litter		*Cymbaria*
77	49°19′57″	102°58′08″	944	Soil + litter	Forb + *Stipa* steppe	Poaceae, *Artemisia*, *Aster*-type, *Potentilla*
						and *Stellera*
78	49°24′57″	100°59′28″	1197	Soil + litter	Mountain steppe	Poaceae, *Artemisia*, *Caragana* and
79	49°30′28″	100°53′04″	1333	Soil		*Cymbaria*
80	49°34′49″	100°49′14″	1516	Soil	Mountain steppe – Taiga	*Larix*, *Pinus*, *Betula*, *Picea*, *Rosa*,
81	49°38′03″	100°13′10″	1338	Soil		Poaceae, *Artemisia*, *Aster*-type, *Poten-*
82	49°45′02″	100°08′18″	1566	Soil + litter		*tilla*, *Stellera*, *Carex* and *Oxytropis*
83	49°49′50″	100°06′22″	1840	Soil + litter		
84	49°56′56″	99°57′56″	1560	Soil	Grass mountain steppe	Poaceae, *Artemisia*, *Aster*-type,
85	50°00′55″	99°58′15″	1677	Soil		*Potentilla*, *Polygonum*, Caryophyllaceae
						and Ranunculaceae
86	50°05′02″	100°00′10″	1614	Soil + litter	Mountain steppe – Taiga	*Larix*, *Pinus*, *Picea*, *Rosa*, *Betula*,
87	50°10′06″	100°01′19″	1588	Soil + litter		*Polygonum*, *Calamagrostis*, *Aegopodium*,
88	50°14′33″	100°03′10″	1599	Soil + litter		*Trisetum*, *Elymus*, Caryophyllaceae,
89	50°20′03″	100°06′25″	1646	Soil + litter		Cypercaceae and Ranunculaceae
90	50°25′08″	100°09′56″	1711	Soil + moss	Taiga forest	*Larix*, *Pinus* and *Picea*
91	50°30′00″	100°24′28″	1672	Soil + moss		
92	50°35′01″	100°30′47″	1685	Soil + moss		
93	50°40′01″	100°31′38″	1687	Soil + moss	Mountain steppe – Taiga	*Larix*, *Pinus*, *Picea*, *Rosa*, *Betula* and
94	50°44′59″	100°31′51″	1669	Soil + moss		Poaceae
95	50°50′04″	100°39′41″	1914	Soil + moss	Taiga forest	*Larix*, *Pinus* and *Picea*
96	50°54′40″	100°44′00″	1873	Soil + moss		
97	50°59′56″	100°43′04″	1766	Soil + moss		
98	51°05′41″	100°44′09″	1681	Soil + moss		
99	51°10′13″	100°44′02″	1670	Soil + moss		
100	51°15′13″	100°50′39″	1758	Soil + moss	Mountain steppe – Taiga	*Larix*, *Pinus*, *Picea*, *Rosa*, *Betula* and
101	51°20′24″	100°50′21″	1758	Soil + moss		Poaceae
102	51°25′06″	100°47′24″	1689	Soil + moss	Taiga forest	*Larix*, *Pinus* and *Picea*
103	51°30′23″	100°41′09″	1696	Soil + moss	Mountain steppe – Taiga	*Larix*, *Pinus*, *Picea*, *Rosa*, *Betula* and
104	51°35′08″	100°45′49″	1842	Soil + moss		Poaceae

the observed characteristics of each pollen sample. The procedure generates a discriminant function based on linear combinations of the predictor variables that provide the best discrimination between the groups (SPSS Inc., 2001; McCune & Grace, 2002). Liu & Lam (1985) used discriminant analysis as an inferential statistical technique to measure the degree of
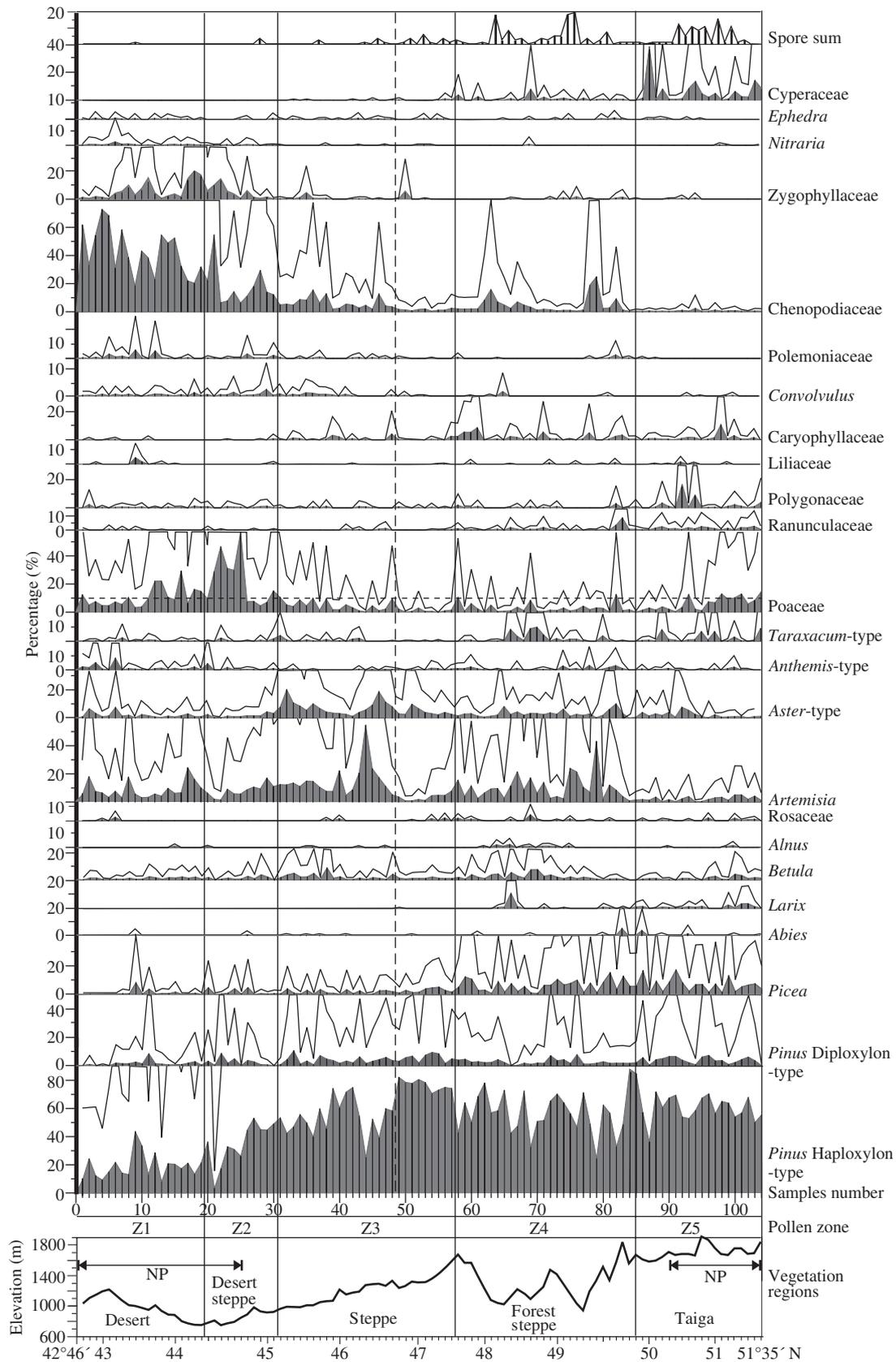
Figure 3 Pollen percentage diagram of the 104 surface samples along the south–north transect in Mongolia (black line: 5× exaggeration). Vegetation zones and elevations along the transect are shown at the bottom. NP, nature reserve area.
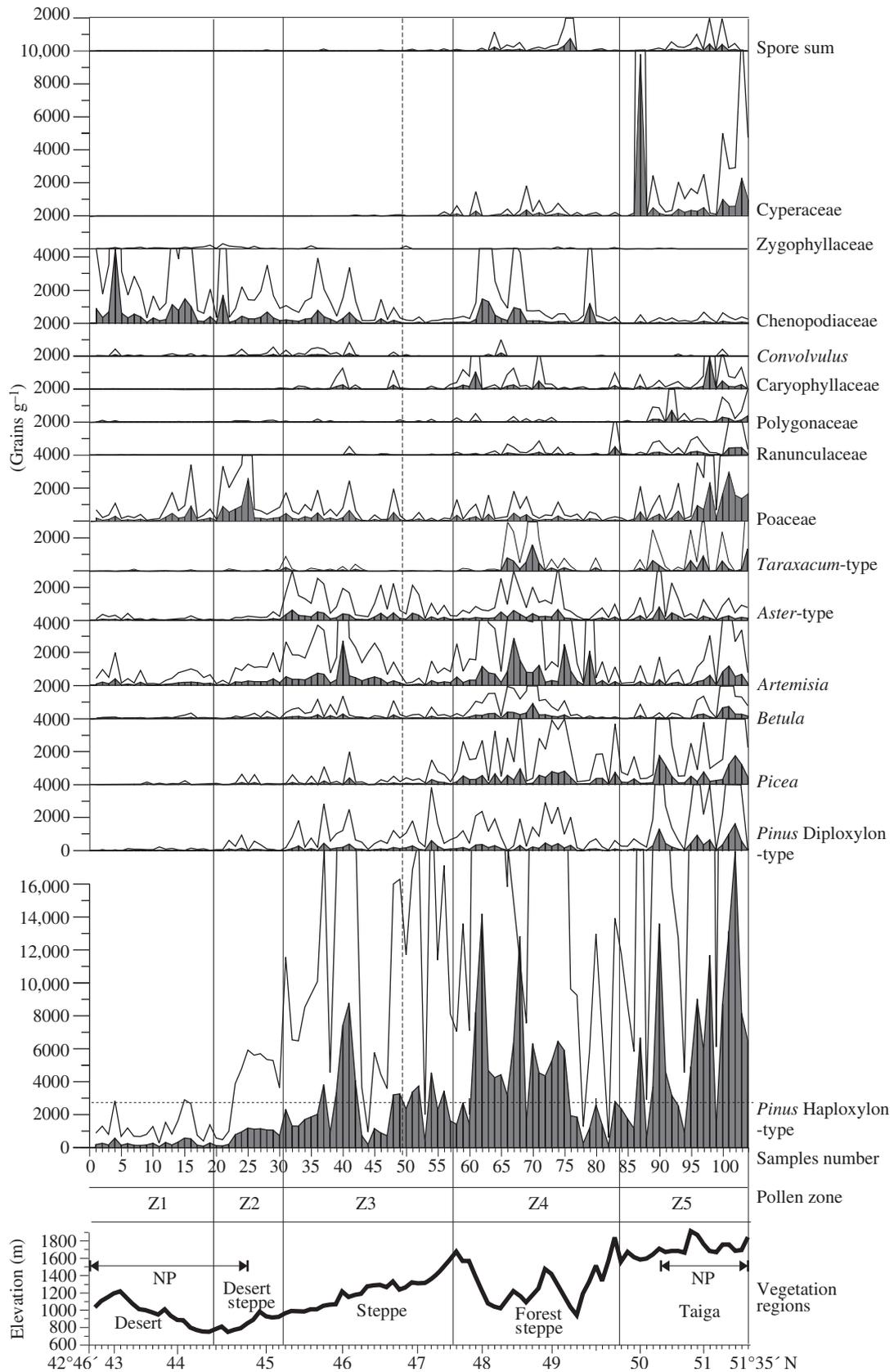
Figure 4 Pollen concentration diagram of the 104 surface samples along the south−north transect in Mongolia (black line: 5× exaggeration). Vegetation zones and elevations along the transect are shown at the bottom. NP, nature reserve area.

