# Holocene grassland vegetation, climate and human impact in central eastern Inner Mongolia

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**Abstract** Phytolith and pollen preserved in the Taipusi Banner paleosol profile, central eastern Inner Mongolia, provide evidence of Holocene grassland vegetation, climate and human impact. The combined phytolith and pollen records reveal a major change in vegetation composition about 5000 a BP. Before 5000 a BP, the vegetation was dominated by Aneurolepidium chinese-Stipa grandis grassland of C<sub>4</sub> grasses. After 5000 a BP, C<sub>4</sub> grasses rapidly retreated, indicating a shift to colder and more arid conditions. The gradual invasion of Stipa krylovii, Agropyron desertorum, Ephedra, Chenopodiaceae and Caragana reveal the onset of grassland degeneration. Between 10000 and 8720 a BP, the Aneurolepidium chinese-Stipa grandis grassland included a small proportion of Artemisia shrub and Echionopos type plants, implying a strong winter monsoon and very weak summer monsoon. From 8720 to 7000 a BP,  $C_4$  grasses were common, indicating a strengthening of the summer monsoon. Between 7000 and 5000 a BP, the Holocene thermal maximum was evident, with a significant expansion of C<sub>4</sub> grasses and the presence of some trees (such as Pinus and Betula, and so on) in or near the study site. From 4200-3000 a BP, a sandy grassland of Artemisia and Agropyron desertorum together with Aster-type taxa occurred. Precipitation amelioration took place between 3000 and 2170 a BP, with a rapid development of Echinops type plants and a small expansion of C<sub>4</sub> grasses. From 2170 a BP to present, human activities accelerated the process of grassland degeneration.

Keywords: phytolith and pollen records, grassland, environment change, human impact, Holocene, central eastern Inner Mongolia.

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Today, grassland degeneration and desertification are becoming one of the most serious threats against human existence and socioeconomic development in the world. During recent years, strong sandstorms have frequently hit regions of northern China, strongly influenced the ecological environment and socioeconomic activities of these regions. The central eastern of Inner Mongolia is regarded as one of the main sources for these sandstorms<sup>[1,2]</sup>. Knowledge of Holocene grassland vegetation can offer useful insights into both present and future environmental change.

Inner Mongolia, situated at the boundary of temperate arid and semiarid zones, is an ideal area to investigate Holocene grassland vegetation and environmental changes. Most previous researches on Holocene vege-

tation history in Inner Mongolia come from lakes and peat bogs in forested regions  $\frac{3-13}{2}$ . However, Holocene palaeosol sequences are well preserved in the more arid interior, in the past, these sequences have received little attention because of the scarcity of continuity and chronological control as well as the lack of sensitivity in grassland palynological records for grassland dynamics. Palynological evidence from these Holocene palaeosol sequences usually obscures the dynamics of Holocene vegetation change. First of all, the pollen record does not have the taxonomic resolution to identify shifts in grass taxa although large-scale climatic change can be recorded if diagnostic trees or shrubs are present. Secondly, the pollen assemblages from arid and semiarid areas are characterized by high percentages of Artemisia and Chenopodiaceae pollen, over representing their contribution to past vegetation. Recently, much progress has been made on applying phytolith analysis to interpret Quaternary grassland vegetation and climate changes<sup>[14–27]</sup>. Phytolith analysis provides an alternate means for studying long-term in situ vegetation in grassland ecosystems, since phytoliths are much more taxonomically diagnostic for grass taxa. Our study aims to reconstruct the Holocene vegetation history in response to palaeoenvironmental change and human impact in central eastern Inner Mongolia, based on phytolith and pollen records.

### 1 Materials and methods

The Taipusi Banner paleosol profile  $(41^{\circ} 58'30''N, 115^{\circ} 10'32''E, 1340 \text{ m a.s.l.})$ , about 70 km south of the Otindag sand region, lies at a transition from steppe to sandy land that is particularly sensitive to the monsoon climate changes (Fig. 1).

The study area is characterized by a temperate arid and semiarid climate. The mean annual temperature is about  $1.4^{\circ}$ C and the mean annual precipitation is 407 mm. Evaporation is four times greater than precipitation, and the aridity index is 1.5-2.2. Current vegetation is *Stipa grandis* grassland with *Aneurolepidium chinese*, *Stipa krylovii*, *Koeleria cristata*, *Poa sphondylodes*, *Agropyron desertorum*, *Cleistogenes squarrosa* as the main associated species. Other families include Compositae, Leguminosae, Rosaceae, Ranunculaceae, Umbelliferae, Cruciferae, Caryophyllaceae and so on. Due to over-grazing and over-cultivating, Stipa grandis-dominated grassland is usually replaced by Stipa krylovii grassland. The distribution of Aneurolepidium chinese-dominated rhizome grassland is primarily determined by the humidity along the slopes. Steppe meadow with Achnatherum splendens, Carex duriuscula, Agrostis gigantean, Iris ensata mainly appears in the river floodplain and low-lying areas. To the east and southeast of the study site, alpine meadow is found at above 1250 m elevation where there is more precipitation (> 400mm). Agropyron desertorum-dominated grassland is found where soils are sandier. The chestnut and dark chestnut soils in the grassland zones correlate with typical steppe and meadow-steppe. The cultivated crops in the study area are mainly Triticum aestivum, Hordeum vulgare, Avena chinese and potato.

In the Otindag sandy land, psammophytic vegetation types are common, including woodlands in the east (i.e. *Pinus tabulaeformi, Picea meyeri, Populus davidiana* and *Betula platyphylla*), sparse *Ulmus pumila* woodland, and psammophytic shrubbery (i.e. *Artemisia* shrub, *Caragana* shrub and so on)<sup>[28]</sup>.

In order to aid in the interpretation of the Taipusi Banner paleosol sequence, 17 surface soil samples were chosen from 14 vegetation types identified in the region (Fig. 1). To establish a workable phytolith reference collection for Inner Mongolia grassland, more than 80 plant species (including 23 common species of Gramineae) were collected from the fenced permanent research stations where there are communities of *Aneurolepidium chinese*, *Stipa grandis* and degenerated grassland in Inner Mongolia.

Samples (20 g per sample) for pollen analysis were processed following HF treatment. A minimum of 200 pollen grains was counted for each sample. Phytolith samples (approximately 15 g per soil sample) were used standard wet oxidation and heavy flotation techniques. Samples were treated initially with hydrogen peroxide (30%) in a boiling water bath to remove organics, then with 10% HCl to remove carbonates, and finally with Na<sub>2</sub>HCO<sub>3</sub> to deflocculate the humid acid,



Fig. 1. Location of Taipusi profile showing the surface samples sites. ● Taipusi site and surface samples (here samples 1, 3 and 5 are collected from degenerated grassland community, *Stipa grandis* grassland community and *Aneurolepidium chinese* grassland community respectively).

each of the above steps was followed by centrifuging and washing with distilled water. Phytoliths were floated on a heavy liquid (specific gravity 2.3), washed twice with distilled water to rinse, and finally washed twice with acetone for quick drying. Phytoliths were mounted on slides with Cedar wood oil that allowed the phytolith to be rotated and viewed in three dimensions. A minimum of 250 phytoliths was tallied in each sample.

