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Moisture Changes in the Northern Xinjiang Basin Over the Past 2400 years as Documented in Pollen Records of Jili Lake

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Regional humidity is important for terrestrial ecosystem development, while it differs from region to region in inland Asia, knowledge of past moisture changes in the lower basin of northern Xinjiang remainly largely unclear. Based on a pollen record from Jili Lake, the *Artemisia*/(Amaranthaceae + *Ephedra*) (Ar/(Am + E)) ratio, as an index of regional humidity, has recorded four relatively dry phases: 1) 400 BCE to 1 CE, 2) the Roman Warm Period (RWP; c. 1–400 CE), 3) the Medieval Warm Period (MWP; c. 850–1200 CE) and 4) the Current Warm Period (CWP; since 1850 CE). In contrast, the Dark Age Cold Period (DACP; c. 400–850 CE) and the Little Ice Age (LIA; c. 1200–1850 CE) were relatively wet. Lower lake levels in a relatively humid climate background indicated by higher aquatic pollen (*Typha* and *Sparganium*) after c. 1700 CE are likely the result of intensified irrigation for agriculture in the catchment as documented in historical records. The pollen Ar/(Am + E) ratio also recorded a millennial-scale wetting trend from 1 CE to 1550 CE which is concomitant with a long-term cooling recorded in the Northern Hemisphere.

Keywords: moisture change, pollen records, the historical period, climate change, arid central asia

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INTRODUCTION

During the Holocene, the "westerlies-dominated climatic regime" (WDCR) is characterized by warm-dry and cold-wet phases in inland Asia on different timescales (Chen et al., 2016; Chen et al., 2019). On millennial timescales, the moisture in the WDCR gradually increased, with the wettest period occurring in the late Holocene, while in arid central Asia (ACA), the wettest phase occurred in the mid-to late Holocene (Chen et al., 2016; Chen et al., 2019). At centennial timescales, the WDCR was generally dry during the Medieval Warm Period (WMP) and relatively wet during the Little Ice Age (LIA), but there were some exceptions in Xinjiang (Chen J. et al., 2015), an important part of the WDCR. It has been suggested that the moisture balance has changed from warm-dry to warm-wet over the last few decades (Shi et al., 2006; Wang et al., 2007). Paleoclimate records from the region that span the late Holocene are mostly located at high altitudes (Huang et al., 2018; Lan et al., 2018; Yang et al., 2019); the lack of paleoclimatic records from low altitude areas, where most people are living, hampers understanding of regional climate change both in the past and into the future.

Recent global warming has resulted in the expansion of drylands around the world, and seriously threatens freshwater resources (Huang et al., 2015; Fan et al., 2020). Many studies suggest a major

