

1 **An 8500-year palynological record of vegetation, climate change and human activity in**
2 **the Bosten Lake region of Northwest China**

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19
20 **Abstract**

21 Palynological data for the XBWu-46 sediment core extracted from Bosten Lake at the
22 south-eastern end of the Tian Shan, Northwest China, contains a climate record divided into
23 three major intervals: a period of increasing aridity (ca. 8540–4000 cal. yr BP), a peak arid
24 phase (ca. 4000 to 2000/1500 cal. yr BP), and an interval of increasing humidity towards the
25 core top (ca. 60 cal. yr BP). Correlation with other climate proxies from different regions
26 implies that hydrological conditions in Northwest China were governed by Asian summer
27 monsoon precipitation during the early and middle Holocene and that the increase in humidity
28 over the last two millennia was controlled by westerly-derived precipitation. Regional
29 evidence for early human activities in the lake sediments starts to accumulate from the onset
30 of the driest interval comprising records of enhanced charred grass fragment concentrations
31 (since ca. 4350 cal. yr BP), and pollen of *Cerealia* type (since ca. 4000 cal. yr BP), *Xanthium*
32 (since ca. 3700 cal. yr BP), and *Cannabis* type (since ca. 2500 cal. yr BP). These signals are
33 likely related to early agro-pastoral populations of regional Andronovo cultures that,
34 according to archaeological data, appeared in the south-eastern Tian Shan around 4000 cal. yr

35 BP. In addition, increased *Xanthium* pollen and charred grass fragment abundances point to
36 enhanced human impact linked to intensified Silk Road activities during the Han dynasty (206
37 BCE–220 CE).

38
39 *Keywords:* pollen, non-pollen palynomorphs, vegetation, moisture conditions, archaeological
40 record, arid Central Asia

41 42 43 **1. Introduction** 44

45 Bosten Lake (also known as Bosten Hu) is the largest natural freshwater lake of the
46 Xinjiang Uyghur Autonomous Region in Northwest China. It is situated in the eastern Tian
47 Shan at the northern rim of the Tarim Basin occupied by the vast Taklamakan Desert (Fig. 1).
48 Hyper-arid conditions in most parts of the Xinjiang region are caused by its position in the
49 rain shadow of the high Central Asian mountains, which block moisture transport from the
50 Atlantic Ocean (Aizen et al., 2001; Domrös and Peng, 1988). In the middle Holocene the
51 study area was supposedly influenced by a stronger-than-present Asian summer monsoon
52 (Chen et al., 2006a; Feng et al., 2006b; Kleinen et al., 2011; Morrill et al., 2003; Rudaya et
53 al., 2009).

54 The major water inflow to Bosten Lake is provided by the Kaidu River (Kaidu He), which
55 originates in the Tian Shan and sensitively reacts on changes in the atmospheric precipitation
56 and melt water supply (Li et al., 2003). The overall scarcity of long and continuous records
57 from the entire NW China region means that the Bosten Lake sedimentary succession
58 represents a unique archive for documenting Holocene changes in vegetation and climate
59 within the lake catchment area (Chen et al., 2006a, b; Huang et al., 2009; Mischke and
60 Wünnemann, 2006; Wünnemann et al., 2006; Zhang et al., 2009). These studies, mainly
61 focusing on chronological problems, lake catchment geomorphology, and sediment
62 geochemistry, revealed sequential intervals of changes referring to the regional climate, river
63 inflow, lake water depth, salinity, and temperature; however, some of these published
64 environmental interpretations remain inconclusive or contradictory, e.g., those concerning
65 salinity changes (Zhang et al., 2009). The challenging fact that various proxies inscribed in
66 the lake sediments apparently record contrasting palaeoenvironmental signals can be partly
67 explained by the topographic and environmental variability within the relatively large
68 catchment area. Accordingly, different data sets may involve decoupled, though,

69 complementary signals, which integrate processes occurring in high and low altitude areas.
70 Palynological analysis may help to decipher environmental drivers of signals from various
71 proxies. Pollen analysis of the radiocarbon-dated bottom sediments from Bosten Lake was
72 carried out in an unpublished PhD thesis (Huang, 2006); however, although, the entire pollen
73 dataset is not yet published internationally in full, several selected proxies (i.e. the *Ephedra*
74 percentage curve and the *Artemisia*/Chenopodiaceae (A/C) ratio) have been used (e.g. Huang
75 et al., 2009), which aim to reconstruct late-glacial and Holocene climate trends in arid Central
76 Asia. Nonetheless, a detailed palynological investigation of the Bosten Lake sediments has
77 not been published to date.

78 From arid Central Asia, numerous multi-proxy studies on the Holocene climate dynamics
79 are already available (e.g. Chen et al., 2008; Huang et al., 2009; Rudaya et al., 2009; Zhao et
80 al., 2009; Ran and Feng, 2013). These comprehensive studies represent a valuable
81 contribution to the ongoing discussion on the temporal and spatial patterns of the Holocene
82 moisture evolution in this environmentally vulnerable region, but also report some
83 contradictory results and interpretations. Zhao et al. (2009) reconstructed a wet period
84 occurring ca. 8500–5500 cal. yr BP at most sites from western Inner Mongolia to Xinjiang
85 and a drying trend during the late Holocene. By contrast, other studies suggest for arid Central
86 Asia a trend of increasing moisture since the end of the late-glacial period with highest
87 moisture level during the late Holocene (Chen et al., 2016; Long et al., 2017; Zhang et al.,
88 2017). Huang et al. (2009), on the other hand, suggested that the regional climate in the
89 Bosten Lake area was relatively dry between ca. 8000 and 6000 cal. yr BP and became more
90 humid afterwards. Despite such differences, which require further investigations, all studies
91 agree that the reconstructed spatial/temporal complexity of the Central Asian climate reflects
92 large-scale interactions of competing factors, including the monsoon and westerly circulation
93 systems and topographically-induced regional atmospheric dynamics (Chen et al., 2008;
94 Rudaya et al., 2009; Zhao et al., 2009).

95 Humans could be another factor influencing the local and regional environments; however,
96 the role of human (particularly agricultural) activities in the Holocene vegetation changes
97 requires further investigation (Zhao et al., 2009). Despite a growing body of archaeological
98 data, the timing and routes of agriculture dispersal in Xinjiang remain controversial. Long et
99 al. (2018), using an extensive set of directly radiocarbon-dated crop remains from
100 archaeological sites in northern China and a Bayesian modelling approach, suggested that
101 wheat cultivation appeared in the Xinjiang region around 2100-1700 cal. yr BP (95%
102 probability range). So far, the oldest direct evidence for crop cultivation (including wheat,

103 barley and millet) in Xinjiang are from the Xiaohe archaeological site (Fig. 1D). This ancient
104 cemetery with over 330 burials was first discovered by Sven Hedin's expedition in 1911 and
105 re-visited by the Swedish archaeologist Folke Bergman, who investigated 12 burials in 1934
106 (Bergman, 1939). In 2002, the Relics and Archaeology Institute of Xinjiang Uygur
107 Autonomous Region started a full-scale scientific investigation of the Xiaohe cemetery
108 (Relics and Archaeology Institute, 2007), excavating about 170 graves and initiating a number
109 of international research projects. Li et al. (2013a) analyzed samples of clay, which plastered
110 four of the so-called "mud coffins" representing the oldest layer of the Xiaohe graves for
111 pollen and plant macrofossils. However, the pollen recovery reported in their study was very
112 poor and did not allow robust interpretation.