## 2 Results

The palaeosol profile consists mainly of sandy soil, 140 cm thick. The profile shows no sign of either erosional hiatuses or aeolian sand layers. The bottom of the sequence is underlain by loess and sand layers. The radiocarbon samples were dated at the Institute of Geology, China Seismology Bureau. Three <sup>14</sup>C ages

are measured at the depths of 30-40 cm, 70-80 cm and 130-140 cm, dated to  $2300\pm95$ ,  $4830\pm130$  and  $9495\pm50$  a BP respectively. The bottom of the profile, based on these dates is estimated to date to ca. 10000 a BP. The ages of sampled horizons were interpolated between radiocarbon-dated horizons.

Thirty pollen and phytolith samples, at intervals of 5 cm, were collected at the Taipusi Banner profile. Due to poor pollen and phytolith preservation from the loess and sand layers only the Holocene pollen and phytolith results from the paleosol sequence of Taipusi Banner are presented here.

About 50 pollen taxa were identified. The pollen assemblages in the profile are dominated by herb and shrub taxa. Except Gramineae and Compositae, weeds include Leguminosae, Rosaceae, Ranunculaceae, Umbelliferae, Cruciferae, Caryophyllaceae, Thymelaeaceae, Liliaceae. Based on features in the exterior wall structure and pollen surface sculpture, four types of Compositae pollen were identified, i.e. Artemisia type, Echionopos type, Aster type and Taraxacum type. Shrub and tree taxa only occupy a small proportion of the pollen assemblage, including Pinus and Picea of Pinaceae, Cupressaceae, Taxodiaceae, Ephedra of Ephedraceae, Betula, Alnus, Carpinus and Ostryopsis of Betulaceae, Ulmus of Ulmaceae, Juglands of Juglandaceae and Quercus of Fagaceae. The components of degenerated grassland are composed of Chenopodiaceae, Caragana and Hedysarum of Leguminosae, Polygonum divaricatum of Polygoniaceae, Tamarix and Myricaria of Tamaricaceae, Nitraria and Zygophyllum of Zygophyllaceae, etc.

The reference phytolith collection for Inner Mongolia was used to identify the phytoliths in the paleosol phytolith samples. Eight diagnostic Gramineae short-cell morphotypes were identified, including rondels, keeled rondels, pyramidal types, crenates, *Stipa* bilobates, panicoid lobates, saddles<sup>[17,20,21]</sup> and *Cleistogenes* bilobates. Grass phytoliths coming from other leaf cells include trichomes, hair bases<sup>[17,20,21]</sup>, weakly indented long cells, deeply indented long cells<sup>[19,20]</sup>, and bulliforms<sup>[25]</sup>. Dendritic types<sup>[19,20]</sup> from glumes and seed epidermis were also counted. Nongrass phytoliths include blocky forms of *Ar*- *temisia*<sup>[19,20]</sup>, *Picea* and *Pinus*<sup>[25]</sup>, polyhedron form of *Betula*<sup>[29]</sup>, hat-shapes from  $Carex^{[25]}$  and other irregular types (Fig. 2).

Based on major changes in pollen and phytolith assemblages, five pollen and phytolith zones (abbreviated as P and PH) and four subzones were defined for the palaeosol sequence. The software TILIA-GRAPH and TGVIEW were used to plot the pollen and phytolith diagrams (Figs. 3 and 4), and CONISS to establish pollen and phytolith zones using sum of squares stratigraphically constrained cluster analysis<sup>[30]</sup>. The pollen and phytolith zones of the Taipusi Banner profile are briefly described below:

Zone P1, PH1 (depth 140-103 cm, ca. 10000-7000 a BP) can be divided into two subzones, i.e. P1-1, PH1-1 and P1-2, PH1-2.

Subzone P1-1 (depth 140-125 cm, ca.10000-8720 a BP) is dominated by herb and shrub pollen, especially *Artemisia* pollen (68.7%). *Echionopos*-type (Compositae), weeds, Gramineae and Chenopodiaceae account for 9.3%, 5.5%, 3.7% and 3.4% respectively. *Aster* type, *Taraxacum* type, Tamaricaceae, *Caragana* (Leguminosae), *Polygonum divaricatum* (Polygoniaceae) and *Ephedra* pollen are present with much low percentage, averaging <1%. No Zygophyllaceae pollen occurs. Tree pollen (<5%) consists mainly of *Pinus* (4.3%).

The Gramineae short-cell phytolith assemblage (PH1-1) is marked by rondels (39.9%), crenates (6.3%) and panicoid lobates (5.7%). Saddles (1.9%), bulliform (0.2%) and keeled rondels (0.1%) are rare in the assemblage. Weakly indented long-cells and *Artemisia* blocky types are found, averaging 23.5% and 5.7% respectively. *Stipa* bilobate, *Pinus* blocky type, *Picea* blocky type, *Betula* polyhedron type and *Carex* hat-shaped type are not present.

Subzone P1-2 (depth 125-103 cm, ca. 8720-7000 a BP) contains very little tree pollen, with only occasional *Pinus* pollen grains. The pollen assemblage is distinguished by an increase in *Artemisia* (74.2%) and a decrease in *Echionopos* type of Compositae (5.2%) and Chenopodiaceae (1%). Gramineae (4.2%) and weeds (8%) values increase slightly. No Tamari-

caceae, Zygophyllaceae and *Ephedra* pollen are present.

The short-cell phytolith assemblage (PH1-2) is marked by rondels (43.7%), bilobates (9.9%) and saddles (10.2%). Rondel, panicoid lobates and saddle values increase significantly. Percentages of crenates (3.8%) and *Artemisia* blocky type (0.6%) decrease sharply, *Pinus* blocky type, *Picea* blocky type, *Betula* polyhedron type and bulliforms are occasionally found. Trichomes and hair bases remain stable. No *Stipa* bilobates and keeled rondels are present.

Zone P2, PH2 (depth 103-76 cm, ca. 7000-5000 a BP) is distinguished by the presence of both more tree pollen taxa and more non-grass phytoliths. Beyond *Pinus*, tree pollen taxa include *Betula*, *Alnus*, *Carpinus*, *Ostryopsis*, *Ulmus*, *Juglands* and *Quercus*. Pollen percentages of *Artemisia* (71.9%), weeds (5.3%) and Gramineae (3.3%) decline slightly. Non-grass phytoliths go up, primarily composed of blocky types of *Pinus* and *Picea*, the polyhedron of *Betula*, and the hat-shaped *Carex*. Trichomes (4%) reduce slightly, and hair bases (1.4%) show a slight increase. In the rondel (35.5%) – saddle (20.3%) – crenate (11.9%) assemblage, saddle value is at its highest, and rondel, bilobate (7.7%) and weakly indented long cells percentages (9.5%) decline. Other types stay relatively stable.

Zone P3, PH3 (depth 76-47 cm, ca. 5000-3000 a BP) is divided into two subzones, P3-1, PH3-1 and P3-2, PH3-2.

