Research paper

Hydrological change and human activity during Yuan–Ming Dynasties in the Loulan area, northwestern China

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Abstract
Human activity on arid lands has been related to oases evolution. The ancient Loulan, an important transportation hub of the ancient Silk Road, developed on an ancient oasis on the west bank of the lake Lop Nur in Xinjiang, China. Previous studies and historical documents suggest that the region has experienced dramatic natural environmental and human activity–related changes over time, transitioning from a particularly prosperous oasis to a depopulated zone with harsh environment after about 1500 a BP (before present, where present = AD 1950). Based on systematic radiocarbon (^{14}C) dating for natural plant remains and archeological sites in the Loulan area, it was revealed that the region re-experienced oasis environment from 1260 to 1450 cal. AD, corresponding to the Yuan–Ming Dynasties, which is the climate transition stage from the 'Medieval Warm Period' to the 'Little Ice Age', encompassing a series of pulse-like flood events which cannot be identified from lacustrine deposition due to the limits of sampling resolution and dating. It was found that humans re-occupied the Loulan area and built canals to irrigate farmlands during the period. The more habitable hydrological conditions that resulted from these environmental changes present one major reason for the re-emergence of human activities in the Loulan area.

Keywords
^{14}C dating, Loulan area, oasis, pulse-like flood events, Yuan–Ming Dynasties

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Introduction

The Lop Nur was the terminal lake of the ancient Tarim River, the depositional center of the Tarim Basin, and the largest historical waterbody known in western China (Figure 1). Precipitation in this region is only about 20 mm/yr, while evaporation can reach up to 3000 mm/yr at present. In historical time, there were numerous ancient civilizations developed in the desert oases of Xinjiang, China. The famous Loulan Kingdom, located on the west bank of the lake of Lop Nur, was one of them (Xia et al., 2007). The Loulan Kingdom first appeared in Chinese historical documents after Zhang Qian, the first official to be sent to the west by Emperor Wu of the Western Han Dynasty (206 BC to AD 24), opened up the Silk Road (Ban, 1962 [92]; Sima, 1959 [91 BC]). This area became an important junction between the west and the east after that. Hanshu stated, for example, that the later name of the Loulan Kingdom was the Shanshan and that this territory comprised 1570 families and about 14,000 people (Ban, 1962 [92]). The previous studies and historical documents indicate that the Loulan Kingdom was changed from an extremely prosperous oasis to an uninhabitable yardang area when Xuanzang, a famous monk of the Tang Dynasty (AD 618–907), passed through the region (Qin et al., 2011; Xuanzang, 1985 [645]). Recent systematical chronological studies of the ancient Loulan city have revealed that this settlement (89°55′3.97″E, 40°30′58.34″N. Figure 1), named LA by Stein (1921), was completely abandoned around AD 600 (Lü et al., 2010; Xu et al., 2017).

Lacustrine sedimentary records from the Lop Nur region are of paramount importance for understanding the Holocene paleoenvironment of this area and have revealed significant information (Jia et al., 2017; Liu et al., 2016; Luo et al., 2009;

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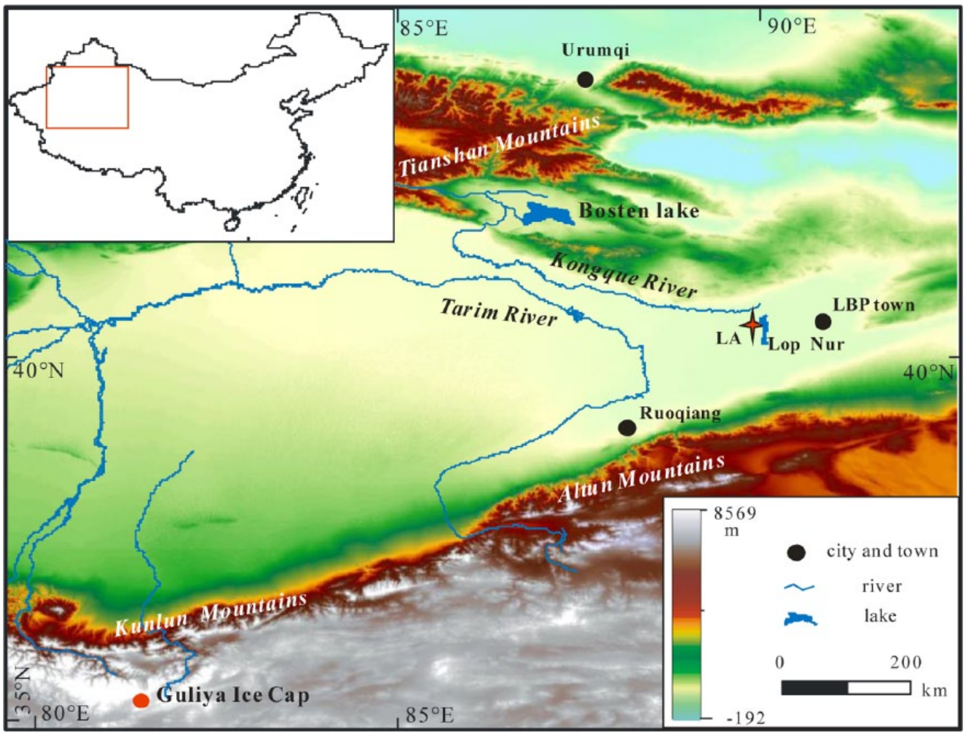

Figure 1. Location of studied area. Red star indicates LA (Stein, 1921), the lake Lop Nur was dried in 1972 (Xia et al., 2007), and red circle indicates Guliya ice core (GIC). The background map was downloaded from http://srtm.csi.cgiar.org.

Yang et al., 2013). However, the high-resolution paleoenvironment study remains problematic because of limited sampling resolution and thick salt encrustation in the ancient lake region of the Lop Nur and strong wind erosion in yardang area on the west bank of the lake. In addition, investigating this area is further complicated by the lack of roads and freshwater. Therefore, it is unknown whether, or not, other oasis stages existed after the Loulan Kingdom was abandoned, and the presence of human activity during additional historical periods also remains a mystery.

We conduct systematic radiocarbon (^{14}C) dating for nature plant remains and archeological sites in the Loulan area to examine whether the region has been a depopulated zone with harsh environment after the Loulan Kingdom was completely abandoned.