113 Aiming to promote a better understanding of regional palaeoenvironmental changes, the
114 current paper presents new records of pollen and non-pollen palynomorphs (NPPs) from the
115 reference sediment core XBWu-46 collected in the southwestern part of Bosten Lake
116 (Wünnemann et al., 2003, 2006). These proxy records are used to address several major issues
117 discussed in the above-mentioned previous studies by reconstructing (i) changes in mountain
118 forest and lowland steppe/desert vegetation reflecting regional climate (mainly moisture)
119 conditions; (ii) limnic conditions and lake evolution; and (iii) past anthropogenic activities
120 and potential human-induced influence on the regional vegetation and direct impact on the
121 lake system. Additionally, we present new results of geochemical and pollen analyses of a
122 radiocarbon-dated clay sample from the mud coffin BM28 in Xiaohe, which likely represents
123 an initial stage of complex agro-pastoral economy in the region (Long et al., 2018) and
124 complements the plant macrofossil analysis presented by Li et al. (2013a).

125

126 **2. Regional setting**

127 Bosten Lake (41°56'–42°14'N, 86°40'–87°26'E; 1044 m a.s.l.) is situated in the intra-
128 mountain Yanqi Basin in the south-eastern part of the Tian Shan, Northwest China (Fig. 1).
129 The lake has a maximum depth of 16 m, a mean depth of 8.8 m, a surface area of ca. 1000
130 km², and a catchment, which covers about 56,000 km². The lake is fed by precipitation and
131 melt water run-off from the upper catchment area. The Kaidu River accounts for about 83%
132 of the water inflow (Fu et al., 2013; Wei et al., 2002; Yang and Cui, 2005;). The lake drains
133 through a south-western outlet into the Kongque River, which ends in a depression formerly
134 occupied by now desiccated Lake Lop Nur (also called Lop Nor).

135 The ancient cemetery Xiaohe is situated in a present-day desert, west of a vast dry basin
136 formerly occupied by Lop Nur (Fig. 1D). The cemetery itself is a striking paradox. The

137 absolute majority of deceased lies in the sand under boat coffins turned upside-down on a
138 giant sand dune rising over the flat desert landscape. Much evidence, including the boat-
139 shaped coffins covered with cattle skins, feathers of water-birds clung to scepters, flattened
140 goose-quills forming the teeth of wooden masks, and numerous wooden poles made of poplar
141 tree (*Populus euphratica* Oliv.) trunks (Li et al., 2013a), indicates a life among rivers and
142 lakes, marshes and riparian forests. Indeed, the site is located in the huge delta area formed by
143 the rivers Kongque and Tarim (Fig. 1D), and the dry valley of the Small River ('Xiaohe' in
144 Chinese) – a former branch of the Kongque River – is about 4 km away from the cemetery (Li
145 et al., 2013a).

146 The modern climate of Xinjiang is extremely continental, with cold winters, hot summers,
147 and very low precipitation outside the high alpine areas. Arid and hyper-arid conditions in the
148 Junggar Basin to the north and in the Tarim Basin to the south of Bosten Lake are caused by
149 their position in the rain shadow of the Central Asian mountains, which almost entirely block
150 moisture transport from the Atlantic Ocean (Domrös and Peng, 1988). In the eastern Tian
151 Shan the northern slopes experience relatively humid conditions, while the southern slopes are
152 relatively dry. The range of mean annual precipitation stretches from 400–500 mm in the
153 subalpine Tian Shan to only 70–80 mm per year in the Yanqi Basin (Fu et al., 2013; Yang and
154 Cui, 2005; Zhang et al., 2004). Close to the lake the mean temperature is about 28°C in July
155 and -10°C in January (Huang et al., 2009).

156 Altitudinal and latitudinal temperature and precipitation gradients in the eastern Tian Shan
157 influence vegetation distribution. In the north moisture-demanding communities reach lower
158 elevations than in the south (Zhang et al., 2004). Major vegetation belts include sparse
159 subnival communities, high-alpine meadows, alpine steppe, subalpine spruce forests with
160 *Picea schrenkiana* (mainly in the north), montane forest-steppe with *Betula*, steppe and desert
161 communities (Fan and Du, 1999; Feng et al., 2006b; Wang, 1961; Zhang, 1992a, 1992b;
162 Zhang et al., 2004). Reed meadows with *Phragmites* and *Typha* are widely distributed west of
163 Bosten Lake, halophytes occur at near-shore sites subject to strong evaporation (Chen et al.,
164 2006a; Mischke and Wünnemann, 2006; Wei et al., 2002; Zhang et al., 2010; Zuo et al.,
165 2007). Ruderal vegetation is common in inhabited areas, and manure of cultivated crops
166 causes phosphorus eutrophication of the lake (Wünnemann et al., 2006; Zuo et al., 2007).

167

168 **3. Material and methods**

169

170 *3.1. Sediment samples*

171 Core XBWu-46 (41°56.9'N, 86°46.5'E) was retrieved at a water depth of 5.88 m ca. 6 km
172 off the Kaidu River mouth (Fig. 1B and C). The 925-cm-long core comprises layers of
173 organic-poor sand with some fine gravel (925–914 cm), fine-grained clayey and carbonate-
174 rich sediments (914–15 cm) with two basal layers of peat (904–900 and 884–880 cm) and a
175 layer with low organic content (600–405 cm), and a layer of dark-grey mud (15–0 cm). The
176 fine-grained sediments show several layers with increased amounts of silt and sand (Mischke
177 and Wünnemann, 2006; Wünnemann et al., 2003, 2006). Sub-sampling was performed by
178 cutting all core segments into 1-cm-thick slices, which were used for different analyses. The
179 pollen analysis presented in this paper was conducted on 50 samples, which allows an average
180 temporal resolution of about 170 years.

181 While most of the coffins found in Xiaohe have a boat shape, a few rectangular coffins are
182 completely plastered with clay. Li et al. (2013a) investigated samples of clay from four of
183 these "mud coffins" for pollen and plant macrofossil analyses. However, the pollen recovery
184 reported in their study was very poor. Therefore, a clay sample from the mud coffin BM28
185 representing the earliest burial layer of the Xiaohe cemetery was used in the present study for
186 analyzing pollen and other microfossils. Additionally, basic geochemical parameters of this
187 single sample such as TIC (total inorganic carbon), TOC (total organic carbon) and the main
188 mineralogic components (by XRD; X-ray diffraction) were determined by common analyses
189 as described in Vogel et al. (2016).