Subzone P3-1 (depth 76–65 cm, ca. 5000–4200 a BP) contains only occasional tree pollen. Pollen percentages of *Ephedra* (5.3%), *Echionopos* type of Compositae (9.2%), *Caragana* (3.2%) and weeds (7.9%) increase. *Artemisia* pollen declines, averaging 65.5%. Compared with Zone PH2, rondel values increases rapidly, reaching 62.1%, while saddles decline remarkably, averaging 1.3%. Rondels, crenates (14.3%) and bilobates (4.5%) dominate the Gramineae shortcell phytolith assemblage. *Stipa*-bilobate phytolith begins to appear.

Subzone P3-2 (depth 65-47 cm, ca. 4200-3000 a BP) is marked by an increase of *Artemisia* (74.5%)

Holocene grassland vegetation, climate and human impact in central eastern Inner Mongolia



Fig. 2. Phytolith types from Inner Mongolian grassland. All enlarged 500× unless stated otherwise. 1, Rondel type from *Aneurolepidium chinese*; 2, *Picea meyeri* blocky type; 3, deeply indented long cell; 4, keeled rondel from *Agropyron desertorum*; 5, crenate from *Koeleria cristata*; 6, dentritic type from the seed and glume epidermis of *Triticum aestivum*; 7, hair base; 8, *Stipa* bilobate from *Stipa krylovii*; 9, panicoid lobate from *Setaria viridis*; 10, dentritic type from the seed and glume epidermis of *Triticum monococcum*; 11, weakly indented long cell; 12, cross from *Cleistogenes squarrosa*; 13, saddle from *Cleistogenes squarrosa*; 14, 15, crenate from *Triticum aestivum*; 16, *Cleistogenes* bilobate from *Cleistogenes squarrosa*; 17, polyhedron type from *Betula platyphylla* (×670); 18, 19, *Artemisia* blocky type; 20, smooth elongate; 21, trichome (×800).



Fig. 3. Pollen diagram of Taipusi profile, central eastern Inner Mongolia.



Fig. 4. Phytolith diagram of Taipusi profile, central eastern Inner Mongolia (\* indicating the occurrence of crenate from *Triticum aestivum* and dendritic types from glume and seed epidermis).

and *Aster* type (1.3%), and decrease of *Ephedra* (3.5%) and weeds (3.7%). *Pinus* and *Ostryopsis* pollen occur sporadically.

In the Gramineae short-cell phytolith assemblage,

i.e. rondels (65.6%)—crenates (12.8%)—bilobates (4.2%) assemblage, no saddles occur. *Stipa*-bilobate and keeled rondel values increase progressively, despite low percentages. The *Artemisia* blocky type in-

creases to 2.9%. Other types hold relatively steady.

Zone P4 (depth 47–33 cm, ca. 3000–2170 a BP) still contains a few *Pinus* and *Ostryopsis* pollen grains. *Artemisia* pollen dominates the pollen assemblage although its value declines (average 48.3%). *Echionopos* type peaks sharply, reaching 28.9%. Chenopodiaceae (2.2%), *Caragana* (2.5%) and weeds (4.8%) exhibit a small increase. *Tamarix, Nitraria* and *Hedysarum* pollen are present.

The Gramineae short-cell phytolith assemblage (PH4) has relatively high values of *Stipa* bilobates (2.5%). Compared with Subzone PH3-2, *Stipa* bilobates replace bilobates (1.5%) and become one of the main components of this assemblage for the first time. Rondels (61.6%) and crenates (9.3%) decline, and saddles appear again in low frequency (averaging 1.3%). Weakly indented long cells are still common, reaching 10.3%. Trichomes (0.8%) are rare.

Zone P5 (depth 33–0 cm, ca. 2170 a BP–present) shows tree pollen increases, especially *Pinus* (7.7%). *Artemisia* and *Echionopos* type pollen decline sharply, averaging 19.6% and 4.9%, respectively, while *Aster* type (3.7%), *Taraxacum* type (2.6%), Chenopodiaceae (11.5%), *Caragana* of Leguminosae (9.2%) and *Polygonum divaricatum* (6.2%) increase. *Tamarix, Myricaria* and *Nitraria* values progressively increase. *Ephedra* (5.8%) increases slightly.

In the phytolith assemblage (PH5), rondels (66.2%), crenates (9.1%) and *Stipa* bilobates (3.5%) still dominate. Dendritic types from glumes and seed epidermis of *Triticium aestivum* are found<sup>[31,32]</sup> for the first time.

## 3 Discussions

3.1 Diagnostic phytoliths from  $C_3$  and  $C_4$  grasses in Inner Mongolia grassland

The variations of  $C_3$  and  $C_4$  grasses species in the grassland can be linked to climate change. Identification of relative proportion of  $C_3$  and  $C_4$  grasses from phytoliths therefore can provide a measure of Holocene climatic change in Inner Mongolia<sup>[33–36]</sup>. The phytolith morphotypes from  $C_3$  and  $C_4$  species in the study area (Table 1) demonstrate that all Pooideae ( $C_3$ )

subfamily grasses produce rondels, especially Stipa baicalens (85.5%), S. grandis (89.7%), S. krylovii (90%) and Aneurolepidium chinese (69.1%). The Stipa bilobate is a useful diagnostic type for identifying Stipa-dominated grassland, mainly come from Stipa plants, especially S. krylovii (7.3%). Koeleria cristata (87.3%), Elymus dahuricus (57.2%) have high percentages of crenate. The keeled rondel is diagnostic of Agropyron desertorum, a dominant species in sandy grasslands. Increases in keeled rondels in the soil assemblages would aid in understanding the grassland desertification processes. Cleistogenes squarrosa (Chloridoideae subfamily) (C<sub>4</sub>) is predominated by panicoid lobate, Cleistogenes bilobate and saddle. The percentage of Cleistogenes bilobate in the soil assemblages would be helpful in identifying *Cleistogenes* squarrosa dominated grasslands. Setaria viridis and Pennisetum centrasiaticum (Panicoideae subfamily) (C<sub>4</sub>) contain mainly panicoid lobate. Annual C<sub>4</sub> grasses in Inner Mongolia were mainly distributed in sandy lands and disturbed areas  $\frac{[37]}{}$ .

### 3.2 Modern pollen and phytolith assemblages

The reconstruction of the relationships between vegetation and modern pollen and phytolith assemblages can provide excellent modern analogue for interpreting fossil sequence. Previous studies have focused on the relationships between vegetation and modern pollen in Inner Mongolia<sup>[38–40]</sup>, but given less attention to modern phytolith assemblages from different vegetation types. In order to interpret the past vegetation, 17 samples were used to reconstruct pollen and phytolith—vegetation relationships. Modern pollen and phytolith assemblages from different vegetation types in the study area are described as below:

(7) *Picea meyeri* woodland (Fig. 1, Sample 7): Tree pollen is predominated by *Betula* (20.6%) and *Picea* (10.3%), and herb characterized by *Artemisia* (26.2%), Chenopodiaceae (18.4%) and Gramineae (8.9%). Phytolith assemblage is marked by high percentages of rondels (30.4%), *Picea* blocky types (15.3%) and crenates (13.1%). Panicoid lobates (1.1%), saddles (0.8%) and crosses (0.3%) contain low value. Fern triangular prisms<sup>[25]</sup> (4.5%), *Pinus* blocky types (2.5%) and ir-