Materials and methods

Populus euphratica bark in ancient river channels

There are many river channels within the Loulan region; we designated these as the North River No. 1 (NR1), the North River No. 2 (NR2), the North River No. 3 (NR3), the South River No. 1 (SR1), and the South River No. 2 (SR2) based on their proximity to the ancient Loulan city LA (Figures 2 and 3). Surveys revealed the presence of extensive *P. euphratica* boles in these ancient river channels, likely either woody debris that was transported within torrents (driftwood) or dead trees that had been growing on both sides of the river (Figure 2). Radiocarbon (^{14}C) ages for *P. euphratica* bark samples (i.e. the outermost part of tree trunks most easily collected in the field) are representative of the latest time of growth. Thus, as trees brought by a flood from upstream to downstream can be assumed to be driftwood, their latest growth time will indicate the time of the flood (i.e. the time that the tree died). A ^{14}C age peak in driftwood will therefore mark a single flood event, while age data from dead trees that grew on both sides of the river will be more discrete as a result of individual differences due to gradual deterioration of the regional hydrological environment.

The ancient river channels at these sampling sites are more than 100 m wide, and tree trunks have numerous cracks and there is some standing dead wood in places. We collected *P. euphratica* bark samples from three locations: site A (40°28′58.72″N, 89°52′41.25″E; Figure 2a) located in the upper reaches of the SR1, site B (89°59′9.14″E, 40°29′38.66″N; Figure 2b) located in the lower reaches of the SR1, and site C (89°54′39.44″E, 40°24′11.23″N; Figure 2c) located in the middle reaches of the SR2. We sampled and numbered a total of 30 *P. euphratica* specimens (Table 1) for this study.

Reed and Chinese tamarisk within Loulan yardang areas

The landform in Loulan is dominated by yardangs. The extension of the long axis of yardangs is about NE 30°, and most of yardangs is not large. These ridges comprise alternating layers of solid clay-silt and loose sand-silt (Lin et al., 2017; Qin et al., 2011). The presence of reeds growing on the surfaces of these yardangs implies that the top of each mound corresponds with the ancient ground surface and also that the environment at the time was suitable for reed growth. The ^{14}C ages recovered from these reeds suggest an earlier period of better hydrological conditions in the Loulan area because these are typically wet plant. We gathered and numbered a total of four reed samples from the top of yardangs for this study (Figure 3).

Chinese tamarisk (*Tamarix chinensis*) is one of the dominant plants in the Loulan area, and tamarisk dunes form as a result of wind-drifted sand blocked by these plants. In addition, because tamarisk cannot survive if the groundwater level falls below a certain depth (Xia et al., 2007), the latest growth age (^{14}C) recovered is indicative of critical water level decrease and thus the environmental degradation of the area. We collected and numbered a total of five Chinese tamarisk twig samples for this study (Figure 3).

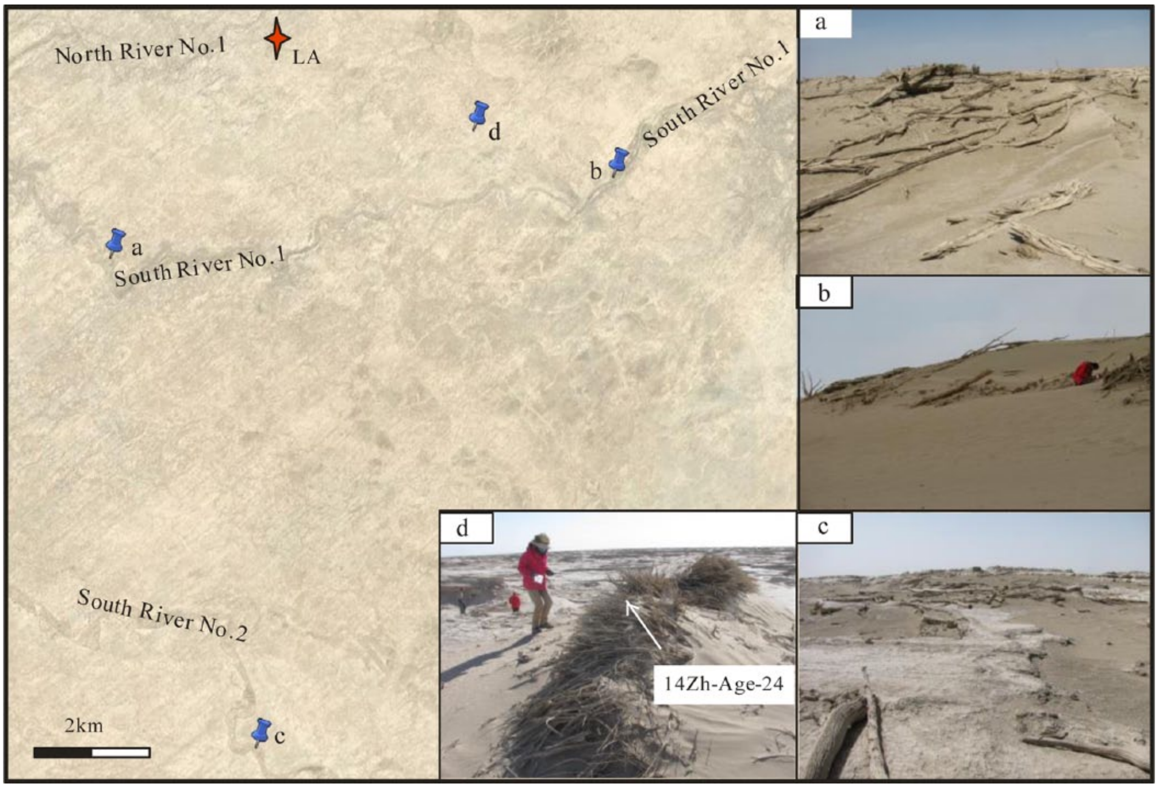

Figure 2. Location of *Populus euphratica* sampling sites and the ruin LD: (a) site A: the upper reaches of the South River No. 1 (SR1), (b) site B: the lower reaches of the South River No. 1 (SR1), and (c) site C: the middle reaches of the South River No. 2 (SR2). (d) The wall of LD was constructed using tamarisk. (Remote sensing image is from Google Earth, the same hereinafter.)