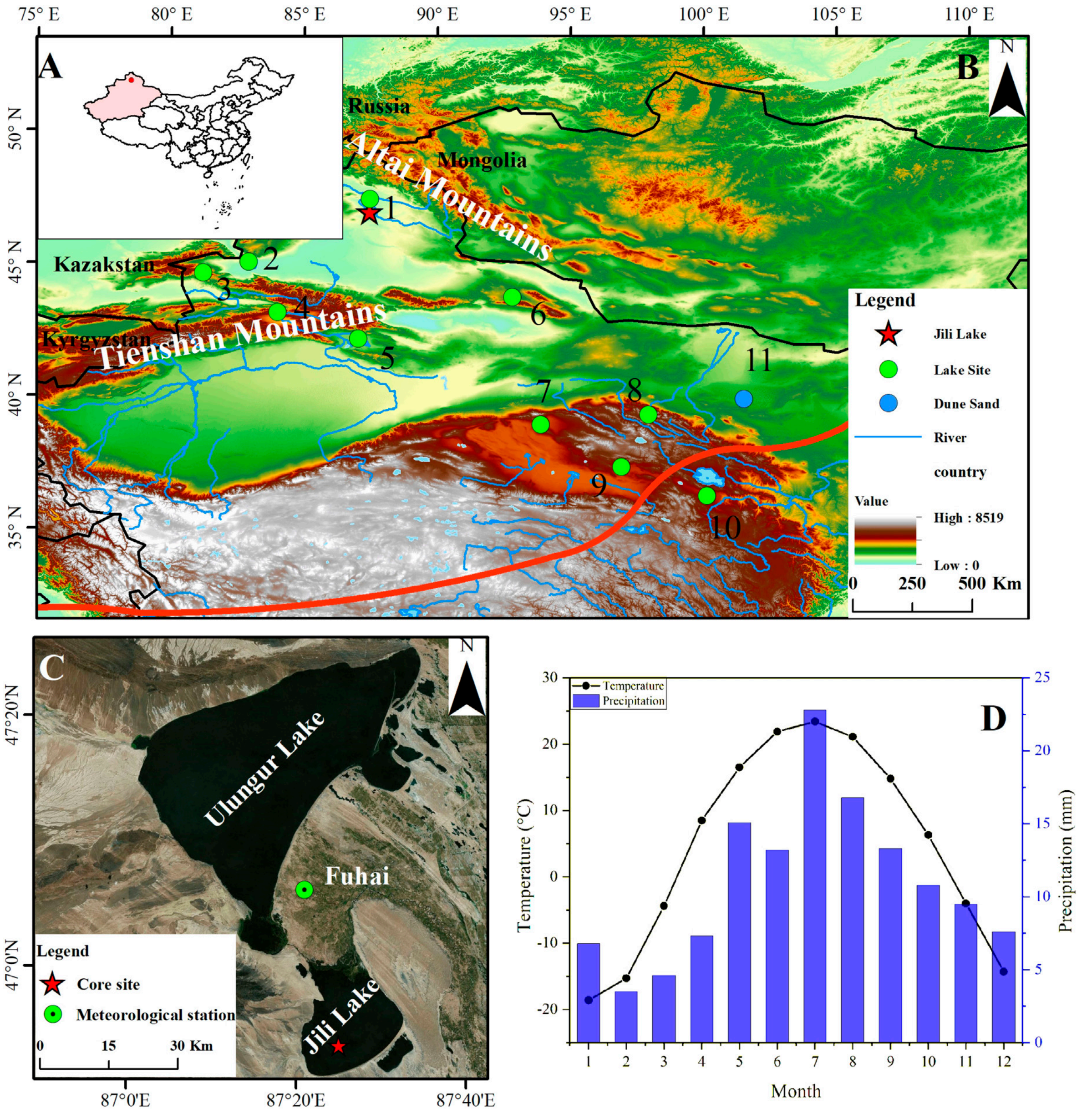

FIGURE 1 | Environmental setting of Jili Lake. **(A)** The study area; **(B)** Location of Jili Lake and other lake sites mentioned in this study: 1 Ulungur Lake; 2 Ebinur Lake; 3 Sayram Lake; 4 Harnur Lake; 5 Bosten Lake; 6 Balikun Lake; 7 Sugan Lake; 8 Tian'E Lake; 9 Hurleg Lake; 10 Genggahai Lake; and 11 BYBS profile. The orange line is the modern limit of the Summer Monsoon (Chen et al., 2008). **(C)** Google Earth image of Jili Lake and Ulungur Lake area, and **(D)** Monthly temperature and precipitation from Fuhai meteorological station (elevation 500 m a.s.l.) for the years 1981–2010 CE.

impact of climate change on regional human activities, with evidence that climate change plays an important role in the abandonment of cities (e.g., Bhattacharya et al., 2015; An et al., 2017; Yao Y.-F. et al., 2020; Jenny et al., 2020). In the Xinjiang area, early cultivation of crops began around 3000 BCE (Li Y., 2020), and an increase in population started at c. 2000 BCE. There is evidence for a widespread prehistoric culture in Xinjiang area, associated with a relatively wetter climate during the late Holocene (An et al., 2019). However, abrupt climate and environment changes might have led to the collapse of some civilizations, such as Xiaohe Culture (Zhang et al., 2017) and Loulan civilization (Fontana et al., 2019; Hao et al., 2019). A diatom record from Bosten Lake indicated that changes in hydro-climate was the main reason for the collapse of the Loulan Kingdom (Fontana et al., 2019). The record of RIK_{37} index from Sayram Lake suggested that humid conditions might have been conducive to the spread of the Mongol Empire across the ACA area during 1206–1260 CE (Yao Y.

et al., 2020). Pollen records from Tian'E Lake in the Qilian Mountains suggested that continuous droughts were an important driving force of the abandonment of several archaeological sites and ancient cities along the Silk Road (Zhang J. et al., 2018). However, there are few humid records from the Northern Xinjiang area that span the last 2,000 years, which can be used to understand the relationship between human activities and climate change.