similarity between modern and fossil pollen assemblages. Since then, discriminant analysis has proved to be an effective tool with which to evaluate objectively the *a prior* classification of surface pollen samples into groups based on their vegetation regions (Sugden & Meadows, 1989; Liu, 1990; Lynch, 1996; Reese & Liu, 2005; Graf & Chmura, 2006). In this paper, we use discriminant analysis to determine how well the modern pollen assemblages can provide modern analogues for certain vegetation types, and to build the discriminant functions for identifying modern analogues from fossil pollen spectra obtained from this region.

Discriminant analysis requires an *a priori* classification of pollen surface samples into groups based on their vegetation regions (Liu & Lam, 1985; Liu, 1990; Lynch, 1996). Here we assigned the 104 modern pollen spectra to five major *a priori* groups based on their regional vegetation and local plant communities (Fig. 1). These five modern pollen sample groups, namely Z1, Z2, Z3, Z4, and Z5, are interpreted to correspond to five vegetation types, i.e. desert, desert-steppe, steppe, forest-steppe, and taiga, respectively.

The subprogram DISCRIMINANT in SPSS 11.0 (SPSS Inc., 2001) was used to perform the discriminant analysis. Two useful parameters can be computed with discriminant analysis (Liu & Lam, 1985). First, the *vegetation zone index* is based on the distance between a sample and the centroid of each *a priori* group in multidimensional space. Then, in palynological terms, *the probability of modern analogue* compares a pollen assemblage with the 'palynological signature' of its assigned vegetation region (as represented by its group centroid). A low probability for a sample suggests that the sample, although geographically derived from or statistically assigned to a vegetation region, in fact contains a pollen assemblage distinct from the palynological signature of this vegetation region (Liu & Lam, 1985).

Cluster analysis

Cluster analysis is a numerical technique that classifies samples (cases) or taxa (variables) into groups according to the dissimilarity between them. It has been widely used to analyse modern pollen data (Birks, 1973; Markgraf *et al.*, 1981). Hierarchical cluster analysis (HCA) is an exploratory tool designed to reveal natural groupings (or clusters) within multivariate ecological data, provided that they can be represented by a distance matrix. It has a long history of use in ecology (McCune & Grace, 2002). It is most useful for clustering a small number (less than a few hundred) of objects. Here we used the hierarchical cluster analysis procedure in the R-mode to study the relationships among the principal pollen taxa.

Non-metric multidimensional scaling

Non-metric multidimensional scaling (NMS), an ordination technique, was performed to determine how taxa distributions in all samples may be influenced by environment gradients

(such as moisture, temperature, and elevation). NMS was chosen as opposed to other ordination techniques (e.g. detrended correspondence analysis, principal components analysis) primarily because it does not assume that variables are linearly related. Furthermore, the use of ranked distances improves the linearity of the relationship between distances measured in the pollen taxa and environmental space (Clarke, 1993; McCune & Grace, 2002). For this reason, NMS has been a popular choice in ecology in recent years (Taylor *et al.*, 2001; Enright *et al.*, 2005; Boucher & Mead, 2006; Soh *et al.*, 2006).

We used average-linkage clustering (between-groups linkage) with the Pearson product-moment correlation coefficient in SPSS 11.0 (SPSS Inc., 2001) for the hierarchical cluster analysis. The non-metric multidimensional scaling procedure was conducted using the 'autopilot (slow and thorough)' mode in PC-ORD 4.14 (McCune & Grace, 2002). The Sørensen (Bray-Curtis) method was used to calculate the distance matrix for ordination.

All the results were plotted using the program CorelDraw 11.0.

RESULTS

Pollen spectra

The 104 surface samples (Table 1) were divided into five pollen zones (Figs 3 & 4), based on their location and local plant community, corresponding to five major vegetation types: (1) desert, (2) desert-steppe; (3) steppe; (4) forest-steppe; and (5) taiga. The main features of the pollen spectra in each vegetation type are described below.