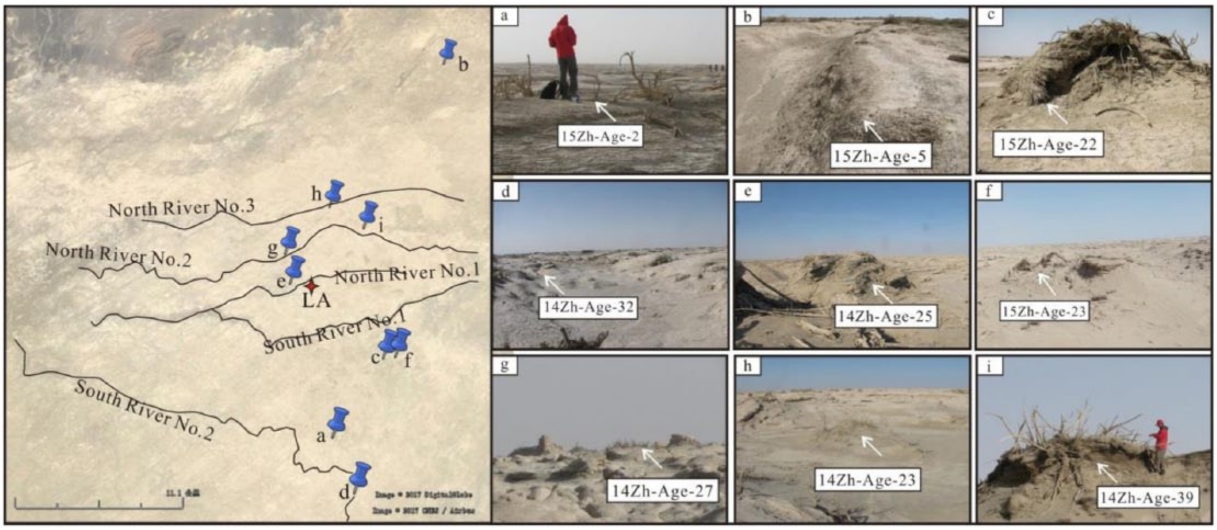

Figure 3. Location of sampling sites of reed and Chinese tamarisk, and the ancient river channels surrounding the ruin LA: (a–d) Reed samples and (e–i) Chinese tamarisk samples. Black lines indicate the ancient river channels.

Archeological sites

The archeological sites investigated in this study comprise two ancient house ruins and artificial canals. Although preservation is poor in all cases due to strong wind erosion, the remains of human activity are still apparent. We collected samples for chronological analysis from each site.

The first of the sites considered in this study was named as the Loulan southeast ruin and designated LD (89°57′23.43″E, 40°30′05.70″N; Figure 2d) (Stein, 1921) and consists of a ruin on a yardang platform approximately 4 km to the southeast (SE) of LA. The platform of this run is elevated 1 m above the surrounding area and is about 1 km to the south of the SR1. This site measures between 22 and 30 m in length and between 15 and 20 m in width and is characterized by the presence of pottery fragments scattered on the ground. The wall at the southern end of this ruin was 1 m high and 20 cm thick, comprising twigs of Chinese tamarisk. One sample was taken from the wall (14Zh-Age-24).

The second site was designated 14-JZ-1 (90°00′0.36″E, 40°34′14.16″N; Figure 4). This newly discovered ruin is located on a yardang platform that is 158 m long and between 31 and 48 m wide. This NE-extended platform is 5 m higher than the surrounding area, there are pottery fragments and slags on the ground, and a northwest (NW)-extended wall built of tamarisk twigs is located to the NE of this structure (Figure 4b). One sample was taken from the wall (14Zh-Age-18). There is a rectangular pit, between 1 and 1.5 m deep, located to the southwest of this

Table 1. ^{14}C ages and calibrated ages of all samples.

Lab code[a]	Field number	^{14}C age/BP	Calibrated age range and probability (2σ)[a]	Material	Location	Landscape
CN186	15Zh-Age-2	650 ± 30	(cal.AD 1343–1394) 0.5441; (cal.AD 1280–1325) 0.455	Reed	89°56′25.28″E 40°25′22.09″N	Beside tamarisk on the yardang platform
CN189	15Zh-Age-5	600 ± 25	(cal.AD 1298–1371) 0.755016; (cal.AD 1379–1407) 0.244984	Reed	90°02′46.18″E 40°41′54.07″N	On the bank of a ancient river
CN193	15Zh-Age-9	720 ± 25	(cal.AD 1257–1298) 0.993179; (cal.AD 1373–11376) 0.006821	*Populus euphratica* bark	89°59′9.14″E 40°29′38.66″N (site B)	In the channel of the SR1
CN194	15Zh-Age-10	340 ± 40	(cal.AD 1462–1642) 1.	*Populus euphratica* bark		
CN196	15Zh-Age-12	500 ± 30	(cal.AD 1398–1448) 0.99583; (cal.AD 1334–1336) 0.00417	*Populus euphratica* bark		
CN198	15Zh-Age-14	550 ± 25	(cal.AD 1389–1429) 0.616276; (cal.AD 1317–1354) 0.383724	*Populus euphratica* bark		
CN199	15Zh-Age-15	545 ± 30	(cal.AD 1388–1435) 0.633952; (cal.AD 1314–1356) 0.366048	*Populus euphratica* bark		
CN201	15Zh-Age-17	655 ± 20	(cal.AD 1355–1389) 0.536737; (cal.AD 1283–1316) 0.463263	*Populus euphratica* bark		
CN202	15Zh-Age-18	360 ± 30	(cal.AD 1451–1529) 0.50077; (cal.AD 1544–1634) 0.49923	*Populus euphratica* bark		
CN203	15Zh-Age-19	440 ± 40	(cal.AD 1410–1519) 0.93182; (cal.AD 1593-1619) 0.06818	*Populus euphratica* bark		
CN204	15Zh-Age-20	530 ± 25	(cal.AD 1393–1437) 0.869061; (cal.AD 1324–1345) 0.130939	*Populus euphratica* bark		
CN206	15Zh-Age-22	585 ± 25	(cal.AD 1303–1366) 0.700458; (cal.AD 1383–1412) 0.299542	Reed	89°59′02.40″E 40°28′21.57″N	A tamarisk dune on a yardang platform
CN207	15Zh-Age-23	580 ± 140	(cal.AD 1167–1642) 1.	Twig of Chinese tamarisk	89°59′36.09″E 40°28′23.39″N	A tamarisk on a yardang platform
CN208	15Zh-Age-24	670 ± 30	(cal.AD 1274–1319) 0.558974; (cal.AD 1351–1391) 0.441026	*Populus euphratica* bark	40°28′58.72″E 89°52′41.25″N (site A)	In the channel of the SR1
CN209	15Zh-Age-25	705 ± 30	(cal.AD 1260–1306) 0.858276; (cal.AD 1363–1385) 0.141724	*Populus euphratica* bark		
CN210	15Zh-Age-26	715 ± 25	(cal.AD 1260–AD 1298) 0.97724; (cal.AD 1371–1378) 0.02276	*Populus euphratica* bark		
CN211	15Zh-Age-27	695 ± 20	(cal.AD 1271–1300) 0.902355; (cal.AD 1368–1381) 0.097645	*Populus euphratica* bark		
CN212	15Zh-Age-28	680 ± 30	(cal.AD 1270–1316) 0.63501; (cal.AD 1354–1389) 0.36499	*Populus euphratica* bark		
CN213	15Zh-Age-29	360 ± 30	(cal.AD 1451–1529) 0.50077; (cal.AD 1544–1634) 0.49923	*Populus euphratica* bark		
CN214	15Zh-Age-30	625 ± 25	(cal.AD 1338–1397) 0.606706; (cal.AD 1291-1331) 0.393294	*Populus euphratica* bark		
CN215	15Zh-Age-31	500 ± 30	(cal.AD 1398–1448) 0.99583; (cal.AD 1334–1336) 0.00417	*Populus euphratica* bark		
CN216	15Zh-Age-32	490 ± 30	(cal.AD 1405-1449) 1.	*Populus euphratica* bark		
CN217	15Zh-Age-33	550 ± 110	(cal.AD 1258–1527) 0.927764; (cal.AD 1553–1633) 0.072236	*Populus euphratica* bark		