190

191 *3.2. Radiocarbon dating and chronological modelling*

192 Five ¹⁴C dates (Table 1) used for age control of the XBWu-46 sediment sequence were
193 reported in Wünnemann et al. (2006). These dates were based on terrestrial plant remains or
194 sediment bulk organic fractions. In the current study, the five conventional ¹⁴C ages were
195 recalibrated with the IntCal13 calibration curve (Reimer et al., 2013) using the OxCal v.4.3
196 software package (Bronk Ramsey, 1995). We adopted a Poisson process depositional model
197 (Bronk Ramsey, 2008) to establish the sequence's age-depth relationship (Fig. 2). The critical
198 values for the agreement index and convergence index in the model were set to, respectively,
199 60% and 95% (Bronk Ramsey, 1995).

200 A bulk micro-sample of plant remains, possibly representing wheat and/or millet straw
201 used to reinforce the mud for construction purposes (Li et al., 2013a), was recovered from the
202 clay cover of the BM28 coffin and sent to the radiocarbon laboratory in Poznan for AMS age
203 determination. The obtained radiocarbon date (Fig. 3) was converted into calendar age using

204 the OxCal v.4.3 software package (Bronk Ramsey, 1995) and the IntCal13 calibration curve
205 (Reimer et al., 2013).

206

207

208 3.3. Palynological analysis

209 Pollen and NPPs were extracted from the lake sediment samples applying hydrofluoric
210 acid and acetolysis treatments and ultrasonic sieving through 7- μ m meshes (Fægri and
211 Iversen, 1989). One *Lycopodium* marker spore tablet (batch no. 938934: 1 tablet contains
212 10,679 \pm 426 spores) was added to each sample for calculating absolute concentrations of
213 palynomorphs (Maher, 1981; Stockmarr, 1971). Taxonomic determinations were performed
214 using transmission light microscopy at magnifications of 400 \times and, in critical cases, 1000 \times .
215 Counted sums generally exceed 500 terrestrial pollen grains per sample. Pollen and NPPs
216 were generally well preserved and determined according to basic references (Jankovská and
217 Komárek 2000; Komárek and Jankovská, 2001; Moore et al., 1991; van Geel et al., 1989,
218 1996; Wang et al., 1997).

219 Pollen percentages for terrestrial taxa were calculated based on the terrestrial pollen sum
220 taken as 100%. Percentages for limno- and telmatophyte plants and spore-producing plants
221 were calculated based on the terrestrial pollen sum plus the sum of palynomorphs in the
222 corresponding group. Percentages for phytoplankton taxa were based on their total counts.
223 The pollen percentage diagram (Fig. 4) was drawn using Tilia software (Grimm, 1993, 2004)
224 and subdivided into assemblage zones and subzones applying square-root transformation of
225 percentage data and stratigraphically constrained cluster analysis by the method of
226 incremental sum of squares (Grimm, 1987).

227 Pollen percentage ratios are frequently used as a semi-quantitative characteristic of
228 regional past climate or environments (e.g. Fowell et al., 2003; Herzschuh et al., 2004; Leipe
229 et al., 2014a). The ratio of *Artemisia* to Chenopodiaceae (A/C) has been used as an indicator
230 of moisture availability in arid to semi-arid environments (El-Moslimany, 1990). In the dry
231 regions of China, the A/C ratio estimates the contribution of relatively moist steppe vegetation
232 with prevailing *Artemisia* in relation to Chenopodiaceae-dominated desert and halophyte
233 communities (An et al., 2006; Feng et al., 2006a; Herzschuh et al., 2004). Zhao et al. (2012)
234 have reviewed application and limitations of the A/C pollen ratio in arid and semi-arid China.
235 They concluded that variance in the A/C ratio can permit identification of modern vegetation
236 types and that the A/C ratio generally has a positive relationship with annual precipitation.
237 Following Luo et al. (2009), A/C values around 1 point to desert-steppe, while ratios below

238 0.5 indicate desert environments. However, soil salinity, vegetation community composition,
239 human activity, and sample provenance (e.g. soil and lake sediments) will affect the values of
240 the A/C ratio in different vegetation zones and therefore it can only be used to reconstruct
241 vegetation types and climate change in regions with annual precipitation <450–500 mm, and
242 in steppe, steppe desert, and desert areas (Zhao et al., 2012). Increased contribution of
243 *Ephedra* (E) pollen has been considered as another indicator for dry steppe and desert
244 conditions (Herzschuh et al., 2004; Huang et al., 2009; Luo et al., 2009; Prentice et al., 1996).
245 However, understanding the environmental factors, which control the growth of *Ephedra* in
246 the study area, needs more investigation. For example, we observed dense *Ephedra* shrub
247 cover in the mountain valley next to the slope covered with low juniper shrubs. Neither
248 vegetation nor climate of the valley could be ascribed as desert. A better knowledge on the
249 *Ephedra* ecology is particularly important for interpretation of the *Ephedra* percentage curves
250 (e.g. Huang et al., 2009 and this study) in the palynological records from the region. In the
251 current study, the A/C index and the arboreal pollen (AP) percentage curve are used to discuss
252 lower altitude desert/steppe and mountain forest development and to illustrate relationships
253 between the regional climate and vegetation.

254 The clay sample representing the BM28 coffin from Xiaohe was chemically treated and
255 microscopically analyzed in the same way as the Core XBWu-46 sediment from Bosten Lake.
256 Due to low pollen concentration, pollen counting was stopped after identification of 300
257 pollen grains.

258

259 **4. Results**

260

261 *4.1. Chronology*

262 The established chronology shows no significant change in sedimentation rate (Fig. 2),
263 which coincides with the fact that there are no significant variations in sediment composition
264 (e.g. different particle sizes) throughout the core (Wünnemann et al., 2006). The 925-cm
265 sediment sequence records a ca. 8500-year environmental history of the Bosten Lake region,
266 starting from ca. 8540 cal. yr BP (median) at the bottom and ending at ca. 60 cal. yr BP
267 (median) at the top. Our results confirm the XBWu-46 core age model, which was developed
268 and discussed in detail by Wünnemann et al. (2006).

269 The result of radiocarbon dating of the short-lived terrestrial plant remains recovered from
270 the clay sample from Xiaohe is shown in Fig. 3. The radiocarbon date 3640 ± 70 ^{14}C yr BP
271 being turned into calendar years represents an interval 4155–3726 cal. yr BP (95.4% range)

272 and 4083–3870 cal. yr BP (68.2% range), suggesting that the onset of burial activities (and
273 probably the onset of human habitation) at the site can be extended back to at least four
274 millennia ago. This approves an earlier estimation, which dated the lowest layer of the Xiaohe
275 cemetery to 3980±40 cal. yr BP (Li et al., 2010). Well-preserved wheat grains from the
276 cemetery were dated to 3710–3380 cal. yr BP (Long et al., 2018), representing the final stage
277 of the cemetery use and most likely the end of the settlement.