Zone 1 (Desert vegetation, sites 1–19) Chenopodiaceae–Zygophyllaceae–*Nitraria*– Poaceae pollen assemblage

The desert pollen assemblage is dominated by Chenopodiaceae (20.35–68.44%), Zygophyllaceae (1.36–17.22%), Poaceae (3.29–22.22%), and *Artemisia* (3.07–18.18%). Minor pollen types include *Nitraria* (1–3%), *Ephedra*, *Anthemis*-type, Polemoniaceae, and *Convolvulus*. The abundance of tree pollen (e.g. *Pinus*, *Picea*, *Betula*, Ranunculaceae and Caryophyllaceae) is low.

Zone 2 (Desert-steppe vegetation, sites 20–30) Poaceae–Chenopodiaceae pollen assemblage

The desert-steppe pollen assemblage is characterized by maximum percentages of Poaceae (7.03–57.04%), together with Chenopodiaceae (6.3–22.18%), *Artemisia* (1.98–10.61%), Zygophyllaceae (1.33–10.07%), and fair amounts of *Convolvulus*, *Nitraria*, *Aster*-type, *Betula* (< 2.5%) and *Picea* (< 5%). The pollen concentration of Poaceae is relatively high, whereas those of other taxa are low. Furthermore the percentages of Chenopodiaceae and Zygophyllaceae seem to increase towards the ecotone with the desert.

Zone 3 (Steppe vegetation, sites 31–57) *Pinus* Haploxylon-type–*Artemisia*–*Aster*-type–Poaceae pollen assemblage

The steppe pollen assemblage is marked by high percentages of *Pinus* Haploxylon-type (39.14–78.44%), *Artemisia* (7.59–23.57%) and *Aster*-type (0.91–22.19%), and by low percentages of Poaceae (1.08–9.91%), Chenopodiaceae, and *Convolvulus*, with trace amounts of *Betula* and *Picea*. The concentrations of *Artemisia*, *Aster*-type, and *Convolvulus* are relatively high. However, some samples (i.e. sites 49–57) contain very high percentages (71.70–78.44%) but very low concentrations of *Pinus* Haploxylon-type, and very low concentrations of *Artemisia* and Poaceae.

Zone 4 (Forest-steppe, sites 58–83) *Pinus* Haploxylon-type–*Picea*–*Artemisia*–*Betula* pollen assemblage

The forest-steppe pollen assemblage (Figs 3 & 4) is distinctive in its variability because of biogeographical differences within the forest-steppe vegetation. In areas near *Larix* forest stands (sites 58–61, 70–74, 80–83) the pollen assemblage is dominated by *Pinus* Haploxylon-type (32.77–70.16%), together with moderate percentages of *Picea* (2.64–15.32%), *Artemisia* (2.64–15.53%), Poaceae (0.82–12.26%), Caryophyllaceae (0.78–8.16%), *Betula* (0.16–7.32%), *Taraxacum*-type, and *Aster*-type. In the mountain steppe zone (sites 66, 67, 69, 75, 76, 78 and 79), where taiga is 1–3 km away, the pollen assemblage is composed of *Pinus* Haploxylon-type (24.16–56.31%), *Artemisia* (7.02–23.92%), *Picea* (1.07–7.55%), and Chenopodiaceae (0.53–18.98%), together with *Betula* (0.61–7.21%), Poaceae (0.96–8.41%), and *Aster*-type. In the river valley or near ecotones (sites 62–65, 68 and 77), the pollen assemblage consists mainly of *Pinus* Haploxylon-type (56.98–78.13%), *Artemisia* (2.82–10.39%), *Picea* (0.57–8.90%), Poaceae (0.52–5.13%), *Aster*-type (0.64–8.53%), Chenopodiaceae (1.30–8.16%), and *Betula* (0.47–4.19%), along with *Taraxacum*-type, *Aster*-type, Ranunculaceae, Caryophyllaceae and Cyperaceae.

All in all, the forest-steppe pollen assemblages are composed mainly of *Pinus* Haploxylon type, *Picea*, *Artemisia*, and *Betula*, with varying contributions from montane forb/shrub and wetland elements (such as Ranunculaceae, Caryophyllaceae, Polygonaceae and Cyperaceae). Pteridophyte spores are typically common, and pollen concentrations of the main taxa are generally high.

Zone 5 (taiga, sites 84–104) *Pinus* Haploxylon-type–*Picea*–Poaceae–Cyperaceae pollen assemblage

The taiga pollen assemblage consists of *Pinus* Haploxylon-type (50.00–84.72%), *Picea* (2.21–16.67%), and Poaceae (1.10–12.97%), with *Artemisia*, *Aster*-type, *Taraxacum*-type, Ranunculaceae, Polygonaceae, Caryophyllaceae, *Betula*, and Rosaceae. The concentrations of the main taxa are also very high. Pollen from montane forbs/shrubs (e.g. Ranunculaceae and Caryo-

phyllaceae), wetland plants (such as Cyperaceae (0.70–14.03%) and Polygonaceae), and fern spores are abundant, as expected from the high effective moisture in this zone. Remarkably, the pollen of *Larix*, the dominant tree in this forest community, occurs only rarely (< 3%).

Numerical analyses

Discriminant analysis

The results of discriminant analysis show that discriminant functions 1 and 2 explain 83.9% and 10.0%, respectively, of the total variance within the data set (Table 2). The five group centroids on the first two discriminant functions (Fig. 5) are clearly separated from each other. The samples of desert, desert-steppe and steppe are most distinct from those of the other major vegetation types. However, some overlap occurs between forest-steppe and taiga. Some of the overlapping samples are from the ecotonal area between forest-steppe and taiga, reflecting the transitional character of the vegetation and the palynological signatures. This transitional character is also indicated by the classification results of discriminant analysis

Table 2 Standardized discriminant function coefficients of the 24 pollen taxa used in the discriminant analysis.

| Pollen taxa	Function 1	Function 2	Function 3	Function 4
Pinus Haploxylon	1.460	4.683	0.452	2.094
Pinus Diploxylon	0.324	1.242	0.199	0.575
Picea	0.486	0.286	0.355	0.371
Abies	−0.057	0.664	0.008	0.174
Larix	0.023	0.443	0.220	0.431
Betula	0.366	0.847	−0.154	0.77
Alnus	0.038	−0.070	−0.156	−0.280
Rosaceae	0.185	−0.387	−0.096	0.068
Polygonum	0.392	0.451	0.551	0.424
Convolvulus	−0.024	0.601	0.266	−0.131
Poaceae	0.566	2.801	0.862	0.774
Caryophyllaceae	0.243	0.102	−0.107	0.181
Ranunculaceae	0.334	0.072	0.112	0.217
Polemoniaceae	0.347	0.692	0.504	−0.418
Anthemis-type	0.230	0.389	0.139	−0.140
Aster-type	0.425	1.353	−0.383	0.662
Taraxacum-type	0.321	0.609	0.182	0.424
Artemisia	0.950	2.387	0.132	0.780
Chenopodiaceae	−0.225	2.683	0.121	1.555
Zygophyllaceae	−0.427	0.880	−0.086	0.480
Nitraria	−0.756	0.131	0.177	0.358
Ephedra	−0.104	0.119	−0.274	0.071
Liliaceae	−0.711	−0.148	−0.331	0.337
Cyperaceae	0.667	1.657	0.553	1.157
Percentage of variance	75.40	15.40	5.70	3.50
Cumulative percentage of variance	75.40	90.80	96.50	100.00
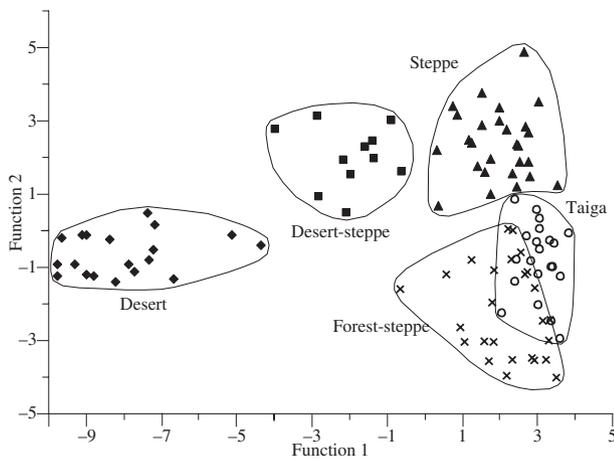
Figure 5 Ordination of the 104 surface samples along discriminant functions 1 and 2.