#### Science in China Ser. D Earth Sciences

Species	Taxa	Photosynthetic pathway
Stipa baicalens	Pooideae, Stipeae, Stipinae	C3
Stipa grandis	Pooideae, Stipeae, Stipinae	C3
Stipa krylovii	Pooideae, Stipeae, Stipinae	C3
Psammochloa villosa	Pooideae, Stipeae, Stipinae	C3
Achnatherum splendens	Pooideae, Stipeae, Stipinae	C3
Elymus dahuricus	Pooideae, Hordeae, Hordeinae	C3
Aneurolepidium chinese	Pooideae, Hordeae, Hordeinae	C3
Koeleria cristata	Pooideae, Aveneae, Aveninae	C3
Avena sativa	Pooideae, Aveneae, Aveninae	C3
Poa sphondylodes	Pooideae, Poeae, Poinae	C3
Festuca ovina	Pooideae, Poeae, Poinae	C3
Triticum aestivum	Pooideae, Hordeae, Triticinae	C3
Agropyron michnoi	Pooideae, Hordeae, Triticinae	C3
Agropyron desertorum	Pooideae, Hordeae, Triticinae	C3
Bromus inermis	Pooideae, Poeae, Brominae	C3
Agrostis alba	Pooideae, Agrostideae, Agrostidinae	C3
Phragmites communis	Arundinoideae, Arundineae, Arundinae	C3
Cleistogenes squarrosa	Chloridoideae, Eragrostideae, Tridentinae	C4
Chloris virgata	Chloridoideae, Chlorideae	C4
Setaria viridis	Panicoideae, Paniceae, Setariinae	C4
Setaria italica	Panicoideae, Paniceae, Setariinae	C4
Pennisetum centrasiaticum	Panicoideae, Paniceae, Setariinae	C4
Zea mays	Panicoideae, Maydeae	C4

le 1 Grass species collected from Inner Mongolia grassland showing their photosynthetic pathway

regular polyhedron types<sup>[29]</sup> from trees (2.2%) occupy a small proportion.

(9) *Populus davidiana* woodland (Fig. 1, Sample 9): Tree pollen is dominated by *Populus* (14.7%). Pine and spruce pollen account for 5.4% and 3.4% respectively. Herb pollen is characterized by high values of *Artemisia* (17.6%), Cyperaceae (14.7%) and Chenopodiaceae (7.8%). Gramineae pollen reaches 6.9%. Phytolith assemblage is predominated by crenates (48.4%), rondels (26%) and weakly indented long cells (4.5%). Fern triangular prisms (3.5%), *Artemisia* blocky types (2.1%) and *Picea* blocky types (0.4%) occupy a small proportion.

(5) Aneurolepidium chinese-dominated grassland (Fig. 1, Sample 5): Pollen assemblage is predominated by Chenopodiaceae (34.9%), Cyperaceae (19.1%) and Gramineae (15.3%). Artemisia pollen reaches 12.8%. Tree pollen shows low values, mainly including Pinus (4.7%) and Betula (2.6%). Phytolith assemblage is distinguished by high values of rondels (56.8%), crenates (9.7%) and weakly indented long cells (7.6%). Stipa bilobates and keeled rondels show low values, averaging 1.8% and 0.3%, respectively. *Artemisia* blocky types (0.6%) and other non-grass phytoliths are rare.

(3) *Stipa grandis*-dominated grassland (Fig. 1, Sample 3): Pollen assemblage is predominated by *Ar*-*temisia* (20.5%), Gramineae (19.1%) and Chenopodiaceae (18.4%). Cyperaceae (6.9%), Compositae (4.6%) and Leguminosae (4.5%) contain a proportion. In Compositae, *Aster* type accounts for 1.7%, *Echionopos* type shows low value, only representing 0.7%. Tree pollen is mainly composed of *Pinus* (6.3%) and *Betula* (4.9%). Rondels (69%), crenates (10%) and *Stipa* bilobates (4%) dominated in the phytolith assemblage. Non-grass phytoliths are rare.

(2) Meadow grassland (Fig. 1, Sample 2): Pollen assemblage is mainly represented by Gramineae (21.9%), Cyperaceae (18.9%) and Chenopodiaceae (15.4%), secondarily, *Artemisia* (14.9%). Compositae (4.7%), Leguminosae (3.9%) and *Humulus* (3.9%) occupy a small proportion. In Compositae, *Echionopos* type and *Aster* type account for 1.3% and 3.1%, respectively. Tree pollen shows low value, mainly in-

cluding *Pinus* (3.5%). Spruce, birch and elm pollen occur sporadically. Phytolith assemblage is predominated by rondels (41.3%), crenates (26.9%) and weakly indented long cells (7.6%).

(11) *Stipa krylovii*-dominated grassland (Fig. 1, Sample 11): Pollen assemblage is predominated by Chenopodiaceae (20.1%), Gramineae (17.9%) and *Artemisia* (17.9%). Cyperaceae (9.4%), Compositae (6.2%) and Leguminosae (6.6%) occupy a proportion. In Compositae, *Aster* type reaches 5%, and *Echionopos* type only 0.3%. Tree pollen reaches 12.3%, mainly including *Betula* (5%), *Pinus* (4.1%) and *Ostryopsis* (1.9%). Spruce and elm pollen occur sporadically. Phytolith assemblage is dominated by rondels (36.3%), crenates (19.2%) and *Stipa* bilobates (13%), *Artemisia* blocky types (2.6%), keeled rondels (2.4%) and saddles (2.2%) occupy a small proportion. Panicoid lobates are rare.

(12) Alpine meadow (Fig. 1, Sample 12): Pollen assemblage is predominated by *Artemisia* (27.5%), Chenopodiaceae (16.3%) and Liliaceae (11.2%). Compositae (6.4%), Gramineae (6.4%) and Cyperaceae (6%) occupy a proportion. In Compositae, *Echionopos* type reaches 4.7%, *Aster* type only 0.9%, *Taraxacum* type is present. Tree pollen shows low value, only representing 4.3%. Phytolith assemblage is predominated by rondels (33.3%), crenates (28.1%) and weakly indented long cells (7.1%). Smooth elongates, hair bases, *Artemisia* blocky types and ferns prisms account for 6.4%, 6.4%, 4.2% and 3.6%, respectively.

(13) *Stipa baicalensis+Aneurolepidium chinese* grassland (Fig. 1, Sample 13): Pollen assemblage is mainly represented by *Artemisia* (29.1%), Gramineae (16.3%) and Cyperaceae (16.3%), secondarily, Chenopodiaceae (10.9%) and Compositae (5.1%). Tree pollen value is low, only occupying 5.9%. Phyto-lith assemblage is characterized by high percentages of rondels (34.3%), crenates (21.4%) and smooth elongates (12%).

(14) *Festuca ovina+Filifolium sibiricum* grassland (Fig. 1, Sample 14): Pollen assemblage is mainly predominated by *Artemisia* (51.4%) and Gramineae (14%). In Compositae (8.2%), *Echionopos* type reaches 5.1%. Chenopodiaceae (3.1%), Cyperaceae (3.1%) and Leguminosae (1.6%) contain a proportion. Tree pollen reaches 7.4%. Phytolith assemblage is characterized by high percentages of rondels (55.2%), crenates (22.5%) and smooth elongates (4%).