278

279 4.2. Pollen assemblage zones of core XBWu-46

280 Results of the palynological analysis of core XBWu-46 are presented in Fig. 4. Three
281 pollen assemblage zones (PAZ) and subzones (PASZ) were defined by splitting the CONISS-
282 derived clusters at a total sum of squares of 2.0 and 1.45, respectively. Total pollen
283 concentration is ca. 30,000–50,000 grains per cm³ through most of the sequence. A few
284 samples demonstrate higher values (ca. 60,000–80,000 grains per cm³). Samples from the
285 bottom sandy layer (below 912.5 cm) revealed very little pollen quantities and were therefore
286 excluded from the percentage calculations. On the other hand, this core sequence revealed
287 abundant grass epidermis fragments and fungal spores.

288

289 4.3. Pollen assemblage and basic geochemical parameters of the BM28 clay sample from 290 Xiaohe

291 Results of the geochemical analysis of the BM28 coffin clay sample show that the main
292 component is quartz (SiO₂). The TIC content is 2.2% and the TOC content is 1.4%. The fine-
293 grained, muddy character of the sample is due to relatively large proportions of the clay
294 minerals illite and chlorite. A few tiny shells of ostracods (seed shrimps) also discovered in
295 the clay sample (Fig. 5A) were identified as juveniles and one poorly preserved adult form of
296 *Pseudocandona* sp.

297 Results of the palynological analysis of the BM28 sample are presented in Fig. 5B and
298 Table 2. The total pollen concentration is also very low, i.e. 550 grains per gram of dry
299 sediment. Altogether, 300 pollen grains assigned to 18 taxa plus another 27 poorly preserved
300 herbaceous pollen grains assigned to *Indeterminata* were recovered from the sample allowing
301 reliable calculation of pollen percentages. The pollen assemblage demonstrates absolute
302 predominance of Poaceae (42.5%) and *Artemisia* (23.5%) pollen, followed by *Typha* (4.3%),
303 Cyperaceae (4%), *Ephedra* (3.7%), and Chenopodiaceae (1.5%). The A/C ratio is 15.4
304 pointing to a moist steppe or meadow environment. This interpretation is supported by
305 relatively high values of *Typha* (4.3%) and Cyperaceae (4%).

306

307 **5. Interpretation and discussion**

308

309 *5.1. Vegetation development and regional climate dynamics*

310 The pollen diagram of the XBWu-46 record (Fig. 4) reveals dominance of herbaceous taxa
311 in the Bosten Lake sediment through the entire record. The most abundant taxa are
312 Chenopodiaceae, *Artemisia*, and Poaceae representing desert, steppe, and coastal vegetation
313 communities. The records of *Picea* (spruce) and *Betula* (birch) pollen demonstrate higher
314 percentages in the lower part of the pollen diagram (zones 1 and 2) suggesting a wider
315 distribution of subalpine mountain forests in the past, prior to ca. 4300 cal. yr BP (Fig. 4).
316 Several pollen records from Xinjiang confirm a wider than present distribution of forests in
317 the Tian Shan during ca. 8000–4300 cal. yr BP in correspondence to warmer and moister
318 climatic conditions (Zhao et al., 2007). Today in the northern Tian Shan coniferous forests
319 with *Picea schrenkiana* occur at altitudes of 1600–2800 m a.s.l., while in the south scattered
320 stands of spruce are restricted to moister sites (mainly valleys) at elevations of 2000–2800 m
321 a.s.l. (Feng et al., 2006b; Zhang et al., 2004).

322 Relatively high frequencies of *Picea* pollen were recorded in modern surface samples
323 collected close to the western reed belt of Bosten Lake (Feng et al., 2006b; Huang et al., 2004;
324 Zhou et al., 2001), reflecting significant water transport of spruce pollen (Wu et al., 2013) by
325 the Kaidu River. The upper section of core XBWu-46 reveals, in turn, low abundances of
326 spruce pollen (Fig. 4). These opposing results might be explained by a filtering effect of
327 coastal reed vegetation, which stops significant parts of the river-transported sediment
328 (probably including large pollen grains) from entering the lake. Thus, *Picea* pollen recorded
329 in the lake sediment likely represent airborne pollen influx. Consequently, higher percentages
330 of spruce pollen in the XBWu-46 record should predominantly reflect air transport from
331 mountain forest, which occupied, under more humid climatic conditions, larger area than
332 today.

333 The gradual long-term trend towards decline of mountain forest vegetation and dominance
334 of desert communities in lower elevated areas between 8500 and 4300 cal. yr BP expressed by
335 the AP and A/C curves (Fig. 4) is superimposed by relatively short oscillations in the AP
336 percentages curve (Fig. 6A), which may reflect changes in the regional precipitation and
337 moisture availability. One of the major oscillations occurs near the base of the record (i.e. in
338 PAZ 1). In the sediment column, it corresponds to intermittent peaty layers, suggesting a
339 relatively low lake level and a dry climate. Previous reconstructions from Bosten Lake

340 ascribed it as a regional evidence of the broadly-recognized cold event around 8200 cal. yr BP
341 that originated in the North Atlantic (Mischke and Wünnemann, 2006; Wünnemann et al.,
342 2006; Zhang et al., 2010).

343 The interval between 8050 and 5350 cal. yr BP shows higher than average AP percentages
344 (Fig. 6A), suggesting moisture conditions generally favorable for the regional mountain forest
345 vegetation. By contrast, the XBWu-46 aquatic pollen record (Fig. 6B) demonstrates lowest
346 percentages during this time interval, indicating relatively high river water inflow, which
347 contributed to a rise in lake level, in line with the other proxies from Bosten Lake used to
348 reconstruct the lake status (Wünnemann et al., 2006; Fig. 6C). The AP percentages (Fig. 6A)
349 show further decrease after 5350 cal. yr BP and reach minimum values between 4000 and
350 2000 cal. yr BP. These changes possibly reflect a decrease in the distribution area of trees and
351 shrubs due to decreased precipitation in the mountains. The decreased moisture availability in
352 the upper catchment corroborates progressive increase in the aquatic pollen percentages
353 between 5300 and 1500 cal. yr BP (Fig. 6B), suggesting spread of aquatic vegetation and
354 shallower lake environments (Fig. 6C). Slightly higher AP percentages are registered after
355 2000 cal. yr BP (Fig. 6A), possibly reflecting slight improvement of the mountain climate and
356 regional water balance. Such interpretation is supported by a distinct drop in the aquatic
357 pollen percentages after 1500 cal. yr BP (Fig. 6B) and a higher lake status reconstructed for
358 the last millennium (Fig. 6C).

359 In contrast to the dynamically changing moisture conditions at higher altitudes, the A/C
360 index (Fig. 4) representing low-altitude Yanqi Basin vegetation shows relatively low (i.e.
361 desert) values through the entire XBWu-46 record, interrupted by four short-term peaks
362 towards desert-steppe environments at around 8200, 6200, 5900, and 2500 cal. yr BP. This
363 indicates rather stable desert environments with a strong presence of *Chenopodiaceae* and
364 *Ephedra* in the Yanqi Basin vegetation during the past 8500 years.