(Table 3), the probability of modern analogue, and the vegetation zonal index (Fig. 6).

A comparison of the predicted group (pollen zone) memberships with the *a priori* groups shows that 97.1% of the samples are correctly classified (Table 3). The misclassified samples generally have very low values (< 0.1) of probability of modern analogue, indicating that they are transitional in character or that they are unique among members of their own groups (Liu & Lam, 1985; Reese & Liu, 2005). For example, sites 82 and 83 are located near the ecotone between forest-steppe and taiga, and site 12 is unique among samples in pollen zone 1. The boundaries between vegetation regions generally correspond to abrupt changes in the vegetation zonal indices (Fig. 6).

In summary, the results of the discriminant analysis confirm that the five vegetation regions have distinctive palynological signatures as represented by the five pollen assemblages, and most of the pollen samples are typical of these major vegetation types (Fig. 6), except that some overlap occurs between the forest-steppe and taiga groups. The statistical analysis can also reflect the small azonal vegetation communities existing within a broad vegetation region and the transitional communities near the ecotone. The numerical techniques are useful in identifying the dominant pollen types

representing each major vegetation type and in depicting the transitional or unique samples.

Hierarchical cluster analysis

The HCA results are presented in a dendrogram (Fig. 7). Pollen taxa are listed along the left vertical axis. The horizontal axis shows the distance between clusters when they are joined (SPSS Inc., 2001).

Two major groupings (A and B) are indicated by HCA (Fig. 7). Group A is composed mainly of montane trees and forbs/shrubs, and B is composed of herbs and shrubs. Within Group A, montane conifers and montane forbs/shrubs requiring lower temperature and moderate humidity (*Pinus* Haploxylon-type, *Pinus* Diploxylon-type, *Abies*, *Picea*, Caryophyllaceae, and Ranunculaceae) cluster together (A1), as do deciduous tree/shrubs and heliophytic taxa (*Betula*, *Alnus*, Rosaceae, *Taraxacum*-type and *Larix*) (A2), and those characteristic of moderate hydroperiod wetlands (Cyperaceae and Polygonaceae) (A3). Group B can be divided into four subgroups. Steppe forbs/shrubs (*Artemisia* and *Aster*-type) constitute B1. B2 is composed of Polemoniaceae, Liliaceae, and *Ephedra*. Xerophilous desert forbs/shrubs (Chenopodiaceae, *Nitraria*, Zygophyllaceae, and *Anthemis*-type) constitute B3. B4 includes *Convolvulus* and Poaceae.

Within the Asteraceae family, the *Anthemis*-type, the *Taraxacum*-type, and the *Artemisia* and *Aster*-type are separated into three distinct subgroups (Fig. 7). The *Anthemis*-type clusters with xeric taxa in subgroup B3, the *Taraxacum*-type clusters with moderate-humidity taxa in subgroup A2, and the *Artemisia* and *Aster*-type are combined into subgroup B1. The separation seems consistent with their distributions within these sub-environments. The palynological identification of these subgroups may provide a useful basis for palaeoenvironmental reconstruction from fossil-pollen assemblages.

Non-metric multidimensional scaling

The NMS procedure suggests two dimensions for the final solution. The variance explained by the first and the second axes was 74.2% and 20.8%, respectively (Fig. 8). The model stress value was 12.7979, and the final instability was

Table 3 Classification results of the surface samples by discriminant analysis. 97.1% of the original grouped cases were correctly classified.

Grouped	Vegetation type	No. of samples	Predicted group membership				
			Desert	Desert-steppe	Steppe	Forest-steppe	Taiga
Original grouped	Desert	19	19* (100.0†)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
	Desert steppe	11	0 (0.0)	11 (100.0)	0 (0.0)	0 (0.0)	0 (0.0)
	steppe	27	0 (0.0)	0 (0.0)	27 (100.0)	0 (0.0)	0 (0.0)
	Steppe forest	26	0 (0.0)	0 (0.0)	0 (0.0)	25 (96.2)	1 (3.80)
	Taiga	21	0 (0.0)	0 (0.0)	0 (0.0)	2 (9.5)	19 (90.5)

*Number of samples classified as that group.
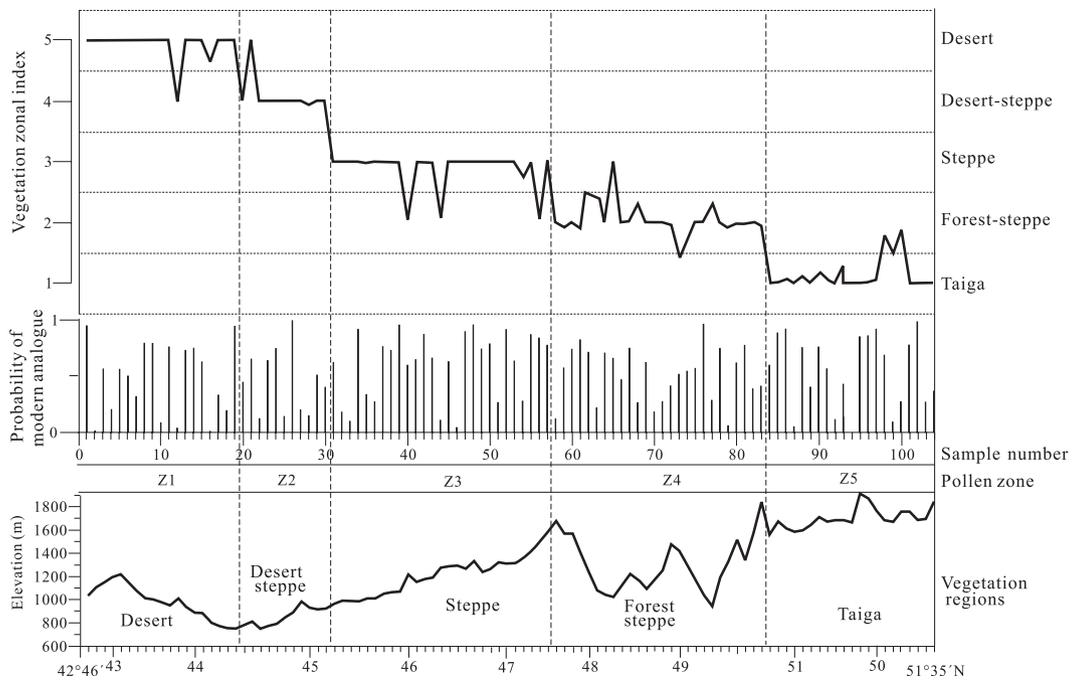†Percentage of samples classified as that group.