(10) *Populus davidiana* woodland margin meadow (Fig. 1, Sample 10): Pollen assemblage is characterized by high percentage of herb pollen. Tree pollen shows low value, only occupying 4.9%. Herb pollen is predominated by *Thalictrum* (49.2%), *Artemisia* (13%), Chenopodiaceae (9.2%) and Cyperaceae (9.2%). Phytolith assemblage is mainly represented by rondes (38.3%), crenates (16.8%) and smooth elon-gates (13%), secondarily, fern prisms (6.1%).

(6) Artemisia frigida shrubbery (Fig. 1, Sample 6): Pollen assemblage is characterized by high percentage of herb pollen. Tree pollen is rare. Herb pollen is predominated by Artemisia (37.1%), Chenopodiaceae (34.5%) and Gramineae (15.7%). Cyperaceae (3.1%), Compositae (2.1%)—among which Taraxacum type shows 0.4%, and Caragana (1.3%) occupy a small proportion. Phytolith assemblage is mainly represented by rondels (30.3%), crenates (23.6%) and smooth elongates (12%), secondarily, Stipa bilobates (9.9%), keeled rondels (3.7%) and Artemisia blocky types (2.5%).

(8, 15, 16) Sparse *Ulmus pumila* woodlands (Fig. 1, Samples 8, 15, 16): Pollen assemblage is characterized by high percentage of herb pollen. Tree pollen (9.5%) shows low value, mainly represented by *Betula* (4.2%), *Picea* (3.6%) and *Ulmus* (1.5%). Herb pollen is predominated by Cyperaceae (51.4%), *Artemisia* (20.2%) and Chenopodiaceae (7.6%). Gramineae pollen reaches 5.7%. Phytolith assemblage is mainly represented by rondels (21.3%), smooth elongates (21%) and crenates (12.8%). Multilobates, panicoid lobates, *Cleistogenes* bilobates, and saddles account for 8.3%, 8%, 7.3%, and 2%, respectively.

(4, 17) *Stipa grandis+Caragana microphylla* grassland (Fig. 1, Samples 4, 17): Pollen assemblage is characterized by high percentages of *Artemisia* (38.4%), Chenopodiaceae (19.7%) and Gramineae (16.3%). *Taraxacum* type is present in Compositae pollen (2.5%), only averaging 0.5%. Tree pollen is distinguished by high values of *Pinus* (5.9%) and *Betula* (2%). Phytolith assemblage is predominated by rondels (52.5%), crenates (15.4%) and *Stipa* bilobates (7.7%). Keeled rondels, *Artemisia* blocky types, *Cleistogenes* bilobates and saddles reach 4%, 1.9%, 1.2% and 0.3%, respectively.

(1) Degenerated grassland (Fig. 1, Sample 1): Pollen assemblage is mainly represented by high percentages of *Artemisia* (13.7%), Chenopodiaceae (28.9%) and Gramineae (14.8%), secondarily, *Polygonum divaricatum* (6.8%), *Caragana* (5.1%) and *Aster* type (3%). Tree pollen accounts for 7.9%. Phytolith assemblage is characterized by high values of rondel (27.9%), crenate (26.5%) and weakly indented long cell (13%). Smooth elongate and *Stipa* bilobate reach 9.7% and 5.3%, respectively.

The surface pollen analysis in the study area can basically verify the conclusions drawn by previous results<sup>[38-40]</sup>. Tree pollen is poorly represented in almost all vegetation types, except in *Picea meyeri* and *Populus davidiana* woodlands, but pine pollen (less than 10%) and birch pollen (1%-20%) are found in almost all surface samples. Neither of these is indicative of local vegetation, since pine pollen is carried by the wind over long distances and birch has high pollen production. Spruce forest exists locally when spruce pollen reaches 10%. Elm pollen has low values (1.5%) even in the *Ulmus pumila* sandy scrub due to low pollen production.

Not surprisingly, Gramineae species dominate in the Aneurolepidium chinese-dominated, Stipa grandis-dominated and Stipa krylovii-dominated grasslands, but their pollen percentages are below 25%, indicating that Gramineae pollen is poorly represented here. Artemisia and Chenopodiaceae pollen are common in the different vegetation types and dominant in the pollen assemblages, indicating that Artemisia and Chenopodiaceae are over-represented.

After Gramineae species, Asteraceae (excluding *Artemisia*), Leguminosae and Cruciferae are the main associated components of grasslands in the study area.

However, their pollen values are low due to under-representation. In Compositae, *Echionopos*-type pollen is high in the alpine meadow due to wet and moist conditions; *Taraxacum*-type pollen usually occurs both in the alpine meadow and degenerated grassland represented by different species; and *Aster*-type pollen is found in all surface samples, but has higher values in the *Stipa krylovii*-dominated grassland and degenerated grassland. In the degenerated grassland, Chenopodiaceae, *Polygonum divaricatum* and *Caragana* occur in high values due to human disturbance.

In the phytolith assemblage, trees and other herbaceous plants have low phytolith production compared with grass taxa. Non-grass types include distinctive blocky types (e.g., *Artemisia*-blocky type is similar to *Picea*, but has more rounded ends). The phytolith production of *Artemisia* species is low, and *Artemisia* blocky type phytoliths are not common even in *Artemisia frigida* shrubbery.

For the grass phytolith types, rondels are dominant in all vegetation types, indicating that they are overrepresented. In the Aneurolepidium chinese-dominated and Stipa grandis-dominated grasslands, rondel values exceed 50%, but in other vegetation types (except Festuca ovina+Filifolium sibiricum grassland), they are below 40%. High percentages of crenates are found in the Populus davidiana forest (48.4%) and alpine meadow (28.1%) due to low phytolith production of tree and other herbaceous plants. However, crenates are less than 10% in the Aneurolepidium chinese-dominated grassland and Stipa grandis-dominated grassland, they are nearly 20% in the Stipa krylovii-dominated grassland. In the Stipa kryloviidominated grassland and degenerated grassland, Stipa bilobates are common, and this form can be used as an indictor of both dry habitat and grassland degeneration. Keeled rondels are usually found in the Stipa krylovii-dominated grassland, Artemisia frigida scrub and Stipa grandis+Caragana microphylla grassland, indicating a sandy grassland habitat. In addition, high values of panicoid lobate and saddle are found in the sparse Ulmus pumila woodland and Picea meyeri woodland, and variations of the panicoid lobate and

saddle can be related with the moisture and temperature conditions. vailed.

#### 3.3 Holocene vegetation and climate history

The pollen assemblage from the Taipusi Banner profile is dominated by *Artemisia* and Chenopodiaceae pollen. However, Gramineae pollen, the main component of grassland, has low values and shows no obvious variation throughout the profile. The pollen record, therefore, provides little insight into Holocene grassland history. This paper makes use of both phytolith and pollen records to reconstruct the Holocene grassland history in central eastern Inner Mongolia.