365 Contrasting moisture conditions at low and high altitudes can be explained by features of
366 the regional climate complicated by effects of topography. The interplay of the major
367 circulation systems (i.e. the Atlantic westerlies and the Asian summer monsoon) responsible
368 for the moisture transport to Central Asia are frequently involved in the discussion and
369 interpretations of environmental proxies (Wünnemann et al., 2006; Zhang et al., 2010;
370 Rudaya et al., 2009; Kleinen et al., 2011). Climate reconstructions derived from lacustrine
371 pollen records from the Himalaya (Fig. 6H) demonstrate that both the westerlies and the
372 summer monsoon have been transporting precipitation to the higher altitudes during the

373 Holocene period, though their contribution to the regional water budget has been variable
374 over time (Leipe et al., 2014a, 2014b; Demske et al., 2016).

375 Our pollen record from Bosten Lake (Fig. 4) suggests that zonal desert vegetation in the
376 low-elevated Yanqi Basin (and probably, in the entire Tarim Basin) outside the mountain
377 river valleys or lake shores remained insensitive to the precipitation variations at high
378 altitudes due to the arid climate characterized by extremely high potential evaporation greatly
379 exceeding actual precipitation elsewhere outside the high mountains.

380 The A/C ratio of the BM28 clay sample is 15.4 and points to a moister (i.e. steppe or
381 meadow) environment which existed in this area that is currently a desert ca. 4000 years ago.
382 Statistical analysis of recent pollen spectra from different vegetation types in arid and semi-
383 arid China shows that A/C ratios may reach up to 33.33 in the steppe and up to 23.09 in the
384 desert steppe regions (Zhao et al., 2012).

385 Former moist sedimentation environments and the aquatic origin of the clay sample are
386 supported by the TIC data that represents mainly calcite (CaCO_3) and a minor portion of
387 dolomite ($\text{CaMg}(\text{CO}_3)_2$). Sediment geochemistry and ostracod (Fig. 5A) records suggest that
388 accumulation likely occurred during the spring/early summer or autumn period within
389 freshwater (salt content less than 2 gram per liter and traces of gypsum ($\text{CaSO}_4 \cdot 2(\text{H}_2\text{O})$)
390 identified by the geochemical analysis) and relatively quiet aquatic (i.e. lacustrine)
391 environments (S. Mischke, personal communication).

392 Relatively high percentages of *Typha* and Cyperaceae pollen (Fig. 5B), representing
393 coastal aquatic vegetation communities, together with relatively high percentages of *Ephedra*,
394 representative of desert environments, indicate the mixed character of the pollen assemblage
395 and thus a mixed vegetation, which contributed pollen to the clay sample. Indeed, one half of
396 the pollen (e.g. Poaceae, Cyperaceae, *Typha*) represent local, mesic vegetation communities
397 growing at lake or river shores, while the other half of the spectrum is more typical for arid
398 steppes and deserts representing regional vegetation.

399 Various proxy-based reconstructions (e.g. Leipe et al., 2014a; Ran and Feng, 2013;
400 Rudaya et al., 2009) and model-based simulations of the Holocene climate and vegetation
401 (e.g. Kleinen et al., 2011) indicate that absolute values and relative contribution of the
402 westerlies and summer monsoon to the regional moisture budget varied greatly, both
403 temporally and spatially across Central Asia. Therefore, the onset, magnitude, and length of
404 the Holocene climatic (i.e. moisture/temperature) optimum in different regions of Asia are
405 among the frequently discussed questions (Leipe et al., 2014a; Rudaya et al., 2009; Stebich et
406 al., 2015; Wang et al., 2005; Zhou et al., 2004; Zhou et al., 2016). The ongoing debates

407 remain hot, particularly regarding the arid regions of north-western China, which are, for an
408 objective reason, still poorly covered by good-quality proxy records.

409 Regionally-averaged moisture indexes demonstrate clearly opposite trends for the south-
410 eastern and north-western parts of China (Ran and Feng, 2013). For south-eastern China (Fig.
411 6E), where climate and annual moisture balance are controlled by the summer monsoon (Fig.
412 6G; Yuan et al., 2004), a pronounced early to middle Holocene moisture optimum prior to
413 5000 cal. yr BP and a subsequent gradual decline was reconstructed (Ran and Feng, 2013;
414 Stebich et al., 2015). By contrast, the reconstruction performed for the Xinjiang region in
415 north-western China reveals a low but growing moisture index between 8500 and 5000 cal. yr
416 BP, a minor decline between 5000 and 4200 cal. yr BP, and a moisture optimum between
417 2200 and 500 cal. yr BP (Fig. 6F). Based on these differences between the regions, Ran and
418 Feng (2013) suggest that the winter temperature variations in the North Atlantic region and
419 the Atlantic westerlies were the major factors controlling the Holocene moisture variations in
420 Xinjiang, while the summer monsoon did not play a significant role there. However, this
421 interpretation is not in agreement with the results presented in the current study. In fact, the
422 key moisture indicators in the Bosten Lake catchment area, such as the AP percentage curve
423 (Fig. 6A), the pollen percentages of aquatic vegetation (Fig. 6B), and the lake status
424 reconstruction (Fig. 6C) resemble the summer monsoon intensity isotope record from Dongge
425 Cave (Fig. 6G) and, to a large extent, the moisture index curve from the monsoon-controlled
426 regions of China (Fig. 6E). On the other hand, comparison to the moisture reconstruction for
427 Xinjiang (Fig. 6F) proposed by Ran and Feng (2013) and for the westerly-controlled forest-
428 steppe region of Kazakhstan (Fig. 6D) by Tarasov et al. (2012) (see also Kremenetski et al.,
429 1997 for a detailed pollen record from Lake Pashennoe and four other sites) does not show
430 such similarity, suggesting that the North Atlantic air masses started to play a more significant
431 role in the moisture balance of the Bosten Lake catchment area only since about 1500 cal. yr
432 BP.

433 The records from the neighboring areas of Kazakhstan, Mongolia, and Russia (Rudaya et
434 al., 2009; Tarasov et al., 2012), situated west and north of Bosten Lake, demonstrate spatially
435 and temporally different Holocene vegetation and climate histories, indicating that the
436 westerly-associated moisture transport played an important role in the environmental
437 dynamics of the regions situated west and north of the Altai and Tian Shan Mountains during
438 the middle and late Holocene. By contrast, the moisture transport associated with the stronger-
439 than-present summer monsoon was of pivotal importance for the environments of eastern

440 Central Asia represented by the Bosten Lake study region during the early and middle
441 Holocene.

442 A high resolution petromagnetic analysis of the Jinjie loess-paleosol sequence (5 in Fig.
443 1A) from the desert part of the Chinese Loess Plateau helps to reconstruct three warm-humid
444 intervals (ca. 8400–3700, ca. 2400–1200 and ca. 810–480 cal. yr BP) during the Holocene
445 (Anwar et al., 2018). The early phase of a substantial paleosol development indicates the
446 middle Holocene climatic optimum associated with a stronger summer monsoon. The two
447 younger (and less pronounced) phases of climate amelioration, however, cannot be traced in
448 the records from monsoonal China (e.g. Fig. 6E), but corroborate the late Holocene moisture
449 increase reconstructed for Xinjiang (e.g. Fig. 6F). This similarity between the Bosten Lake
450 records presented in Fig. 6A–C and the reconstruction derived from the desert area of the
451 Chinese Loess Plateau (Anwar et al., 2018) suggests that increased moisture levels in both
452 regions were controlled by enhanced westerly-controlled precipitation.