Table 1. (Continued)

Lab code[a]	Field number	^{14}C age/BP	Calibrated age range and probability (2σ)[a]	Material	Location	Landscape
CN218	15Zh-Age-38	670 ± 25	(cal.AD 1277–1315) 0.573035; (cal.AD 1356–1389) 0.426965	*Populus euphratica* bark	89°54′39.44″E 40°24′11.23″N (site C)	In the channel of the SR2
CN219	15Zh-Age-39	550 ± 25	(cal.AD 1389–1429) 0.616276; (cal.AD 1317–1354) 0.383724	*Populus euphratica* bark		
CN220	15Zh-Age-40	615 ± 25	(cal.AD 1296-1399) 1.	*Populus euphratica* bark		
CN221	15Zh-Age-41	650 ± 30	(cal.AD 1343–1394) 0.5441; (cal.AD 1280–1325) 0.4559	*Populus euphratica* bark		
CN223	15Zh-Age-43	630 ± 25	(cal.AD 1340–1397) 0.598662; (cal.AD 1288–1329) 0.401338	*Populus euphratica* bark		
CN224	15Zh-Age-44	510 ± 40	(cal.AD 1390–1450) 0.851468; (cal.AD 1318–1352) 0.148532	*Populus euphratica* bark		
CN225	15Zh-Age-45	680 ± 25	(cal.AD 1273–1311) 0.670154; (cal.AD 1359–1387) 0.329846	*Populus euphratica* bark		
CN226	15Zh-Age-46	595 ± 25	(cal.AD 1299–1369) 0.743178; (cal.AD 1380–1409) 0.256822	*Populus euphratica* bark		
CN227	15Zh-Age-47	595 ± 25	(cal.AD 1299-1369) 0.743178; (cal.AD 1380–1409) 0.256822	*Populus euphratica* bark		
CN228	15Zh-Age-48	595 ± 25	(cal.AD 1299–1369) 0.743178; (cal.AD 1380-1409) 0.256822	*Populus euphratica* bark		
CN229	15Zh-Age-49	650 ± 30	(cal.AD 1343–1394) 0.5441; (cal.AD 1280–1325) 0.4559	*Populus euphratica* bark		
CN273	14Zh-Age-23	375 ± 20	(cal.AD 1449–1521) 0.705578; (cal.AD 1575–1624) 0.294422	Twig of Chinese tamarisk	89°55′58.90″E 40°34′48.35″N	A tamarisk dune within NR3 river channel
CN275	14Zh-Age-25	440 ± 25	(cal.AD 1423–1477) 1.	Twig of Chinese tamarisk	89°57′30.29″E 40°23′23.96″N	A tamarisk dune on the bank of a river
CN277	14Zh-Age-27	625 ± 20	(cal.AD 1341–1396) 0.608678; (cal.AD 1292–1328) 0.391322	Twig of Chinese tamarisk	89°52′59.65″E 40°32′35.32″N	A tamarisk around a beacon tower
CN282	14Zh-Age-32	555 ± 20	(cal.AD 1390–1423) 0.588499; (cal.AD 1318–1351) 0.411501	Reed	89°54′2.12″E 40°31′25.66″N	On a yardang platform in the north-west of the LA
CN268	14Zh-Age-18	470 ± 30	(cal.AD 1410–1456) 1.	Twig of Chinese tamarisk from wall	90°00′0.36″E 40°34′14.16″N	A newly discovered ancient ruin (14-JZ-1) on a yardang platform
CN274	14Zh-Age-24	580 ± 25	(cal.AD 1305–1364) 0.675015; (cal.AD 1384–1414) 0.324985	Twig of Chinese tamarisk from wall	89°57′23.43″E 40°30′05.70″N	A ruin on a yardang platform in the southeast of the LA
CN267	14Zh-Age-17	560 ± 35	(cal.AD 1304–1365) 0.531711; (cal.AD 1384–1431) 0.468289	Reed	89°56′06.8″E 40°34′50.7″N	A reed layer covered by the artificial piled bank of a canal
CN286	14Zh-Age-36	585 ± 20	(cal.AD 1307–1363) 0.710805; (cal.AD 1385-1410) 0.289195	Reed	89°57′51.08″E 40°33′49.50″N	A reed layer covered by the artificial piled bank of a canal
CN288	14Zh-Age-38	420 ± 40	(cal.AD 1420-1523) 0.822733; (cal.AD 1572–1630) 0.177267	Charcoal	89°57′52.76″E 40°33′52.56″N	In the artificial piled bank of a canal
CN289	14Zh-Age-39	570 ± 25	(cal.AD 1309–1361) 0.603608; (cal.AD 1386–1419) 0.396392	Twig of Chinese tamarisk	89°57′53.87″ E 40°33′48.77″N	A tamarisk dune near a canal

[a]CN: Laboratory code of the Cosmogenic Nuclide Chronology Lab, Institute of Geology and Geophysics, Chinese Academy of Science. Ages were calibrated with Calib Rev 7.0.4.