Lake sediments are an excellent archive of past climate change (Birks et al., 2012), and pollen analysis from lacustrine sediments can help to understand the regional climatic changes through time (Bartlein et al., 1986; Wen et al., 2010). Changes in the relative abundance of fossil pollen preserved in lake sediment archives reflect changes in vegetation in response to various driving force (e.g., precipitation, temperature, human impact), and pollen assemblages from lakes with a larger catchment reflect regional, not just local, changes in climate and vegetation (Sugita, 1994; Nielsen and Sugita, 2005; Xu et al., 2016). Here, we present the results of pollen analysis from Jili Lake (174.0 km^2) located in the northern Xinjiang area to infer the history of climate and vegetation change over the last c. 2400 years. By combining these data with other evidence, for example, charcoal and historical documents (e.g., regional population and cultivation history), we explore the relationship between environment and human activities in this study area.

STUDY AREA

Jili lake (46°51′–47°00′ N, 87°20′–87°32′ E, 483 m a.s.l.) is a large and shallow lake in the inland area of the Eurasian continent, located in the Junggar Basin between the Tianshan Mountains and the Altai Mountains (**Figures 1A**, **B**). The study area sits within a mid-latitude temperate continental climate. As recorded at the nearby Fuhai meteorological station (47°06′ N, 87°21′ E, **Figure 1C**), the mean annual temperature in the region is 4.7°C and the average annual precipitation is 131 mm (**Figure 1D**). Jili Lake receives water mainly from the Ulungur River from the Altai Mountains to the north, and it outflows to Ulungur Lake (**Figures 1B,C**). In 2015, the lake covered a surface area of c. 170 km^2, and had an average depth of c. 10 m (Wang and Dou, 1998; Liu et al., 2018).

In recent decades the surface area of Jili Lake has expanded, and its main water supply comes from the Ulungur river; the water level in Jili Lake has been affected by dam construction and intensified water exploitation (Li et al., 2015; Cheng et al., 2016). Desert vegetation in the vicinity of Jili Lake comprises mostly Amaranthaceae, but the northern part of the catchment mainly has many shrub-coppice covered dunes. The Gobi Desert area lies to the west, and a shrub-coppice dune chain to the south (Lang, 2020). In the Jili Lake area, Amaranthaceae and *Artemisia* accounted for more than 60% of the surface pollen sum, except for *Ephedra*, *Tamarix*, *Jujube*, *Nitraria*, Poaceae and *Allium* (Yan and Xu, 1989). The aquatic plants mainly consist of *Phragmites*, *Myriophyllum spicatum* and *Potamogeton pectinatus*, which are distributed in shallow water areas along the lake shore (Wang et al., 1981; Wang and Dou, 1998).

MATERIALS AND METHODS

Core Sampling and Age-Depth Model

In February 2018 a sediment core, 253 cm in length (JL18-02-A), was collected from the southwestern area of Jili Lake using a Piston corer. The core was frozen and transported to Lanzhou University, sampled at a 1-cm intervals, and freeze-dried. The lithology of the c. 120 cm of the core can be divided into three intervals: 0–6 cm - cyan mud with loose sediments; 6–34 cm - the color of sediments is brown; 34–123 cm - pale silty clay with relatively compact sediments.

We focused on the upper 120 cm of the core because there was a hiatus in the sediment below this depth based on 7 radiocarbon dates (Lang, 2020). For the age-depth model of the upper 120 cm, three bulk organic samples from the core were processed for accelerator mass spectrometry (AMS) radiocarbon dating at the Beta Analytic Radiocarbon Dating Laboratory in Miami, Florida, United States (**Table 1**) (Lang, 2020). The ^{14}C specific activity values of the lake-water DIC sample and the samples from the upper most layers of cores largely approximate to the pMC (percent modern carbon) values of the modern atmosphere (105.4 ± 1.0 pMC in 2007; Fellner and Rechberger, 2009), indicating that the CO_2 exchange between the lake and atmosphere tends to be balanced, reflecting that the "reservoir effect" of the lake water is low. The age-depth model for Jili Lake (**Figure 2**) was calculated using "Clam" version 2.2 (Blaauw, 2010) and the IntCal13 calibration curve (Reimer et al., 2013). The core depth-chronology has a linear relationship and it provides a record of sediment deposition over the last 2400 years.