The Taipusi Holocene profile can be divided into two major zones, i.e. pre and post-5000 a BP, in which the phytolith assemblages are dominated by rondels throughout (Fig. 4). Before about 5000 a BP (depth 76 cm), rondel values were below 50%, crenates were less than 10%, *Stipa* bilobates were not present, and panicoid lobates and saddles were common. Although there is no modern analogue for this assemblage, comparisons with the modern surface soil analysis indicate that the vegetation before 5000 a BP was similar to the *Aneurolepidium chinese+Stipa* grandis-dominated grassland.

After 5000 a BP, an obvious change in the phytolith and pollen zones occurred. Rondel and crenate values exceed 60% and 10%, respectively. The percentages of panicoid lobates and saddles decreased sharply. *Stipa* bilobate and keeled rondel phytoliths, *Ephedra*, Chenopodiaceae, *Caragana* and *Aster*-type pollen values increased. *Stipa krylovii*, *Agropyron desertorum*, *Ephedra*, Chenopodiaceae, etc. expanded gradually in the grassland, implying sandy desertification and grassland degeneration due to an increasingly dry environment.

In more detailed terms, between 10000 and 8720 a BP, the pollen and phytolith records indicate that the grassland was dominated by *Aneurolepidium Chinese+Stipa grandis*. The presence of *Echionopos*-type plants and dry, salty-resistant plants (i.e. *Artemisia*, Chenopodiaceae, *Caragana*, *Ephedra*, *Agropyron desertorum* and etc.) suggests a winter monsoon pre-

Between 8720 and 7000 a BP, more C<sub>4</sub> grasses were present in the Aneurolepidium chinese+Stipa grandis-dominated grassland, based on the sharp increase in phytolith saddle types (reaching 11.1%). In the modern vegetation/soil assemblages, Cleistogenes squarrosa is the main grass that produces saddle forms, however no modern vegetation/soil produced saddles as abundantly as these early Holocene soils samples. Obviously, the high value of phytolith saddle throughout the profile cannot be completely ascribed to Cleistogenes squarrosa plant. However, the high frequency of saddles, based on the distribution of saddles in grass subfamilies, can be mainly attributed to the presence of Chloridoideae taxa (C4 plants). Because C<sub>4</sub> grasses in Inner Mongolia is favorable for high summer precipitation, abundant C4 grasses indicates the summer monsoon strengthened between 8720 and 7000 a BP.

From 7000 – 5000 a BP, some trees (including *Pinus*, *Picea*, *Betula*, *Juglans*, and so on) were present in or near the site. In addition,  $C_4$  grasses continued to expand in the *Aneurolepidium chinese+Stipa grandis* grassland. These indicators suggest that the climate was warm and humid, corresponding to the Holocene climatic optimum.

From 5000—3000 a BP, the phytolith record indicates the presence of *Stipa grandis*-dominated grassland, with a remarkable decrease in saddle forms, documenting a shift to a cold and dry climate. From 4200 and 3000 a BP, a significant increase in keeled rondels and *Stipa* bilobate forms suggests the grassland degenerated with the expansion of *Stipa krylovii*, *Agropyron desertorum, Ephedra* and *Caragana* and so on.

Between 3000 and 2170 a BP, *Echionopos* type plants flourished in the *Stipa grandi*-dominated grass-land, with some  $C_4$  grasses, implying minor precipitation amelioration.

From 2170 a BP to present, a drier *Stipa grandis*-dominated grassland included more salt-resistant and psammophilous plants, such as Chenopodiaceae, *Ephedra, Caragana, Polygonum divaricatum, Tamarix, Nitrari*a and *Hedysarum*. Grassland degeneration intensified. Epidermal phytoliths from grass glumes (dendritic and scutiform phytolith) and the presence of crenates from *Triticum avesticum* in small quantities reveal the beginning of agriculture in the study area.

The pollen and phytolith results document an abrupt climatic change at about 5000 a BP. Before 5000 a BP. C<sub>4</sub> plants were common and widely distributed in Aneurolepidium chinese-dominated grassland. After 5000 a BP, C<sub>4</sub> plants retreated and Stipa krylovii, Agropyron desertorum, Ephedra and Caragana expanded, indicating the onset of colder and drier conditions. In terms of changes in the monsoon, from 10000 to 8720 a BP, the winter monsoon prevailed, the summer monsoon strengthened from 8720 to 7000 a BP. Between 7000 and 5000 a BP, precipitation reached its Holocene maximum. From 5000 - 4200 a BP, the summer monsoon declined dramatically. Between 3000 and 2170 a BP, precipitation increased. From 2170 a BP to present, human activities accelerated grassland degeneration.

Holocene monsoon change deduced from Taipusi pollen and phytolith sequence can be correlated with the previous studies. The monsoon variation in the study area during 10000 and 7000 a BP is somehow similar to the Holocene monsoon changes across the desert/loess transition of north-central China<sup>[41]</sup>. Based on pollen records, mammal fossils, paleosols, lake levels, ice caps and archeological data, Shi et al.<sup>[42]</sup> suggested that a Holocene megathermal in China occurred from 8500-3000 a BP and divided this epoch into four stages, i.e. unstable conditions with alternations between warm and cold internals from 8500 to 7200 a BP, stable warm and wet climate (megathermal maximum) from 7200 to 6000 a BP, severe conditions with intense fluctuations from 6000 to 5000 a BP, and relatively warm, wet conditions from 5000 to 3000 a BP. Although this reconstruction does not address the issue of regional variability in the timing of the onset of the summer monsoon, or the period of the Holocene optimum, the above unstable conditions from 8500 to 7200 a BP would correspond to a strengthening period of summer monsoon documented at the Taipusi profile. Holocene optimum was evident in the study area between 7000 and 5000 a BP. Recently, An et al.<sup>[43]</sup> focused on the spatial and temporal distribution of East Asian summer monsoon precipitation during Holocene using geological data, including lake levels, pollen profile, and loess/paleosol records, and indicated the Holocene optimum was asynchronous in central and eastern China, reaching a maximum at different times in different regions, e.g., ca. 10000-8000 a BP ago in northeastern China, 10000-7000 a BP in north- central and northern east-central China, ca. 7000-5000 a BP ago in the middle and lower reaches of the Yangtze River, and ca. 3000 a BP ago in southern China. It is worth to note that summer precipitation reached its Holocene maximum between 7000 and 5000 a BP in central eastern Inner Mongolia, which is disagreement with the above north-central China result. In addition, Morrill et al.<sup>[44]</sup> determined the timing and spatial pattern of abrupt changes in Asian monsoon precipitation since the deglaciation and concluded that there was a widespread weakening in monsoon strength during middle Holocene (~ 4500-5000 cal. a BP). Obviously, an abrupt change to cold and dry conditions at about 5000 a BP in the study area is synchronous with the global change.

The current studies support the Holocene monsoon history of eastern sandy lands (including Otindag sandy land)<sup>[45]</sup>, although no evidence showed that the winter monsoon prevailed at the initial of Holocene in eastern sandy land. Qin et al.<sup>[46]</sup> reconstructed the spatial and temporal pattern of desert-loess transition during the Holocene and indicated that the climate was warm and cool from 3000 a BP to present. Clearly, precipitation amelioration between 3000 and 2170 a BP in Taipusi record basically verified the above result.