Figure 6 Results of the discriminant analysis for the 104 surface samples, presented as values of vegetation zonal index and probability of modern analogue.
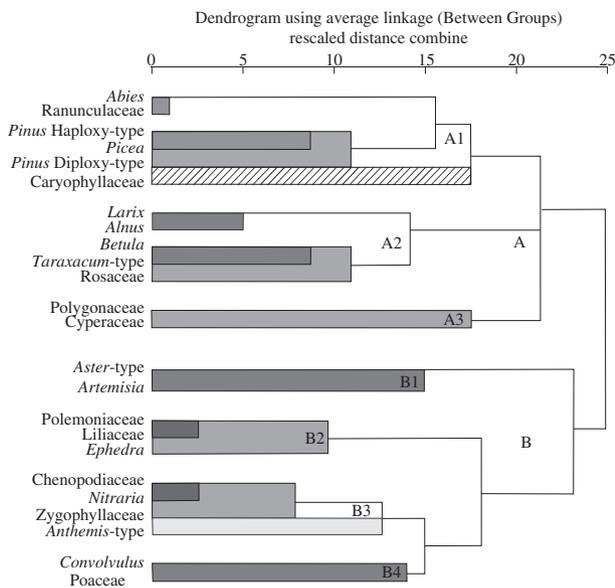

Figure 7 Dendrogram of pollen taxon groups classified by hierarchical cluster analysis.

Figure 8 Non-metric multidimensional scaling plot of pollen taxa in two-dimensional ordinal space. Ch, Chenopodiaceae; *Ni, Nitraria*; Zy, Zygophyllaceae; Pm, Polemoniaceae; Po, Poaceae; *Co, Convolvulus*; *An, Anthemis*-type; *Ep, Ephedra*; Li, Liliaceae; *Ar, Artemisia*; As, *Aster*-type; *Be, Betula*; Ro, Rosaceae; *Al, Alnus*; *Ta, Taraxacum*-type; Pg, Polygonaceae; *Pi, Picea*; *Ab, Abies*; Ra, Ranunculaceae; PD, *Pinus* Diploxylon-type; PH, *Pinus* Haploxylon-type; Ca, Caryophyllaceae; *La, Larix*; Cy, Cyperaceae.

0.00000887 (< 0.00001). The axes extracted were stronger than those expected by chance (*P* = 0.0196) based on the Monte Carlo test. The NMS ordination and the positions of the 24 pollen types on the first two NMS axes are shown in Fig. 8.

The first axis, on which Zygophyllaceae and Chenopodiaceae have the highest positive values and *Picea* and *Abies* have the highest negative values, probably reflects the temperature gradient. Montane forest trees, montane forbs/shrubs and
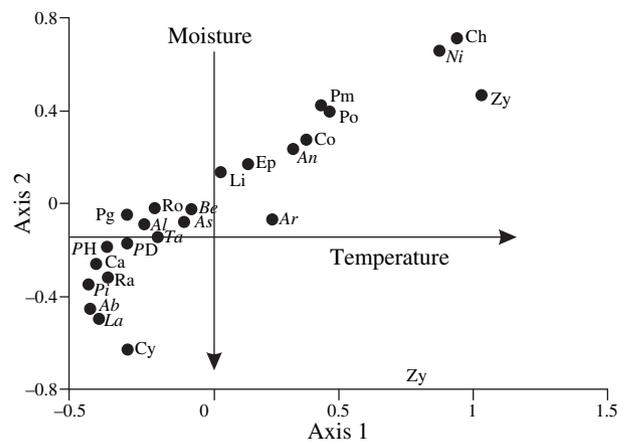
moderate hydroperiod wetland plants, such as *Picea*, *Abies*, *Pinus*, *Larix*, *Betula*, *Alnus*, Rosaceae, Ranunculaceae, Caryophyllaceae, *Taraxacum*-type, Cyperaceae and Polygonaceae, have negative values on the first axis. Xerophytic desert forbs/shrubs and steppe forbs/shrubs, such as Chenopodiaceae, *Nitraria*, Zygophyllaceae, Polemoniaceae, Poaceae, *Convolvulus*, *Anthemis*-type *Ephedra*, Liliaceae and *Artemisia*, have

positive values on the first axis. There is good agreement between NMS and HCA results except for the *Aster*-type.

The second axis, on which the xerophytic plants (Chenopodiaceae and *Nitraria*) have the highest positive value and the hydroperiod wetland plants (Cyperaceae) have the highest negative value, probably reflects the moisture gradient. Figure 8 also shows a clear separation between birch forest/shrubs and the cold-moist needle-leaved forest component. It seems that birch forest/shrubs occur in drier places than cold-moist needle-leaved forest, as indicated by their modern geographic distribution.

In addition, a gradient of increasing elevation can be traced diagonally from the top right to the low left corner, as represented by the ordination of lower-elevation desert shrubs (Chenopodiaceae, *Nitraria*) and alpine conifers (*Larix, Abies, Picea*) in the plot, respectively.

DISCUSSION

The relationship between surface pollen and vegetation can be affected by various factors, including pollen production and dispersion mechanism. In Mongolia, as well as in other regions, the complex relationship between pollen and vegetation should be understood in the light of these factors and processes.

Pollen assemblages and vegetation

The most remarkable characteristic of pollen zone 1 is the highest percentages of Chenopodiaceae and lowest of *Pinus* Haploxylon-type. The highest frequencies of xerophytic desert forb/shrub taxa (Chenopodiaceae, Zygophyllaceae and *Nitraria*) suggest that these pollen taxa are derived from the local vegetation, i.e. desert. The presence of *Pinus* Haploxylon-type at relatively low percentages, despite the absence of pine trees in the desert, is the result of long-distance transport of this pollen.

Samples in pollen zone 2 are dominated by Poaceae and *Pinus* Haploxylon-type, along with Chenopodiaceae, *Artemisia*, and Zygophyllaceae. These samples are derived from the desert-steppe. The rather high percentages of Poaceae (up to 60%) in our samples contrast with results from some other studies. The latter studies from the Chinese desert-steppe show dominance by Chenopodiaceae and *Artemisia* pollen even though grasses are very common in the vegetation (Li *et al.*, 2005; Liu *et al.*, 2006). The high abundance of Poaceae pollen in our samples (sites 21–25) is probably explained by the fact that these samples are derived from a nature reserve, where the natural vegetation is protected. By contrast, Poaceae pollen percentages are relatively low in samples collected outside the nature reserve, where the vegetation has been disturbed by human activities. Most of the samples used in previous studies on the Chinese desert-steppe were derived from anthropogenically disturbed areas.

The samples in pollen zone 3 come from the *Artemisia–Stipa* grass steppe, where the natural vegetation is not protected and has been heavily disturbed by grazing. This zone is characterized by high percentages and concentrations of *Pinus* Haploxylon-type, *Artemisia*, and *Aster*-type, but Poaceae occurs only in low percentages. Another interesting observation is that percentages of *Pinus* Haploxylon-type are very high in some samples (sites 49–57). It is notable that these samples were collected near the capital of Mongolia (Ulaanbaatar), where much of the steppe has been converted into pasture. Some researchers have suggested that the pollen frequency of *Artemisia* is higher than that of Poaceae in the grass-dominated steppe owing to the lower representation of Poaceae pollen, meaning that *Artemisia* dominates the palynological signature from steppe (Liu *et al.*, 1999). However, Liu *et al.*'s surface samples were collected from over-grazed steppes where grasses were selectively eaten by grazing animals before flowering, and therefore the over-representation of *Artemisia* in these steppe samples is probably an artefact of human disturbance. Based on our data from both inside and outside the nature reserve we argue that Poaceae abundance tends to be suppressed in the modern pollen rain from steppes where the human impact is pervasive. As a corollary, the very high pollen percentages of *Pinus* Haploxylon-type in zone 3 may also be an artefact of human disturbance (overgrazing).

The variable pollen assemblages of pollen zone 4, the forest-steppe group, contain three subtypes reflecting the mosaic character of this vegetation region (see Figs 3, 4 & 6). This pollen zone is characterized mainly by high percentages of *Pinus* Haploxylon-type, *Picea*, *Artemisia* and *Betula*, the sporadic but occasionally abundant presence of montane forbs/shrubs and pteridophyte spores, and high pollen concentrations of the main taxa.