453 The question about the moisture evolution and climate development in arid Central Asia
454 caused a sharp controversy and hot scientific polemic during the past hundred years (e.g.
455 Boomer et al., 2000). For example, G.Ye. Grumm-Grzhimailo, N.V. Pavlov, V.A. Smirnov,
456 V.M. Sinitsyn, and A.V. Shnitnikov advocated for a drying trend during the historical period,
457 while L.S. Berg, K. K. Markov, and some others argued against this hypothesis (Gumilyov
458 and Aleksin, 1963). Debates have been ongoing into the current decade, with new results
459 highlighting the spatial/temporal complexity of the environmental dynamics in Central Asia
460 and warning against over-simplified conclusions and interpretations (see discussions in
461 Morrill et al., 2003; Tarasov and Wagner, 2015).

462 The Bosten Lake sedimentary archive does not represent the only example of
463 controversial interpretations. Mathis et al. (2014) presented a pollen study conducted on the
464 middle Holocene (ca. 8350–2000 cal. yr BP) sediments from the high-altitude lake Son Kul (7
465 in Fig. 1A) in the central Tien Shan (Kyrgyzstan). Their reconstruction of vegetation and
466 climate dynamics suggests that warmer/moister climate conditions occurred between 8350
467 and 5000–4500 cal. yr BP and more continental and arid conditions prevailed after 4500 cal.
468 BP. The authors proposed that regional rainfall in the central Tien Shan and western Central
469 Asia is likely to be predominantly controlled by the Eastern Mediterranean cyclonic system,
470 referring to the close correspondence between climate archives of Son Kul and the Eastern
471 Mediterranean and Caspian Sea regions, on one hand, and from the Xinjiang region, on
472 another hand. A multi-proxy study on the Son Kul sediment core (Huang et al., 2014),
473 including grain size, magnetic susceptibility, sediment geochemistry, and isotope analyses on

474 bulk and biogenic materials, helped to recognize that the long-term negative hydrological
475 balance was interrupted by several short stages with marked increase of precipitation (e.g.
476 8300–8200, 6900–6700, 6300–6100, 5500–5400, 5300–5200, and 3100–3000 cal. yr BP),
477 which also imply that moisture sources could have changed during the Holocene. Another
478 research team working on the same lake used diatom, ostracod, sedimentological,
479 geochemical, and stable isotope analyses on a ca. 6000-year-old lake sediment core to
480 reconstruct shifts in water balance (Schwarz et al., 2017). In addition to an alternative name
481 (i.e. Son Kol), their study provided an alternative interpretation of the lake history suggesting
482 a closed basin lake/dry climate ca. 6000–3800 and ca. 3250–1950 cal. yr BP and an open
483 lake/wet climate at 3800 and after 1950 cal. yr BP. A complex interplay of the driving factors
484 was suggested to explain these regime shifts, including changing intensity and position of the
485 westerlies and the Siberian Anticyclone that triggered changes in the amount of winter
486 precipitation (Schwarz et al., 2017). In line with the Bosten Lake studies, these publications
487 emphasize the importance of multi-proxy approaches to identify triggers, thresholds, and
488 cascades of aquatic ecosystem transformations and pinpoint a necessity for regional climate
489 modeling experiments to explore the effect of Eurasian atmospheric circulation patterns on
490 the Holocene climate variability in Central Asia.

491

492 *5.2. Vegetation development and human impact in the Bosten Lake pollen record*

493 The decline of arboreal pollen in the Bosten Lake sedimentary record, particularly after
494 5000 cal. yr BP likely reflects a reduction of the forest vegetation in the catchment area. The
495 decreasing trend in the AP curve (Fig. 6A) coincides with other evidence of decreasing
496 moisture availability (Fig. 6B and C), suggesting that a progressive aridification of the
497 regional climate probably played an important role in the vegetation changes recorded in the
498 pollen diagram (Fig. 4). However, exploitation of wood resources by prehistoric human
499 populations, as another possible reason for the forest decline, cannot be ruled out (Ren, 2000;
500 Ren and Beug, 1999). Increased frequencies of charred grass fragments (Fig. 4), particularly
501 since ca. 5000 cal. yr BP, might indicate fires caused by human activities. Archaeological data
502 from Xinjiang (Hosner et al., 2016) demonstrate an increase in archaeological site numbers
503 from 44 sites assigned to the period between 9000 and 4000 cal. yr BP to 153 sites assigned to
504 the interval between 4000 and 2000 cal. yr BP.

505 Concerning the region around Bosten Lake, however, archaeological evidence of early
506 habitation is scarce. Charred *Picea* wood fragments from the Yuergou tombs in the nearby
507 Turfan Basin indicate use of spruce by the people living there between 2400 and 2300 cal. yr

508 BP (Jiang et al., 2013). Another famous prehistoric archaeological site of the region – the
509 Yanghai graveyard located in a present-day gravel desert (Beck et al., 2014; Jiang et al., 2006;
510 Kramell et al., 2014) about 43 km southeast of the modern city of Turfan – reveals more than
511 500 excavated tombs (Jiang et al., 2009) and a long period of their use, suggesting substantial
512 increase in human population and intensified human activities in the region between ca. 3100
513 and 1800 cal. yr BP (Beck et al., 2014).

514 Pollen indicators from Bosten Lake (Fig. 4) suggest a weak anthropogenic impact after
515 4350 cal. yr BP corresponding to generally low abundances of charred grass remains between
516 4350 and 2400 cal. yr BP. Evidence of cultivation comprises individual pollen grains of
517 *Cerealia* type registered four millennia ago. This date corroborates the earliest finds of wheat
518 and barley agriculture in Xinjiang associated with the Xiaohe graveyard (Fig. 1D; Long et al.,
519 2018; Mallory and Mair, 2008). Because of overlapping morphological characteristics in
520 cereal and wild grass pollen (Beug, 2004; Faegri and Iversen, 1989; Moore et al., 1991) the
521 record of large Poaceae grains (>37 µm) with thick non-cereal anuli assigned to *Elymus* type
522 (Fig. 4) could rather represent wild grasses growing in the sand or in dry sandy places.