Pollen and Charcoal Analyses

A total of 96 samples were taken from the core for pollen analysis. Pollen grains were extracted from 1–3 g of dried sample, and preparation used HCl (10%) and HF (40%) to remove carbonates and silicates (Fægri and Iversen, 1989). Samples were sieved through a 10-μm mesh to remove small clay-sized particles, and clean samples were mounted in glycerin on glass slides. Pollen grains and charcoal particles were identified and counted using a Nikon ECLIPSE 80i optical microscope at ×400 magnification. More than 500 pollen grains and 300 charcoal particles were counted for each sample, and charcoal particles were grouped by long axis length: >100, 50–100, and <50 μm. To calculate pollen and charcoal concentration, one *Lycopodium* tablet (27,637 grains) was added to each sample prior to chemical pre-treatment (Maher, 1981). The percentages of pollen were calculated based on the sum of all counted terrestrial pollen grains, and the aquatic pollen percentages were calculated based on the sum of all counted pollen grains. The pollen diagrams were plotted using Tilia software (Grimm, 2011), and the pollen zones were divided by stratigraphically constrained cluster analysis using CONISS (Grimm, 1987).

TABLE 1 | Results of AMC ^{14}C dating of core JL18-02-A.

Samples No.	Beta No.	Depth (cm)	Material	δ^{13}C (‰)	^{14}C age (yr BP)	Calendar age (cal. yr BP, 2σ)
JL18-02A1-001	503015	1.24	BOM	−27.7	101.63 ± 0.38 pMC	-
JL18-02A1-048	503016	59.43	BOM	−24.2	1050 ± 30 BP	1050–924
JL18-02A1-096	515954	118.86	BOM	−25.3	2350 ± 30 BP	2464–2324
JL18-07 (20 cm)	509850	—	DIC	—	93.5 ± 0.30 pMC	-

Note: BOM, Bulk organic matter; DIC, Dissolved inorganic carbon.

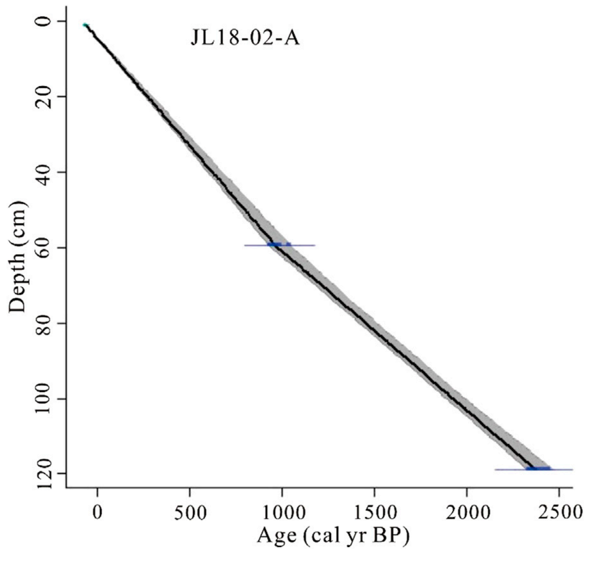

FIGURE 2 | Clam age-depth model for core JL18-02-A from Jili Lake.

Indicators of Climatic Humidity and Human Activities

Based on the investigations of modern surface pollen in northern Xinjiang, it has shown that *Artemisia* and Amaranthaceae (old name is Chenopodiaceae) (APG, 1998), are dominant species in desert-steppe and desert areas (Yu et al., 1998; Luo et al., 2009; Li et al., 2017). A lot of modern pollen investigations have shown that the *Artemisia* and Chenopodiaceae ratio (A/C ratio) is a valid indicator/proxy of humidity in desert and desert-steppe areas (e.g., El-Moslimany, 1990; Sun et al., 1994; Huang et al., 2009; Zhao et al., 2009; Li et al., 2010; Zhao et al., 2012; Zhang D. et al., 2018). As *Ephedra* is also one of the main taxa in desert areas like Amaranthaceae (Huang et al., 2009; Huang et al., 2018), here we use the sum of Amaranthaceae and *Ephedra* (Am + E) to indicate a relatively dry condition, and use the ratio of *Artemisia* (Ar) and (Am + E) as a new indicator of climatic humidity like A/C ratio.