In pollen zone 5, it is noteworthy that the frequency of *Larix* pollen is very low (maximum 3.23% in site 102), even in the *Larix*-dominated taiga. Here the pollen assemblage is dominated by *Pinus* Haploxylon-type, *Picea*, Poaceae, and Cyperaceae, together with taxa from montane forbs/shrubs, wetland plants, and pteridophyte spores.

In summary, the different vegetation zones in Mongolia contain different pollen assemblages that can be distinguished qualitatively and quantitatively. Pollen from xeric desert taxa (Chenopodiaceae, Zygophyllaceae, and *Nitraria*) is most abundant in the desert region, whereas abundant Poaceae pollen characterizes the desert-steppe region. High percentages of *Artemisia* and *Aster*-type characterize the steppes, where grasses are depleted as a result of overgrazing (Hilbig, 1995). Both forest-steppe and taiga contain high pollen percentages of *Pinus* Haploxylon-type and *Picea*, but these two vegetation types can be distinguished by the abundance of steppe forbs (*Artemisia*, *Aster*-type) and temperate summer-green tree taxa (*Betula* and *Alnus*) in the forest-steppe sites, and the abundance of montane forbs/shrubs and graminoid taxa (Poaceae and Cyperaceae) in taiga sites.

Pollen dispersal and representation

Pollen dispersal is an important factor affecting the representation of the various taxa in the modern pollen rain. Here we

select 10 important taxa to discuss their patterns of pollen dispersal and representation.

Pinus

Three species of pine are present in Mongolia: *Pinus pumila*, *P. sibirica* and *P. sylvestris*. Of these, *P. sylvestris* produces Diploxylon-type pollen and the other two species (*P. pumila*, *P. sibirica*) produce Haploxylon-type pollen. *Pinus pumila* and *P. sibirica* grow in the Hangay and Hentiy mountains and in the Hovsgol Nuur area. *Pinus sylvestris* is widespread along the sandy river terraces of the Orhon, Selenge, and Onon (Hilbig, 1995).

Pinus is dominant in the modern pollen rain in all the vegetation zones in the study area except the desert. *Pinus* percentages are lowest in the desert vegetation and highest in the overgrazed area, where the steppe has been converted to pasture. The high percentages of pine pollen in pasture areas can be explained by the effective long-distance transport of pine pollen from the forest-steppe and the suppression of local pollen production as a result of overgrazing. However, *Pinus* pollen concentrations are low in the steppe, rise to moderate values in forest-steppe, and are highest in taiga. The highest percentages and concentrations of *Pinus* pollen occur in the taiga, probably reflecting the local presence or even abundance of pine tree in the taiga. The lowest *Pinus* pollen percentages and concentrations occur in the desert and desert-steppe, but even here, where pine trees are absent, *Pinus* pollen may still occur with values in the order of 10–50% as the result of long-distance transport by wind. *Pinus* percentages and concentrations are moderate in the forest-steppe because pine pollen can be derived locally from pine trees growing on the north-facing slopes and at higher elevations (Figs 3 & 4).

In general, pine trees may not be locally present at sites where *Pinus* pollen occurs at values < 50%. Our conclusion is supported by previous studies indicating that *Pinus* pollen is well dispersed and is greatly over-represented in the pollen rain (e.g. Li, 1993; Li *et al.*, 1993). The concentration of *Pinus* pollen must be considered in palaeovegetational reconstructions from fossil pollen data.

Picea

Picea pollen occurs at < 5% and only discontinuously in the desert, desert-steppe and steppe zones. The pollen concentration of *Picea* begins to increase from the forest-steppe (site 58) northwards. The highest *Picea* percentages correspond closely to the distribution of spruce trees in the forest-steppe and taiga zones. Indeed, the dispersal distance of *Picea* is shorter than that of *Pinus*.

Larix

Although *Larix* is the most common tree in the modern forest-steppe and taiga, the pollen abundance of *Larix* is very low. Many previous studies have shown that *Larix* pollen is usually greatly under-represented and that its percentages fluctuate greatly (Igarashi, 1996; Noshiro *et al.*, 1997; Minckley & Whitlock, 2000; Andreev *et al.*, 2001). *Larix* has low pollen productivity and poor pollen dispersal. *Larix* pollen attained slightly higher percentages (5–10%) only within *Larix* stands, whereas outside *Larix* stands the pollen usually decreased dramatically (almost to zero) (Noshiro *et al.*, 1997; Minckley & Whitlock, 2000). Gunin *et al.* (1999) suggested that the pollen dispersal distance from the *Larix* tree is usually less than 200–350 m, and that the pollen is easily destroyed by water. Andreev *et al.* (2001) pointed out that *Larix* pollen is relatively rare, even in surface samples from larch forests, and that its low frequency in pollen spectra does not reflect its true regional abundance, as evidenced by surface samples from larch forests in many areas of East Siberia. They further suggested that a low but consistent presence of *Larix* in fossil pollen spectra indicates the presence of larch trees growing close to the site (Noshiro *et al.*, 1997; Gunin *et al.*, 1999; Minckley & Whitlock, 2000; Andreev *et al.*, 2001). Kataoka *et al.* (2003) also reported that *Larix* is generally under-represented in pollen surface samples from the Lake Baikal region.

Poaceae

In our study area, Poaceae pollen percentages have higher values in the desert, desert-steppe and taiga than in the steppe and forest-steppe zones, where grasses are supposed to be prevalent. This phenomenon can probably be explained by the fact that the desert, desert-steppe, and taiga areas investigated are situated in nature reserves, where the true abundance of grasses in the natural vegetation is maintained (a fact confirmed by the high total pollen concentration values). By contrast, the steppe and forest-steppe areas sampled are disturbed by livestock, which feed on grasses selectively over steppe forbs.

Many researchers have found that, owing to its low representation, Poaceae pollen values are usually below 5% in most samples, and the presence of Poaceae pollen even at low percentages (3–10%) probably indicates the existence of grassland/steppe vegetation dominated by grasses (Huang *et al.*, 1993; Wang *et al.*, 1996; Li, 1998; Liu *et al.*, 1999; Li *et al.*, 2005). However, our data show that, although Poaceae is under-represented as a result of its low pollen productivity, higher percentages (about 10–40%) may be found in areas where the natural vegetation is better preserved.

Betula, Chenopodiaceae, Artemisia, and Aster-type

Betula pollen occurs in all the vegetation zones, especially in the forest-steppe, with values of 1–8%. The broad distribution indicates that it is well dispersed. Chenopodiaceae pollen is present in all sites but is particularly abundant in desert, desert-steppe, steppe, and forest-steppe. Therefore Chenopodiaceae pollen may be somewhat over-represented. *Artemisia* pollen not only is present at all sites but is abundant in most samples. Likewise, *Aster*-type is present at

all sites. Both *Artemisia* and *Aster*-type pollen seem to be over-represented relative to the abundance of their plants in the vegetation.

Cyperaceae and Zygophyllaceae

Cyperaceae pollen occurs only in the forest-steppe and taiga, whereas Zygophyllaceae pollen is present only in the desert and desert-steppe. The occurrence of these pollen types is consistent with the distributions of their plant populations.

Pollen–climate indices

Several methods have been developed and tested for the quantitative reconstruction of climate variables, for example the response surface analysis and transfer function methods. However, these methods cannot be effectively applied to this region because modern climatic data are sparse in Mongolia. The ratios of various pollen types have been used effectively as environmental indicators and can often help to identify trends that are difficult to see from the percentages and concentrations alone. For example, Liu *et al.* (2005, 2007) used the Poaceae/Asteraceae (P/A) pollen ratio as an index of moisture availability in the Altiplano of South America. Similarly, the A/C (*Artemisia*/Chenopodiaceae) ratio has been used as a moisture indicator in the Middle East (El-Moslimany, 1990) and Central Asia (e.g. Van Campo *et al.*, 1996; Liu *et al.*, 1998; Demske & Mischke, 2003; Herzschuh *et al.*, 2004). Yu *et al.* (1998) and Cour *et al.* (1999) reported that Chinese desert areas yield A/C values below 0.5. Fowell *et al.* (2003) suggested a semi-quantitative 'aridity pollen index' expressed as a ratio of desert-steppe (*Artemisia*–Chenopodiaceae) to steppe (Poaceae) taxa to distinguish dry steppe from moist meadow steppe and forest-steppe vegetation in north-central Mongolia. Accordingly, higher values of the index are indicative of decreasing moisture availability.