523 Further evidence of human activities inferred from the pollen record (Fig. 4) includes
524 appearance of *Xanthium* (cocklebur) (after 3700 cal. yr BP) and *Cannabis* type (after 2500
525 cal. yr BP) pollen. Contemporaneous archaeological sites near Bosten Lake comprise the
526 sedentary Xintala (Yengidala) Culture site dated to 1700–1400 BCE, with evidence for the
527 cultivation of wheat and millet, and the Chawuhu (Charwighul) Culture site located north of
528 the lake in the Tian Shan dated to 1000–400 BCE, which both can be related to the
529 Andronovo Culture (Zhang, 2009). In time the initial spread of *Xanthium* near Bosten Lake
530 precedes archaeological evidence from the Yuergou tomb site in the Turfan Basin, where
531 numerous fruits and spikelets of *Xanthium strumarium* were discovered (Jiang et al., 2013).
532 Continuous presence of *Xanthium* between 3100 and 1400 cal. yr BP at Bosten Lake covers
533 the period of the Subeixi Culture related to the historical Cheshi State people (Li et al.,
534 2013b), who cultivated cereals and hemp and collected *Xanthium* for unknown purpose (Jiang
535 et al., 2013).

536 In sedimentary records from northern China, pollen of *Xanthium* is commonly regarded as
537 a human activity indicator (Makohonienko et al., 2008). This genus grows in segetal and
538 ruderal habitats, in roadsides and riverbanks and is classified primarily as a weed of cultivated
539 fields (Zhang and Hirota, 2000). In the past, the cocklebur was utilized in China as a leafy
540 vegetable and it was intentionally planted (Li, 1969). Similarly, the record of *Cannabis* type

541 pollen at Bosten Lake corresponds to fossil seeds (*Cannabis cf. indica*) recovered from the
542 Yanghai tombs, which were dated to ca. 2700 cal. yr BP (Jiang et al., 2006).

543 Appearance of these anthropogenic indicators in the Bosten Lake pollen record can be
544 linked not only to local populations of the Xintala and Chawuhu Cultures, but also to agro-
545 pastoral populations from the Turfan Basin (Beck et al., 2014; Jiang et al., 2013), as well as
546 likely from other even more distant regions of Asia (Spengler et al., 2016). In particular,
547 moister regional environmental conditions in western Central Asia after 5000 cal. yr BP may
548 have increased the appeal of adopting an agricultural component into the economy of local
549 groups and inspired them for searching new lands suitable for agriculture further east (Long et
550 al., 2018; Spengler et al., 2016). It is easy to imagine that Bosten Lake and the catchments of
551 the Kaidu and Kongque rivers offered very suitable environments for these agro-pastoralists
552 coming from the west. It could have been also a desirable refuge for agro-pastoral tribes
553 living in the arid and generally more challenging oases environments along the Tarim River
554 and its tributaries (e.g. in Xiaohe, Fig. 1D), as soon as increasing aridity and unstable river
555 water supply threatened their livelihood and shoved the inhabitants of the desert oases
556 towards the mountains (Wagner et al., 2011).

557 Ancient populations in the Lop Nur area southeast of Bosten Lake are represented by the
558 Xiaohe and Gumugou cemeteries dated to ca. 4100–3500 cal. yr BP (Long et al., 2018; Tang
559 et al., 2013). Archaeological materials (e.g. Mair, 2006; Relics and Archaeology Institute,
560 2007) demonstrate that these people possessed a mixed agro-pastoral economy (i.e. grazing
561 cows and sheep, growing wheat, barley, and millet) supplemented by hunting and fishing.
562 Such way of life in the extreme arid environments of Xinjiang is only possible with a stable
563 water supply provided by traversing rivers and permanent lakes or with a very sophisticated
564 and reliable irrigation system (i.e. historical *karez*). Both archaeological and environmental
565 data suggest that water supply was sufficient to support various human activities and riparian
566 forest vegetation along the river valleys in the area between Bosten Lake and the terminal lake
567 Lop Nur. Extensive use of wood seen in the Xiaohe cemetery also indicates that the past
568 human population significantly impacted on local vegetation, which could have (together with
569 worsening climate conditions) destabilized the fragile sustainability of the natural system
570 around them during a relatively short time interval of about five centuries. After that they
571 were forced either to die or to find other habitats and adapt their lifestyle to new environments
572 (Wagner et al., 2011).

573 Higher abundances of *Xanthium* pollen and charred grass fragments recorded between
574 2200 and 1800 cal. yr BP (Fig. 4) indicates further intensified human activities in the region

575 in line with archaeological records (Hosner et al., 2016). During the Han Dynasty (206 BCE–
576 220 CE) the Silk Road network became an increasingly important east-west trade connection
577 through the Tarim Basin including the northern route across the Bosten Lake area. Since ca.
578 1200 cal. yr BP, *Triticum* and *Rumex* pollen as well as charred grass fragments point to the
579 development of local settlements and an increasing anthropogenic impact on the regional
580 vegetation as well as on the limnic system of Bosten Lake.

581

582 *5.3. Environmental and archaeological records from the study region during the 2nd and 1st* 583 *millennium BCE*

584 In China, the interval between 4500 and 2000 cal. yr BP is in focus of many archaeological
585 and palaeoenvironmental projects. It is particularly noted for its major cultural and
586 environmental changes (Hosner et al., 2016; Long et al., 2018; Wagner et al., 2013), including
587 a major weakening of the Asian summer monsoon (e.g. Fig. 6E and G), strengthening of the
588 mid-latitude westerly flow (Fig. 6D and F), intensified west-east contacts and cultural
589 exchanges, including spread of bronze metallurgy and wheat agriculture from western Central
590 Asia to eastern Asia (Long et al., 2018; Tang et al., 2013), appearance of elites and central
591 state formation (Liu and Chen, 2012; Wagner and Tarasov, 2014), and development of the
592 mounted pastoral economy in the northern and western regions (Long et al., 2018; Wagner et
593 al., 2011). The multidisciplinary ‘Silk Road Fashion’ project (e.g. Beck et al., 2014; Kramell
594 et al., 2014; Schröder et al., 2016) reported, among other findings, the invention of trousers in
595 the late second millennium BCE Turfan Basin and its likely affiliation with horseback riding
596 and increased mobility.