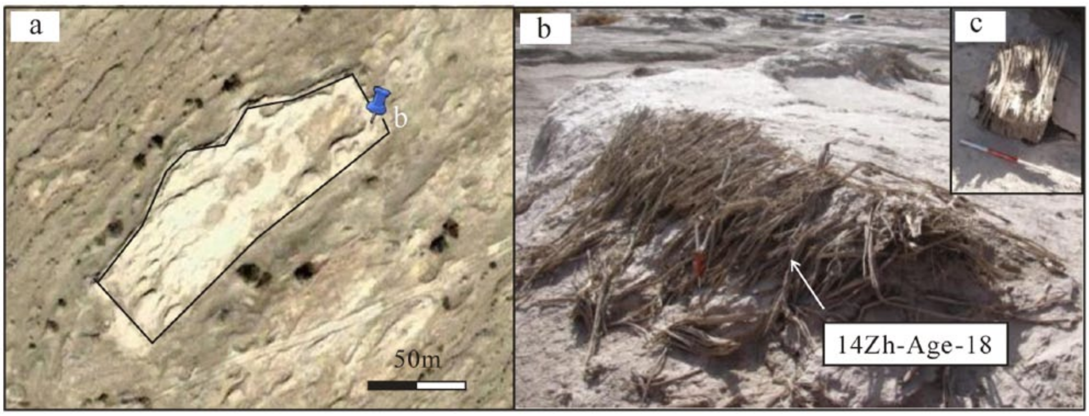

Figure 4. Newly discovered ancient ruin (14-JZ-1): (a) remote sensing map of the ruin, (b) sampling site of the wall constructed using Chinese tamarisk, and (c) Wooden foundation.

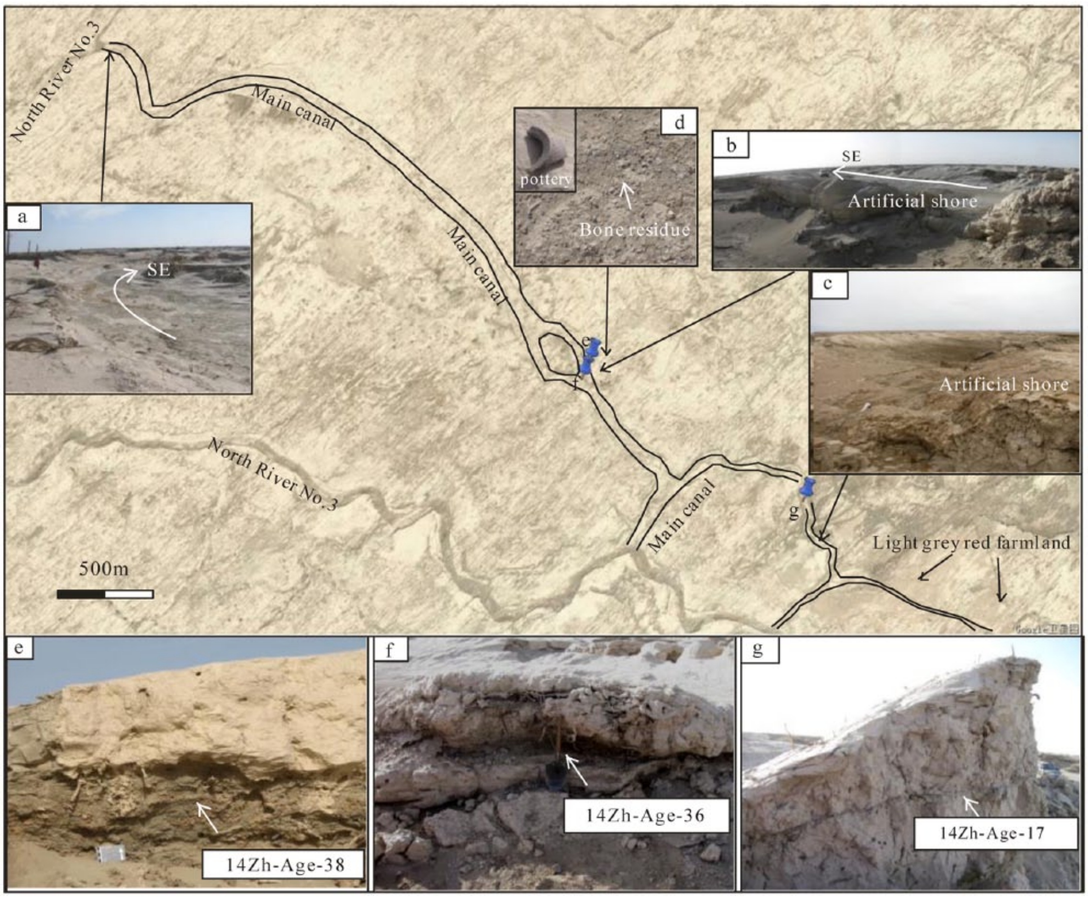

Figure 5. Features of newly discovered canal and location of sampling sites: (a–c) features of canal in field, (d) pottery and bone residues near canal, (e) charcoal sample, and (f, g) reed samples.

wall. The discovery of a wooden foundation in the pit (Figure 4c) suggests that this ruin was probably an ancient semi-subterranean dwelling.

The third site considered in this study was newly discovered artificial canals (89°56′06.8″E, 40°34′50.7″N) that linked with the NR3 and the NR2 to enable NW-to-SE diversion of water. Field observations reveal that most of the main canals in this region are relatively smooth and straight, have a bed that comprises a clay layer, and are artificial banks that appear distinctive compared with the water-eroded banks of natural rivers. These main canals also have channel beds with arc-shaped cross-sections; the clay layer thicknesses of these arc-shaped artificial banks increase from the middle of the canal outward (Figure 5b, c and g), in marked contrast to those of the nearby natural rivers, and layered reeds covered by clay are artificially piled on the bank. Two samples were taken from this reed layer (14Zh-Age-17, Figure 5 g; 14Zh-Age-36, Figure 5f), as well as one charcoal specimen from the reddish brecciform sintered-clay in the artificial bank (14Zh-Age-38, Figure 5e). Pottery fragments, bone residuals, slags, and stone tools are scattered on and around the canal bed surface (Figure 5d), suggesting that there may be an ancient settlement here.