As discussed above, however, Poaceae species in desert, desert-steppe, steppe, forest-steppe and taiga could be abundant locally in the azonal vegetation communities, except in some areas that are disturbed by overgrazing. Owing to the possible distortion of Poaceae pollen abundance by human activities in these arid and semi-arid environments, the 'aridity pollen index' expressed as a ratio of desert-steppe (*Artemisia*–Chenopodiaceae) to steppe (Poaceae) taxa may not be an appropriate indicator to use for palaeoclimatic reconstruction. Our reservation about this pollen index is supported by recent vegetation analyses from the Alashan Plateau (Herzschuh *et al.*, 2004).

In this paper, we propose two new pollen–climate indices for Mongolia that are based on the extensive modern pollen data base generated in this study – a moisture index (M) and a temperature index (T) (Table 4). The two indices are calculated based on the ratios between groups of pollen taxa that represent different moisture or temperature conditions in the study region. These groups of climate-sensitive pollen taxa are classified largely based on the results of the HCA (Fig. 7) and NMS (Fig. 8), but some memberships in each group are modified based on knowledge of ecological conditions acquired from the field or on considerations pertaining to the pollen representation of specific taxa (e.g. Poaceae, discussed above).

We divided the main pollen taxa into six groups based on their relationships to six major vegetation communities (Table 4). Group S1, including Chenopodiaceae, *Nitraria*, and Zygophyllaceae, is the main component of the xeromorphic desert. Group S2, containing Polemoniaceae, *Convolvulus*, *Anthemis*-type, *Ephedra*, and Liliaceae, occurs commonly in desert-steppe. Group S3, including *Artemisia* and *Aster*-type, is representative of the meso-xeromorphic steppe. These three groups are basically composed of the members of groups B1 to B4 delineated by HCA and NMS (Figs 7 & 8), with the exception of Poaceae. Poaceae is excluded from this and all other groups because its abundance could be distorted by human disturbance, as discussed above. Groups S4 to S6 represent the cold-moist needle-leaved forest and montane forbs, birch forest/shrubland, and moderate hydroperiod steppe vegetation types, respectively. The 13 pollen taxa included in these three groups are the same as those in groups A1, A2, and A3 classified by HCA and arranged by NMS (Figs 7 & 8).

Table 4 Main pollen taxa in the six pollen taxon groups (S1–S6) used in the calculation of the pollen ratios, which were used in the derivation of the two pollen–climate indices – the temperature index (T) and moisture index (M).

Group	Type	Main pollen taxa
S1	Xeromorphic desert	Chenopodiaceae, *Nitraria*, Zygophyllaceae
S2	Desert-steppe	Polemoniaceae, *Anthemis*-type, Liliaceae, *Ephedra*, *Convolvulus*
S3	Meso-xeromorphic steppe	*Artemisia*, *Aster*-type
S4	Birch forest/shrubs	*Betula*, *Alnus*, Rosaceae, *Taraxacum*-type
S5	Cold-moist needled forest	*Picea*, *Abies*, *Larix*, *Pinus* Haploxylon-type *Pinus* Diploxylon-type Ranunculaceae, Caryophyllaceae
S6	Moderate hydroperiod steppe	Cyperaceae, Polygonaceae
	Pollen–climate indices	**Calculation**
T	Temperature index	$T = (P_{S1} + P_{S2} + P_{S3})/(P_{S4} + P_{S5} + P_{S6})$
M	Moisture index	$M = (P_{S5} + P_{S6})/(P_{S1} + P_{S2} + P_{S3} + P_{S4})$

Temperature index. The temperature index (T) is calculated as follows:

$$T = (P_{S1} + P_{S2} + P_{S3})/(P_{S4} + P_{S5} + P_{S6}).$$

The rationale for this is based on the results of HCA and NMS, which clearly divide the pollen taxa into two main groups. As mentioned above, the pollen groups S4–S6 used in the above equation are equivalent to A1–A3 delineated by HCA, whereas S1–S3 are derived from B1–B4. Accordingly, the ratio of pollen percentages (P) between these two groups could be used as a temperature index – the higher the ratio, the higher the temperature.

Moisture index. The moisture index (M) is calculated as the ratio of pollen percentages (P) between groups S1, S2, S3, S4, and groups S5, S6:

$$M = (P_{S5} + P_{S6})/(P_{S1} + P_{S2} + P_{S3} + P_{S4}).$$

The rationale for this is based on the results of HCA and NMS, modern biogeographical patterns, and field observations of vegetation distributions. The xeromorphic desert, desert-steppe and meso-xeromorphic steppe vegetation types (S1, S2 and S3) occur mainly in the lowlands and in the warmer, southern part of the study region. The birch forest/shrubland (S4) occurs mainly on sunny (south-facing) slopes of mountains and needs lower moisture to grow than the coniferous forests (S5) and moderate hydroperiod steppes (S6) in Mongolia.

To test the validity of these new indices we calculated the pollen percentage of each pollen group (S1 to S6) for each surface sample and plotted these values for all the samples along our transect to examine their spatial variation (Fig. 9a–f). We also plotted the curves for the moisture index and the temperature index along the same transect. It is clear that the moisture index is highest in the taiga, moderate in the forest-steppe and steppe, and lowest in the desert-steppe and desert (Fig. 9i), whereas the temperature index is highest in the desert and desert-steppe, decreases in the steppe and forest-steppe, and is lowest in the taiga (Fig. 9h). As a complement to the moisture index we also plotted the A/C (*Artemisia*/ Chenopodiaceae) pollen ratio along the transect, which basically parallels our moisture index curve (Fig. 9g). In order to compare our pollen–climate indices directly with actual climate data we extracted the mean annual precipitation (MAP) and mean annual temperature (MAT) data from the climatic maps of Mongolia (Orshikh *et al.*, 1990) and plotted these values along our transect (Fig 9j,k). The trends of our moisture and temperature indices mimic the spatial gradients of precipitation and temperature in Mongolia very closely. For example, the steady rise in precipitation from desert-steppe to steppe, the precipitation peak within the forest-steppe (sites 72–75), and the precipitation maxima in the taiga are captured by the moisture index curve (see arrows in Fig. 9i,k). Similarly, the gradual decline in temperature northwards across the steppe, as well as the abrupt temperature drop across the ecotone from the forest-steppe to taiga are also well represented by the temperature index curve (Fig 9h,j).

SUMMARY AND CONCLUSIONS

This paper presents modern pollen spectra from 104 surface samples collected along a generally south–north transect across Mongolia. The transect traverses five major vegetation zones, namely desert, desert-steppe, steppe, forest-steppe, and taiga, following a broad climatic gradient of decreasing temperature and increasing precipitation with increasing elevation. The 104 modern pollen spectra suggest that each vegetation zone is characterized by a distinctive pollen assemblage, as follows: (1) desert zone: Chenopodiaceae–Zygophyllaceae–*Nitraria*–Poaceae pollen assemblage; (2) desert-steppe zone: Poaceae–*Pinus* Haploxylon-type–Chenopodiaceae pollen assemblage; (3) steppe zone: *Pinus*-Haploxylon-type–*Artemisia*–*Aster*-type–Poaceae pollen assemblage; (4) forest-steppe zone: *Pinus* Haploxylon-type–*Picea*–*Artemisia*–*Betula*, montane forb/shrub–pteridophyte pollen assemblage; and (5) mountain taiga zone: *Pinus* Haploxylon-type–*Picea*–Poaceae–Cyperaceae, montane forb/shrub–pteridophyte pollen assemblage. HCA classifies the 22 main pollen taxa into two major groups and seven subgroups. The two main groups basically contain xerophytic plants characteristic of desert and steppe vegetation types in one, and mesophytic trees, shrubs and herbs characteristic of montane environments in the other. Discriminant analysis, which correctly classifies 95.2% of the surface samples into their respective *a priori* groups, confirms that each major vegetation zone can be quantitatively represented by a distinctive palynological signature, which can provide a basis for the reconstruction of palaeovegetational and palaeoclimatic reconstructions based on fossil pollen assemblages from the study region.