The signal of regional human activity can be indicated by some specific pollen types and charcoal abundance. For example, Poaceae pollen grains among the 35–50 μm size range were considered to be cereal-type Poaceae (mostly might be wheat pollen), which can be used as an indicator of agricultural activity (Li et al., 2008; Li et al., 2012). Charcoal is a particularly useful proxy for recording the disturbance of vegetation by humans, in which macro-charcoal (>100 μm) could indicate changes in local fire occurrence in the past (Whitlock and Larsen, 2001; Li et al., 2008).

RESULTS

A total of 62 pollen taxa and spore types were identified and 53477 pollen grains were counted, with an average of 557 pollen grains per sample. The main herbaceous taxa were *Artemisia*, Amaranthaceae, Poaceae and Asteraceae. Across the three zones as identified by CONISS, the percentages of *Artemisia* and Amaranthaceae exceeded 80% of the terrestrial pollen sum. The arboreal taxa with lower percentages were mainly *Betula* and *Pinus*. The percentage abundance of fern spores was very low, and aquatic pollen types were mainly *Sparganium* and *Typha*. The assemblage characteristics of each pollen zone are briefly described as follows (**Figure 3**).

Zone Ⅰ (119–87 cm, c. 380 BCE-400 CE)

The major pollen types included Asteraceae (0.2–3.6%, mean 2.3%), *Ephedra* (0.6–3.09%, mean 2%), Polygonaceae (0.2–3.6%, mean 2.74%), Rosaceae (1.0–5.8%, mean 2.1%), and *Typha* (1.0–2.8%, mean 1.60%). The sum of tree pollen types is c. 5.1% and including *Pinus*, *Picea*, *Betula* and *Salix*. The abundance of Poaceae (0.3–2.5%, mean 1.4%) and Cyperaceae (0–0.9%, mean 0.3%) was low, and the Ar/(Am + E) ratio (0.2–0.7, mean 0.4) had the lowest value in the whole core sequence. Overall, this zone had the lowest pollen concentration (c. 18873 grains/g). The pollen assemblages in this zone, can be further divided into two sub-zones. Sub-zone Ⅰ-1 (119–106 cm, c. 380–70 BCE) can be readily distinguished from sub-zone Ⅰ-2 (106–87 cm, c. 70 BCE-400 CE) by the decreasing percentage of Poaceae pollen.

Zone Ⅱ (87–40 cm, c. 400–1350 CE)

This zone was typified by an increase in Poaceae (0.5–13.2%, mean 6.5%) and Cyperaceae (0.2–1.5%, mean 0.8%) at the expense of *Artemisia* (mean 34%), Asteraceae (0.5–2.6%, mean 1.4%), and Rosaceae (0–2.4%, mean 0.5%) whose percentages decreased. This zone also sees the first appearance of cereal-type Poaceae (0–0.6%, mean 0.3%).