Chronology analysis

A total of 44 systematically collected samples from the Loulan area were dated using accelerator mass spectrometry (AMS) ^{14}C to reliably determine their ages. All the samples were initially

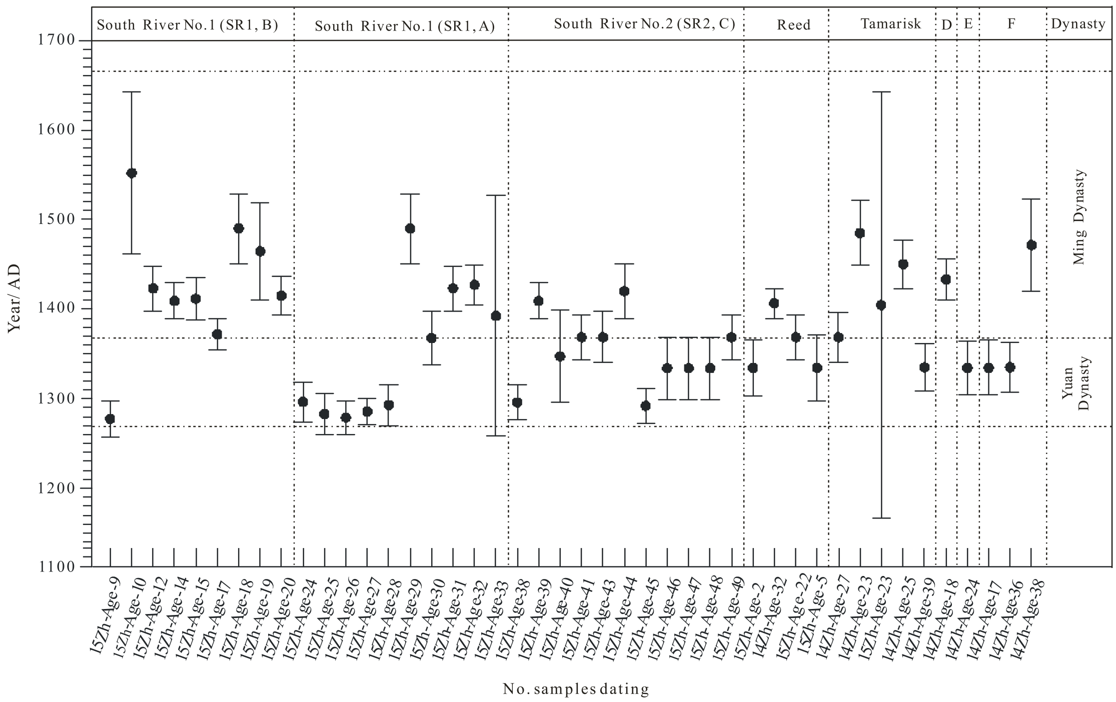

Figure 6. The ^{14}C ages and historical chronology of all samples. (D: 14-JZ-1; E: LD; F: canal. Solid circles are the calibrated ages of median probability, and the length of the error bar represents the range of calibrated age (the same hereinafter).)

washed with tap water to eliminate any soil and extraneous contamination and then again with ultrapure water; samples were then successively treated with 1% HCl for 1 h to remove carbonates and then for the same time with 1% NaOH, followed by a hot solution of 0.5% HCl for 30 min at 80°C to remove humic acids. Following rinsing with deionized water, samples were then dried overnight in an oven at 105°C before being combusted with CuO to produce CO_2 at 850°C for 3 h under vacuum conditions. Resultant CO_2 was then reduced to graphite at 525°C for 6 h using Zn and Fe as catalysts (Getachew et al., 2016; Xu et al., 2017). All pretreatment and graphite synthesis was performed in the Cosmogenic Nuclide Chronology Lab at the Institute of Geology and Geophysics, Chinese Academy of Science, while AMS ^{14} C measurements were performed in the Key Laboratory of Heavy Ion Physics, Peking University. Resultant ^{14} C dates were calibrated using the software Calib Rev 7.0.4, and 2σ calibration ages are presented in Table 1.

Results

All the AMS ^{14} C dating results and calibrated ages generated in this study are presented in Table 1. Results show good consistency between natural plant remains and archeological sites, corresponding with the Yuan Dynasty (AD 1271–1368) and Ming Dynasty (AD 1368–1644) (Figure 6).

Measured ages from the sample collected from the upper reaches of SR1 span the range between 1270 and 1500 cal. AD and are thus mostly distributed within the Yuan Dynasty. However, one sample (15Zh-Age-9) from the lower reaches of the SR1 was dated in this study to 1257–1298 cal. AD and so is consistent with the Yuan Dynasty, while all other measured dates are consistent in age with the early Ming Dynasty. In addition, samples from the middle reaches of the SR2 and reed samples from yardangs within the Loulan area are consistent with the late Yuan Dynasty and Ming Dynasty. It is noteworthy that the age of one Chinese tamarisk twig (15Zh-Age-23) falls 1167–1642 cal. AD, encompassing a very long time span, while two twig samples, 14Zh-Age-39 and 14Zh-Age-27, are consistent with the Yuan Dynasty and others, 14Zh-Age-23 and 14Zh-Age-25, correspond with the Ming Dynasty.

The ages of the layered reed in canal banks we measured fell 1304–1365 cal. AD (14Zh-Age-17) and 1307–1363 cal. AD (14Zh-Age-36), consistent with the Yuan Dynasty. In contrast, the age of the charcoal sample recovered from reddish sintered-clay breccia was 1420–1523 cal. AD (14Zh-Age-38), consistent with the early Ming Dynasty and slightly younger than the reeds.

The Chinese tamarisk twig samples from the LD site as well as the newly discovered ancient house (14-JZ-1) were dated to 1305–1364 cal. AD and 1410–1456 cal. AD, consistent with the late Yuan Dynasty and the early Ming Dynasty, respectively.

Finally, we calculated the statistical frequency of *P. euphratica* ages from bark samples collected from ancient river channels at an interval of 25 years. The majority of ^{14} C dating error across this 25-year time span (Table 1) suggests that these ages fall within the same interval and so all trees were dead at roughly the same time. Results reveal the presence of three peaks between 1260 and 1450 cal. AD, and then relatively discrete statistics are obtained after 1450–1550 cal. AD (Figure 7).

Discussion

Hydrological changes

Historical literature records that the Lop Nur region was recharged by the ancient Tarim River as well as a tributary called the Kongque River (Sima, 1959 [91 BC]; Ban, 1962 [92]). As the Loulan region falls within the lower reaches of the ancient Tarim River, an abundance of surface water has proved the decisive factor in sustaining the development of oasis.