Holocene vegetation and desertification history documented in pollen records from two lakes in the southeastern Inner Mongolia demonstrated an abrupt change to arid condition occurring at about 5900 a BP. Deciduous woodlands were replaced by pine woodlands and then steppes in response to the climatic deterioration<sup>[7]</sup>. In comparison with Taipusi record, it

was evident that grassland and regional vegetation changes indeed took place during middle Holocene, in response to a dramatic weakening of summer monsoon.

Grassland vegetation during 1984–2001 in Duolun County, about 120 km east of the Taipusi profile, shows that irrational land use accelerated the processes of grassland degeneration<sup>[47]</sup>. Archaeological excavations in the study area indicate that the grazing-dominated land use still maintained the grassland ecosystem balance, whereas farming-dominated land use has strong impact on the grassland. During the last decade, population growth and increasing social requirement further lead to seriously degenerated lands<sup>[48]</sup>. Taipusi pollen and phytolith records indicate climatic deterioration contributed to grassland degeneration after 5000 a BP. While archaeologists identify cultivation practices in the area much earlier, negative impacts on the grasslands can only be directly linked to agriculture in the Taipusi profile beginning ca. 2170 a BP.

### 4 Conclusions

(1) The reconstruction of the relationships between vegetation, modern pollen and phytolith can provide insights into interpreting the fossil sequence. Modern pollen and phytolith analyses indicate that Artemisia and Chenopodiaceae pollen are over-represented, and Gramineae, Asteraceae, Leguminosae and Cruciferae show under-representation in arid and semiarid areas. In Asteraceae, Echionopos type pollen is high in the alpine meadow due to wet and moist conditions, Taraxacum type pollen usually occurs both in the alpine meadow and degenerated grassland represented by different species, and Aster type pollen is found in all surface samples, but has higher values in the Stipa krylovii-dominated grassland and degenerated grassland. In the degenerated grassland, Chenopodiaceae, Polygonum divaricatum and Caragana occur in high values due to human disturbance. In the modern phytolith assemblages, rondels and crenates are dominant in the Aneurolepidium chinese-dominated and Stipa grandis-dominated grasslands and S. krylovii-dominated grassland, rondels are over-representing. Stipa bilobates and keeled rondels can be used as an indictor of both dry habitat and grassland degeneration. In addition, high values of panicoid lobate and saddle are found in the sparse *Ulmus pumila* woodland and *Picea meyeri* woodland, and variations of the panicoid lobate and saddle can be related with the moisture and temperature conditions.

(2) A major change in vegetation composition occurred at about 5000 a BP, in agreement with global change. Before 5000 a BP, the vegetation was dominated by *Aneurolepidium chinese* — *Stipa grandis* grassland of C<sub>4</sub> grasses. After 5000 a B P, C<sub>4</sub> grasses rapidly retreated, indicating a shift to colder and more arid conditions. The gradual invasion of *Stipa krylovii*, *Agropyron desertorum, Ephedra*, Chenopodiaceae and *Caragana* reveal the onset of grassland degeneration.

(3) Between 10000 and 8720 a BP, the Aneurolepidium chinese—Stipa grandis grassland developed a small proportion of Artemisia shrub and Echinops type plants, implying a strong winter monsoon and very weak summer monsoon. From 8720 to 7000 a BP,  $C_4$  plants were common, indicating a strengthening of the summer monsoon.

(4) Between 7000 and 5000 a BP, the Holocene thermal maximum was recorded, with a significant expansion of  $C_4$  plants and the presence of some trees (such as *Pinus* and *Betula*, and so on) in or near the study site.

(5) From 5000-3000 a BP, a dramatic arid event was recorded; from 4200-3000 a BP, a sandy grassland of *Artemisia* and *Agropyron desertorum* together with *Aster* type taxa occurred. Precipitation amelioration took place between 3000 and 2170 a BP, with a rapid development of *Echionopos* type plants and a small expansion of C<sub>4</sub> grasses.

(6) From 2170 a BP to present, the occurrence of dendritic types from glumes and seed epidermis of *Triticium aestivum* show that human activities accelerated the process of grassland degeneration.

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#### Reference

- Ye, D. Z., Chou, J. F., Liu, J. Y. et al., Causes of sand-stormy weather in northern China and control measures, Acta Geographica Sinica (in Chinese), 2000, 55(5): 513-520.
- Qiu, X. F., Zeng, Y., Miao, Q. L., Temporal spatial distribution as well as tracks and source areas of sand dust storms in China, Acta Geographica Sinica (in Chinese), 2001, 56 (3): 316–322.
- Cui, H. T., Kong, Z. C., Preliminary analysis on the climatic fluctuations during Holocene Megathermal in the central eastern Inner Mongolia, in The Climates and Environment During Holocene Megathermal in China (eds. Shi, Y. F., Kong, Z. C.) (in Chinese), Beijing: China Ocean Press, 1992, 72–89.
- Song, C. Q., Wang, B. Y., Sun, X. J., Implication of paleovegetational changes in Diaojiao Lake, Inner Mongolia, Acta Botanica Sinica (in Chinese), 1996, 38 (7): 568-572.
- Song, C. Q., Lu, H. Y., Sun, X. J., Establishment and application of transfer functions of the pollen-climate factors in northen China, Chinese Science Bulletin(in Chinese), 1997, 42(20): 2182–2185.
- Liu, H., Cui, H., Pott, R. et al., The vegetation of the woodland steppe ecotone in southeastern Inner Mongolia, China, Journal of Vegetation Science, 2000, 11: 525-532.
- Liu, H., Xu, L., Cui, H., Holocene history of desertification along the woodland—steppe border in northern China, Quaternary Research, 2002, 57: 259–270. [DOI]
- Yang, X. D., Wang, S. M., The vegetational and climatic environmental changes in Hulun Lake and Wulungu Lake during Holocene, Oceanologia et Limnologia Sinica (in Chinese), 1996, 27 (1): 67–72.
- Ren, G. Y., Zhang, L. S., Late Holocene vegetation in Maili region, northern China, as inferred from a high-resolution pollen record, Acta Botanica Sinica (in Chinese), 1997, 39 (4): 353–362.
- Ren, G. Y., Influence of human activites on the late Holocene vegetation changes at Mali, northern China, Scientia Geographica Sinica (in Chinese), 1999, 19 (1): 42–48.
- Liang, Y. L., Vegetation and environment changes since 3600 B.P. in Sanggendalai region of Inner Mongolia, Journal of Desert Research (in Chinese), 1991, 11 (2): 33-38.
- Li, S., Sun, W., Li, X. Z. et al., Sedimentary characteristics and environmental evolution of Otindag sandy land in Holocene, Journal of Desert Research (in Chinese), 1995, 15(4): 323–331.
- Gao, S. Y., Jin, H. L., Chen, W. N. et al., The desert of Holocene Megathermal in China, The Climates and Environment during Holocene Megathermal in China (eds. Shi, Y. F., Kong, Z. C.) (in Chinese), Beijing: China Ocean Press, 1992, 161–167.
- Brown, D., Prospects and limits of a phytolith key for grasses in the central United States, J. Archaeol. Sci., 1984, 11: 345-368.
   [DOI]
- 15. Piperno, D., Phytolith Analysis, New York: Academic Press, 1988,

1-277.