597 The selection of environmental records from Bosten Lake (Fig. 6A–C) and other regions of
598 Asia (Fig. 6D–H) clearly demonstrates the transitional character of the interval between 4000
599 and 2000 cal. yr BP both in the eastern (i.e. monsoon-controlled) and in the western (i.e.
600 westerly-controlled) part of Asia. The trends in the moisture changes recorded in both regions
601 are opposite, however. While the eastern part of Asia (including China and northern India;
602 Fig. 6G and H) experienced decreasing moisture supply due to weakening of the summer
603 monsoon, the western part (Kazakhstan and South Siberia; Fig. 6D) prospered from the
604 strengthening of the westerly-related moisture transport through the middle latitudes and
605 lower evaporation losses (Kleinen et al., 2011; Rudaya et al., 2009). The Xinjiang region,
606 situated in the transitional zone between the two major atmospheric circulation systems, thus
607 became an epicenter of the turbulent changes recorded in the environmental and
608 archaeological archives. Its complex topography superimposed the large scale climate

609 changes, making their effects stronger or milder and resulting in locally variable
610 environments, even within relatively short distances as, for example, suggested by the
611 different signals shown by the A/C (Fig. 4) and AP (Fig. 6A) records from Bosten Lake and
612 by the A/C (Fig. 6I) and grain size (Fig. 6J) records from the Liushui loess profile in the
613 Kunlun Mountains (Fig. 1A) representing opposite trends in moisture development along the
614 altitudinal gradient at multi-decadal/centennial scale (Tang et al., 2013). Kravchinsky et al.
615 (2013) also demonstrated that Central Asian loess sediments well reflect large-scale climate
616 variability. Multi-decadal peaks in the grain size record from their Burdukovo loess-soil
617 section analysis (6 in Fig. 1A) resemble closely the Liushui record (even considering possible
618 age confidence interval variations) and may indicate rather global tendency than purely
619 regional interplay.

620 The combined use of high-resolution palaeoenvironmental and archaeological records (e.g.
621 Leipe et al., 2014a, 2018) and robust chronological modelling (e.g. Long et al., 2017, 2018)
622 will definitely help in getting more accurate reconstructions that allow for more reliable
623 interpretations of complex human-environment interactions in the study region and to avoid
624 over-simplistic and deterministic models.

625

626 **7. Conclusions**

627

- 628 • The fossil pollen record from core XBWu-46 (ca. 8540–60 cal. yr BP) contains two main
629 environmental signals represented (i) by the AP percentages reflecting changes in the
630 mountain and riparian forests and (ii) by the A/C pollen ratio reflecting variations in
631 lowland desert vegetation around Bosten Lake.
- 632 • During the early and middle Holocene, the moisture budget of the study region was mainly
633 controlled by the interplay of declining Asian summer monsoon precipitation in the south-
634 eastern Tian Shan and higher-than-present Northern Hemispheric summer insolation.
- 635 • During the late Holocene (after ca. 2000 cal. yr BP) the hydrology of eastern Central Asia
636 was mainly controlled by increasing precipitation linked to enhanced westerly
637 disturbances, while influence of the strongly weakened Asian summer monsoon was
638 insignificant or absent.
- 639 • The onset of human activities around Bosten Lake dates to 4000–3700 cal. yr BP likely
640 related to early agro-pastoral groups, which probably originated from more distant western
641 Central Asia regions. Human activities increased ca. 2200–1800 cal. yr BP due to

642 intensified trade activities related to the Silk Road during the Han dynasty (206 BCE–220
643 CE).

- 644 • Our findings underline the complex linkage between the recorded dynamic human
645 activities and changing environmental conditions in eastern Central Asia, which manifests
646 the need for interdisciplinary research projects to improve our understanding of past
647 regional human–environment interactions.

648

649 **Data availability**

650 Datasets related to this article can be found online in the Open Access information system
651 PANGAEA at <https://doi.org/XXXX/PANGAEA.XXXX>.

652

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994

995 **Figure captions**

996

997 **Fig. 1.** Topographic maps showing (A) locations of Bosten Lake (red triangle) and its
 998 catchment area, the Xiaohe archaeological site (red square) and the Lop Nur Basin, and other
 999 archives from eastern Eurasia (circles) discussed in the current paper, including (1) Pashennoe
 1000 Lake (Kremenetski et al., 1997), (2) Dongge Cave (Yuan et al., 2004), (3) Liushui
 1001 archaeological site and loess section (Tang et al., 2013), (4) Tso Moriri Lake (Leipe et al.,
 1002 2014a), (5) Jinjie section (Anwar et al., 2018), (6) Burdukovo section (Kravchinsky et al.,
 1003 2013), (7) Son Kul (Huang et al., 2014); (B) the Bosten Lake catchment area in the eastern
 1004 Tian Shan (elevation based on Shuttle Radar Topography Mission (SRTM) V4.1 data (Jarvis
 1005 et al., 2008) with color range from dark green to brown indicating lowest and highest
 1006 elevation, respectively); (C) the Bosten Lake (1050 m a.s.l.) bathymetric map (white numbers
 1007 show lake depth in meter) with the XBWu-46 core location; and (D) location of the Xiaohe
 1008 archaeological site and Lop Nur in the present-day desert area of the eastern Tarim Basin with
 1009 white numbers (elevation in meter a.s.l.) indicating prominent heights and depressions.
 1010 Selected country names and modern political borders in (A) are shown for orientation.

1011

1012 **Fig. 2.** Age-depth model (this study) applied to the XBWu-46 core pollen record (Fig. 4)
 1013 presented here. Used calibrated radiocarbon datings (Table 1) are shown by their 95%
 1014 confidence intervals (grey silhouettes), median ages (white dots), and lab numbers. The

1015 uppermost and lowermost white dots represent, respectively, the top and bottom of the
1016 XBWu-46 sediment sequence.

1017
1018 **Fig. 3.** Radiocarbon date and calibrated age of the clay sample from the BM28 mud coffin
1019 discussed in this study. The pink and grey curves show probability density distribution of,
1020 respectively, uncalibrated and calibrated ranges of the ^{14}C date. The 68% and 95% ranges are
1021 highlighted at the bottom of the calibrated distribution (grey curve). The blue curve is the
1022 IntCal13 calibration curve (Reimer et al. 2013).

1023
1024 **Fig. 4.** Simplified diagram showing results of the palynological investigation of the XBWu-46
1025 core from Bosten Lake.

1026
1027 **Fig. 5.** (A) Photos of the ostracod valves recovered from the same sample. (B) Simplified
1028 pollen composition and taxa percentages of the clay sample from the BM28 mud coffin
1029 discussed in this study.

1030
1031 **Fig. 6.** Selected results of this study highlighting the past climate changes in the Bosten Lake
1032 catchment area along with published proxy records discussed in the text. Locations of the
1033 records are given in Fig. 1. The graphs demonstrate: (A) – changes in arboreal pollen (AP)
1034 and (B) in aquatic pollen percentages from Bosten Lake (this study); (C) – changes in the
1035 reconstructed lake status/relative water depth of Bosten Lake (after Wünnemann et al., 2006);
1036 (D) – AP percentages from Lake Pashennoe, Kazakhstan (after Tarasov et al., 2012); (E) – the
1037 regionally-averaged moisture index for the south-eastern China region and (F) for the
1038 Xinjiang region (after Ran and Feng, 2013); (G) – oxygen isotope record from the Dongge
1039 Cave stalagmite D4 (after Yuan et al., 2004); (H) – pollen-based annual precipitation
1040 reconstruction from Tso Moriri (after Leipe et al., 2014a); (I) – *Artemisia/Chenopodiaceae*
1041 (A/C) ratio and (J) – mean grain size record from the Liushui loess profile in the Kunlun Shan
1042 (after Tang et al., 2013).

1043