The statistically significant frequency peak identified in the ages of *P. euphratica* bark in this study indicates a concentrated time of death, corresponding with our driftwood samples. Results reveal the presence of three age peaks between 1260 and 1450 cal. AD, which implies that the Loulan area experienced at least three flood events over this period and that perhaps C2 lasted longer than the others (Figure 7). These differences in the intensity of flood events lead to differences in the time of death of plant between A, B, and C (Figure 6). Specifically, results show that our reed and tamarisk samples appear to be dated to the end of flood events, indicating low groundwater level during intermittent

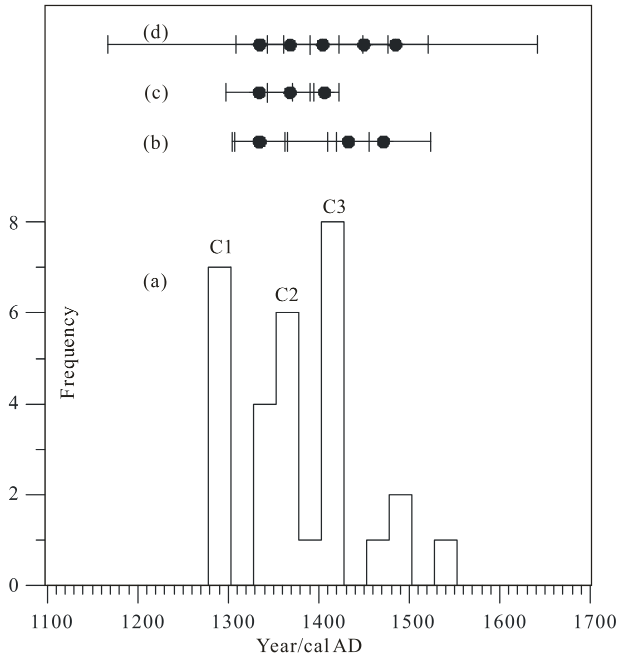

Figure 7. The age distribution of all samples: (a) pulse-like statistic frequency of *Populus euphratica* samples' age. C*n* (*n* = 1, 2, and 3) indicates ancient flood event, (b) ages of archeological sites, (c) ages of reeds, and (d) ages of Chinese tamarisks.

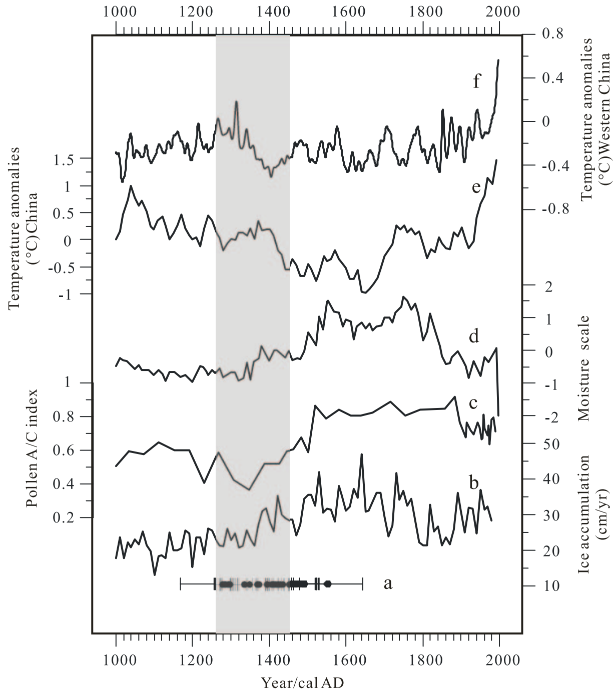

Figure 8. Correlation between ages of all samples and regional climatic records: (a) the ^{14}C ages in this paper, (b) ice accumulation of Guliya ice core (Thompson et al., 1995; Yao et al., 1996), (c) *Artemisia/Chenopodiaceae* (A/C) pollen ratio of the Bosten Lake (Chen et al., 2006), (d) moisture scale of the Central Asia (Chen et al., 2010), (e) reconstruction of Chinese temperature anomalies (Yang et al., 2002), and (f) reconstruction of western Chinese temperature anomalies (Shi et al., 2012). Grey vertical bar denotes the range between 1260 and 1450 cal. AD. Paleoclimatic data download from https://www.ncdc.noaa.gov/data-access/paleoclimatology-data.

periods. We therefore conclude that the Loulan area experienced multiple wet (water resource abundance) and dry (water resource shortages) cycles between 1260 and 1450 cal. AD.

The ages of the two ancient houses sampled in this study are consistent with the Yuan Dynasty and Ming Dynasty and corroborate human activity at this time. Reed layers may have been found on the artificial shoreline because the people who lived in the Loulan area at this time dredged the canal during periods of flooding and placed sediments directly onto growing reeds. The presence of reddish sintered-clay breccia in the artificial bank can also be interpreted as evidence that the Loulan area population at this time maintained the canal after flooding events; given the occurrence of these events, the age difference between the reed layer and the charcoal suggests that this repair work took place between 1260 and 1450 cal. AD and also reflects the fact that humans possess only a limited ability to adapt to pulse-like hydrological changes in arid areas. It is therefore important to understand the contemporary relationship between human activity and the distribution of pulse-like natural water resources in arid areas if we are to avoid irreparable errors due to the uneven deployment of water and its current overuse.

Regional paleoenvironmental patterns

The 'Medieval Warm Period' (MWP), which lasted from AD 1000 to 1300, and the Little Ice Age (LIA), which lasted between 1400 and 1900 cal. AD, were two key climatic events that occurred over the last 2000 years (Ruddiman, 2008). It is also noteworthy that the period between 1260 and 1450 cal. AD was the transitional phase between the MWP and the LIA. Because the Lop Nur region is surrounded by actively uplifted mountains such as the Kunlun–Altun Mountains and the Tianshan Mountains, the climate of this area is now predominately under the influence of westerlies (Qin et al., 2011; Xia et al., 2007). This region developed into one of the core arid areas of Eurasia from at least the beginning of the Quaternary (Zhu et al., 1981), and concomitant hydrological changes have depended entirely on meltwater from glaciers and snow, as well as on orographic rainfall (Xia et al., 2007; Zhang et al., 2003).

A decadal-level resolution curve synthesized from lakes, ice cores, and other paleoclimatic records in Central Asia over the past millennium indicates that moisture levels increased between 1260 and 1450 cal. AD (Chen et al., 2010). At the same time, Lake Bosten, the source of the Kongque River, is one of the major tributaries of the ancient Tarim River, and the *Artemisia/Chenopodiaceae* (A/C) pollen ratio appears to be increasing (Chen et al., 2006), indicative of increasing humidity within the basin catchment. This increase in regional humidity may be the result of either increased precipitation or reduced evaporation (Figure 8).

The Kunlun Mountain range is also an important water source area for the Tarim River – in this region, the Guliya ice core (GIC) of particular significance as evidenced by high-resolution climate records from this area. Ice accumulation within the GIC can be utilized as an effective proxy for Central Asian precipitation changes (Thompson et al., 1995; Yang et al., 2009; Yao et al., 1996); the data show an increase in ice accumulation between 1260 and 1450 cal. AD, which in turn implies an increase in precipitation within the Kunlun Mountain range.

Temperature reconstructions for China based on historical records, tree rings, and ice core data reveal a decrease in warmth between 1260 and 1450 cal. AD (Shi et al., 2012; Yang et al., 2002). Notably, temperature generally declined during the transition stage from the MWP to the LIA, which may have also resulted in decreases in regional evaporation.