- Pearsall, D., Paleoethnobotany: A Handbook of Procedures, San Diego, CA: Academic Press, 2000, 1–700.
- Kerns, B., Diagnostic phytoliths for a Ponderosa pine-bunchgrass community near Flagstaff, Arizona, The Southwestern Naturalist, 2001, 46 (3): 282–294.
- Wooller, M., Beuning, K., Introduction to the reconstruction and modeling of grass-dominated ecosystems, Palaeogeogr. Palaeoclim. Palaeoecol., 2002, 177: 1-3. [DOI]
- Blinnikov, M., Busacca, A., Whitlock, C., A new 100000-year record from the Columbia Basin, Phytoliths—Applications in Earth Science and Human History, Rotterdam: A. A. Balkema, 2001, 27–57.
- Blinnikov, M., Busacca, A., Whitlock, C., Reconstruction of the late Pleistocene grassland of the Columbia basin, Washington, USA, based on phytolith records in loess, Palaeogeogr. Palaeoclim. Palaeoecol., 2002, 177: 77-101. [DOI]
- Fredlund, G., Tieszen, L., Modern phytolith assemblages from the North American Great Plains, Journal of Biogeography, 1994, 21: 321-335.
- Fredlund, G., Tieszen, L., Phytolith and carbon evidence for Late Quaternary vegetation and climate change in the Southern Black Hills, South Dakota. Quat. Res., 1997, 47: 206–217. [DOI]
- Fredlund, G., Bousman, C., Boyd, D., The Holocene phytolith record from Morgan Playa, Plains Anthropologist, 1998, 43: 187– 200.
- Stromberg, C., The origin and spread of grass- dominated ecosystems in the late Tertiary of North America: preliminary results concerning the evolution of hypsodonty, Palaeogeogr. Palaeoclim. Palaeoecol., 2002, 177: 59–75. [DOI]
- Wang, Y. J., Lu, H. Y., The Study of Phytolith and Its Application (in Chinese), Beijing: China Ocean Press, 1993, 1–228.
- Lu, H. Y., Liu, K. B., Morphological variations of lobate phytoliths from grasses in China and the southeastern United States, Diversity & Distrubutions, 2003, 9(1): 73-87. [DOI]
- Lu, H.Y., Jia, J. W., Wang W. M. et al., On the meaning of phytolith and its classification in Gramineae, Acta Micropalaeontologica Sinica (in Chinese), 2002, 19(4): 389–397.
- The Intergated Survey Team to Ningxia and Inner Mongolia Autonomous Regions, CAS, Vegetation of Inner Mongolia (in Chinese), Beijing: Science Press, 1985, 1–884.
- Kealhofer, L., Piperno, D. R., Opal Phytoliths in Southeast Asian flora, Washington, D.C.: Smithsonian Institution Press, 1998, 1– 38.
- Grimm, E., Tiliagraphy Version 1.8. Illinois State Museum Research and Collection Center, Springfield, IL, 1993.
- Rosen, A. M., Preliminary identification of silica skeletons from Near Eastern archaeological sites: an anatomical approach, In: (eds. Rapp, G. R., Mulholland, S. C.), Phytolith Systematics: Emerging Issues: Advances in Archaeological and Museum Science 1, New York: Plenum Press, 1992, 129–147.

Holocene grassland vegetation, climate and human impact in central eastern Inner Mongolia

- 32. Ball, T. B., Gardner, J. S., Brotherson, J. D., Identifying phytoliths produced by the inflorescence bracts of three species of wheat (*Triticum monoccocum*, *T. dicoccon* and *T. aestivum*) using computer-assisted image and statistical analysis, Journal of Archaeological Science, 1996, 23, 619–632.
- Terr, J. A., Stowe, L. G., Climatic patterns and distribution of C (-4) grasses in North America, Oecologia, 1976, 23, 1–12.
- Ehleringer, J. R., Implications of quantum yield differences on the distribution of C3 and C4 grasses, Oecologia, 1978, 31: 255-267.
   [DOI]
- Tieszen, L. L., Senyimba, M. M., Imbamba, S. K. et al., The distribution of C3 and C4 grasses and climate carbon isotope discrimination along an altitudinal and moisture gradient in Kenya, Oecologia, 1979, 37: 351–359.
- Wu, N. Q., Lu, H. Y., Nie, G. Z. et al., The study of phytoliths in C3 and C4 grasses and its paleoecological significance, Quaternary Sciences (in Chinese), 1992, 3: 241–251.
- Tang, H.P., Liu, S.R., Zhang, X.S., The C4 plants in Inner Mongolia and their eco-geographical characteristics, Acta Botanica Sinica (in Chinese), 1999, 41(4): 420-424.
- Liu, H., Cui, H., Pott, R. et al. The surface pollen of the woodland-steppe ecotone in southeastern Inner Mongolia, China, Review of Palaeobotany and Palynology, 1999, 105, 237-250.
- Wang, F.Y., Song, C.Q., Sun X.J., Study on surface pollen in middle Inner Mongolia, China, Acta Botanica Sinica (in Chinese), 1996, 38(11): 902-909.
- 40. Li, W. Y., Yan, S., Quaternary palynology in Chaiwobao, Xinji-

angm (eds. Shi, Y. F. et al.), Quaternary Environmental and Hydrological Condition in Chaiwobao Basin, Xinjiang (in Chinese), Beijing: Science Press, 1984, 9–72.

- Xiao, J., Nakamura, T., Lu, H. et al., Holocene climate changes over the desert/loess transition of north-central China, Earth and Planetary Science Letters, 2002, 197, 11-18.
- Shi, Y. F., The Climates and Environments of Holocene Megethermal in China (in Chinese), Beijing: China Ocean Press, 1992, 1–213.
- An, Z., Porter, S. C., Kutzbach, J. E. et al., Asynchronous Holocene optimum of the East Asian Monsoon, Quaternary Science Review, 2000, 19: 743-762. [DOI]
- Morrill, C., Overpeck, J. T., Cole, J. E. et al., A synthesis of abrupt changes in the Asia summer monsoon since the last deglaciation, The Holocene, 2003, 13(4): 465-476. [DOI]
- Dong, G. R., Wang, G. Y., Li, X. Z. et al., Monsoon change during the last deglacion in sandy land of eastern China, Science in China, Ser. D (in Chinese), 1996, 26(5): 437-444.
- Jin, H. L., Dong, G. R., Su, Z. Z. et al., Reconstruction of the spatial patterns of desert/loess boundary belt in North China during the Holocene, Chinese Science Bulletin, 2001, 46(12): 969–975.
  [Abstract] [PDF]
- Yang, C., Liu, Y. R., Liu, M. L. et al., Analysis on the changing tendency of sandy grassland vegetation in Duolun county, Inner Mongolia, Journal of Desert Research, 2002, 12(4): 393–397.
- Wang, T., Zhu, Z. D., Some problems on desertification in Northern China, Quaternary Sciences (in Chinese), 2001, 21(1): 56–64.