This study sheds light on several important issues in pollen dispersal and representation in the arid and semi-arid regions of Central Asia. As expected, *Pinus* is greatly over-represented in the modern pollen rain, in that pine trees may not be locally present in areas where *Pinus* pollen occurs at < 50% in a pollen sample, especially if the pollen concentration of *Pinus* is low. *Picea* is also slightly over-represented in areas outside the distribution range of spruce trees, apparently as a result of the long-distance dispersal ability of its saccate pollen. By contrast, *Larix* is grossly under-represented, as its pollen rarely exists at > 3% even within the taiga where larch trees are common. Another interesting finding of this study is that Poaceae pollen percentages are higher in samples collected within nature reserves, where the natural vegetation is better preserved than outside. This raises the possibility that the under-representation of Poaceae in the modern pollen rain from semi-arid steppe or grassland environments, a phenomenon previously reported in the palynological literature, is actually an artefact of human disturbance. Overgrazing by livestock can significantly reduce the flowering populations of grasses and suppress its pollen production, resulting in an increase in the pollen representation of steppe forbs such as *Artemisia*.

Based on the quantitative pollen–vegetation relationships derived from our regional modern pollen data set, we have
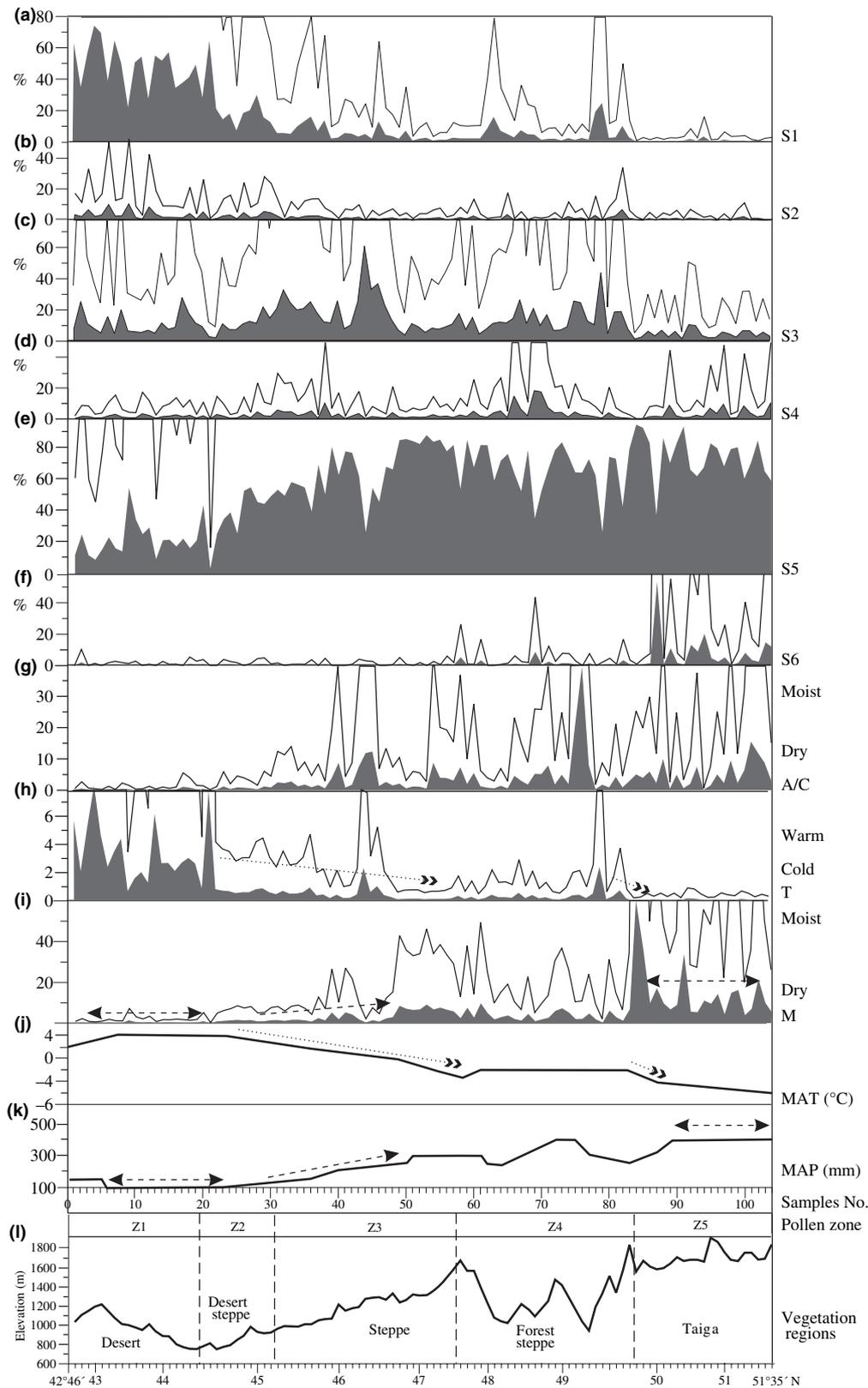
Figure 9 Grouped pollen percentages of the six pollen groups (S1–S6) used in the calculation of pollen–climate indices (panels a–f); the A/C ratio (g); the temperature index, T (h); the moisture index, M (i); the mean annual temperature, MAT (j); the mean annual precipitation, MAP (k); and elevations (l) of the 104 surface samples along the south–north transect across Mongolia. Black line: 5× exaggeration. Single or double arrows with dotted lines in (h), (i), (j), (k) denote parallel trends between the pollen index curves (T, M) and the corresponding climatic gradients (MAT, MAP). The data for MAP (mm) and MAT (°C) are derived from Orshikh *et al.*, (1990).

developed two pollen indices to represent the principal climatic gradients in Mongolia. The temperature index is based on the ratio between the pollen percentages of 13 pollen taxa characteristic of montane forests and steppes and 10 pollen taxa characteristic of xeromorphic deserts and meso-xeromorphic steppes; and the moisture index is based on the ratio between 14 pollen taxa characteristic of lowland, warmer, or sunny environments and nine pollen taxa from alpine conifers and herbs from moderate hydroperiod steppes. A comparison between these pollen–climate indices and trends derived from the climatic map of Mongolia suggests that they mimic the regional gradients of precipitation and temperature very closely.

Pollen records of late-Quaternary climatic and vegetational changes from Mongolia and even the whole of Central Asia are still relatively rare. One of the major challenges facing palynologists working in these semi-arid and arid regions is the inadequate coverage of modern pollen-rain studies in such a vast territory, resulting in a poor understanding of the relationships between modern pollen and the corresponding patterns of vegetation and climate. Our data set of 104 pollen surface samples from a pivotal region along a distinct climatic and vegetational gradient from desert to taiga across Mongolia fills a major gap in the regional data network for Central Asia. The pollen–vegetation–climate relationships established in this study, including the two new pollen–climate indices, provide a quantitative basis for palaeoclimatic reconstruction based on fossil pollen data from this region.

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