The dominant climatic factors that influence the Loulan area are orographic precipitation (i.e. inputs of water) and temperature (i.e. loss of water to evaporation). Records show that an ecological oasis characterized by plentiful runoff and groundwater appeared in the Loulan area between 1260 and 1450 cal. AD

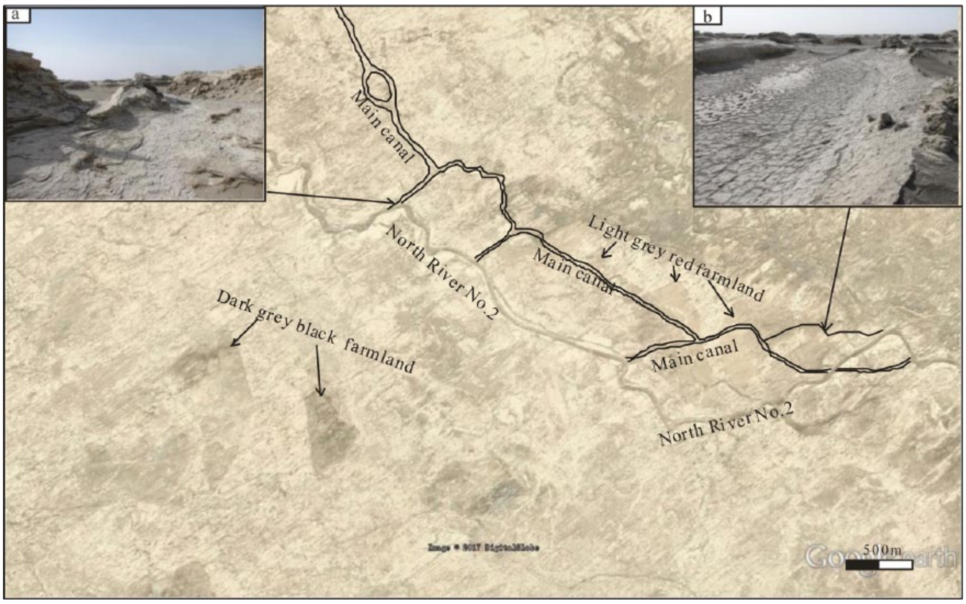

Figure 9. The remotely sensed features of the eastern part of the canal and farmland: (a) the entrance of a canal and (b) canal.

because of increasing precipitation and meltwater and decreasing evaporation within the region.

Human activities

There are numerous archeological sites within the Loulan area, but most are dated to within the period encompassed by the Han–Jin Dynasties (206 BC to AD 420) (Xia et al., 2007). It is noteworthy that the human activity evidencing the Yuan Dynasty and Ming Dynasty was, however, the first to be discovered in this region, although these populations are not recorded in the Chinese historical literature.

Some scholars have argued that the LD site can be dated to the Han–Jin Dynasties based on the presence of cultural relics found on the ground (Xinjiang Uygur Autonomous Region Bureau of Cultural Heritage, 2015). The results of this study suggest that the age of the LD is between 1305 and 1364 cal. AD, coincident with the middle Yuan Dynasty and implying the presence of humans in the Loulan area and that the population utilized Chinese tamarisk to construct a wall. The newly discovered ancient human house (14-JZ-1) and canal discussed in this paper are located to the NE of LA, indicating that the population of the Yuan–Ming Dynasties built canals to divert water from rivers. The presence of a reddish brecciform sintered-clay in the artificial canal bank corroborates this and provides direct evidence for human activity at this time.

Paper documents and wooden tablets unearthed from LA also record information about artificial canals (Xia et al., 2007) and indicate that the construction of these structures had been very popular in the area since the Han Dynasty. The newly discovered artificial canals might be built following the routes of earlier waterways (Figures 5 and 9). High-spatial-resolution Google Earth satellite images show light gray red farmlands with regular and straight boundaries in the eastern canal section in contrast to dark gray black farmlands of Loulan Kingdom (Qin et al., 2011) (Figure 9). These color differences suggest that the time of cultivation of these farmlands was later within the Han–Jin Dynasties (i.e. the time of the Loulan Kingdom). Canals always pass near to, or cross through, these farmlands, suggesting that water utilization was important (Figure 9). Existing spatial relationships between canals and farmland further suggest that these likely formed simultaneously during the Yuan–Ming Dynasties before development of the latest yardangs. Remotely sensed images also reveal that the total area of light gray red farmland is at least 120 ha, also indicative of the presence of a certain-sized population in the area at this time. However, the scale of farmland recognized in this study is much smaller than that of the Loulan Kingdom (Qin et al., 2011), with light gray red areas mainly concentrated to the NE of LA. We speculate that the several branch canals which could divert water from the NR2 and the NR3 (Figures 5 and 9) were designed to facilitate irrigation for agricultural development. The prosperity of this ancient oases civilization in Xinjiang region was intimately connected with the natural environment (Qin et al., 2011; Xu et al., 2017; Zhang et al., 2012); thus, habitable hydrological conditions resulting from climate change was likely one major reason for the re-emergence of human activities in the Loulan area during the Yuan–Ming Dynasties.

The ancient people who lived during the time encompassed by the Yuan–Ming Dynasties in the Loulan area practiced cultivation and irrigation, typical economic activities characteristic of central China. The sheer scale of the farmlands and canal systems present in this area suggests that they were developed and built by organized armies or landlords rather than by individual families. The characteristics imply that the people may be related to central China. Any tomb or indicative archeological relic of Yuan Dynasty or Ming Dynasty was not found during our field investigations, however, and the question of whether, or not, these people originated in central China or are from the western region of the country requires additional research.

Conclusion

1. The Loulan area was characterized by an effective hydrological environment that featured wet (water resources abundant) and dry (shortage of water resources) pulse-like climate-led hydrological events due to at least three flood events between 1260 and 1450 cal. AD. Throughout this period, the Loulan area was characterized by oasis vegetation.
2. The ruins of the Yuan–Ming Dynasties discussed in this paper imply that ancient people not only lived in this region after extinction of the Loulan Kingdom but they also built canals to irrigate their farmlands. The human activities were first discovered during an attempt to complete a gap in the Chinese historical literature about human activities in the Loulan area during the Yuan–Ming Dynasties.

3. Hydrological conditions more conducive to human settlement that resulted from natural climate change may be the major reason explaining the re-emergence of human activities in the Loulan area during the Yuan–Ming Dynasties. Humans, however, possess only a certain ability to adapt pulse-like hydrological changes in arid areas. It is important to characterize these historical changes to better understand the contemporary relationship between human activity and pulse-like natural water resources in arid area.

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