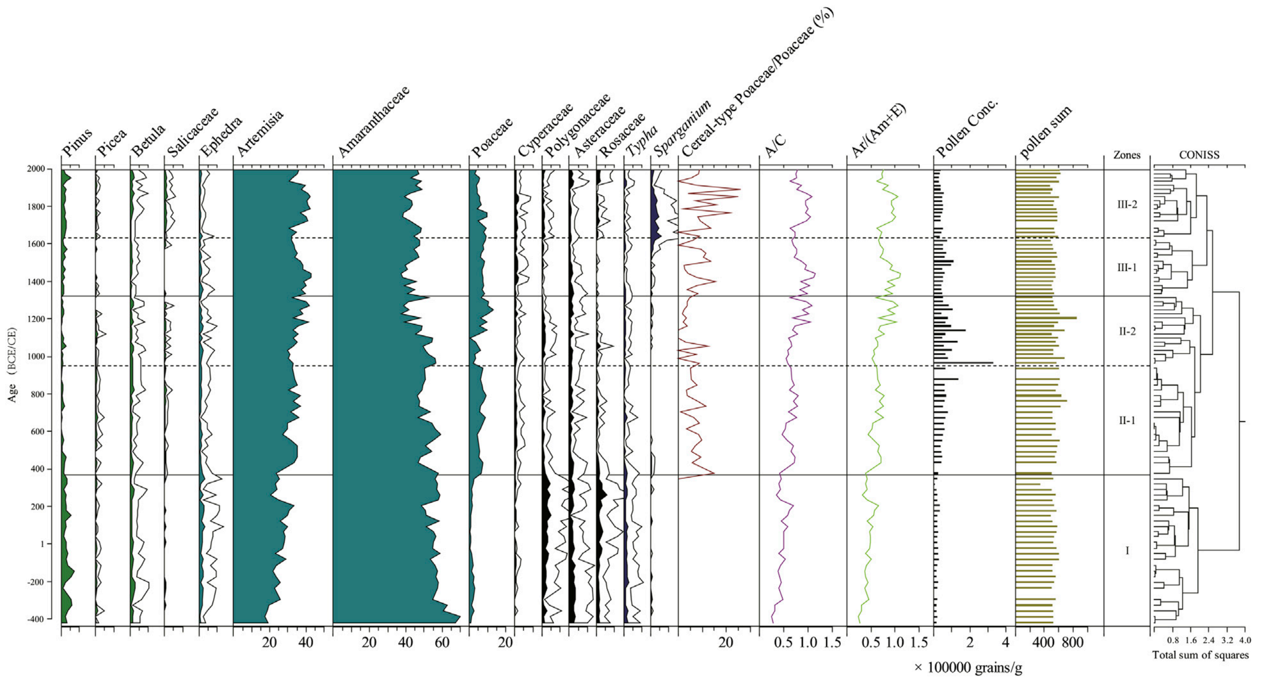

FIGURE 3 | Pollen percentage diagram for core JL18-02-A spanning the last 2400 years.

This zone can be further divided into two sub-zones. Sub-zone II-2 (52–40 cm, c. 1160–1350 CE) can be readily distinguished from Sub-zone II-1 (86–52 cm, c. 400–1160 CE) by the following features: further increases in *Artemisia* (32.6–41.7%, mean 36.8%), Poaceae (5.6–13.2%, mean 9%) percentages and Ar/(Am + E) ratio (0.6–1.1, mean 0.8) and the presence of cereal-type Poaceae/Poaceae, Amaranthaceae (37.3–52.3%, mean 43%), and a decrease in pollen concentration (now with a mean 82166 grains/g).

Zone III (40–0 cm, c. 1350 CE to Present)

There were no obvious changes in the percentage of Poaceae pollen (3.1–9.8%, mean 6.7%) but there was a higher abundance of Cyperaceae pollen (0.4–2.2%, mean 1.1%) compared to the previous zone. In Zone III, there was an obvious increase in aquatic pollen (*Typha* and *Sporangium*) percentages (0.4–6.5%, mean 2.3%), tree pollen percentages (0.8–9.6%, mean 3.9%) and Cereal-type Poaceae/Poaceae (0–33.3%, mean 10.6%). The Ar/(Am + E) ratio was relatively higher (0.6–1.1, mean 0.8), but was interrupted by a brief period (c. 1550–1700 CE) with lower values (0.7–0.8, mean 0.7).

Sub-zone III-2 (23–0 cm, c. 1650 CE to present) is distinguished from sub-zone III-1 (40–23 cm, c. 1350–1650 CE) by an apparent increase in *Artemisia* (30.7–42.3%, mean 32.3%), *Salix* (0.2–2.7%, mean 0.9%), *Sparganium* (1.8–6.5%, mean 2.6%), Rosaceae (0–2.3%, mean 1.0%), and Cereal-type Poaceae/Poaceae (0–33.3%, mean 12.1%) and a slight decrease in Poaceae (3.1–9.8%, mean 6.1%).

DISCUSSION

Pollen Source Area and a Test of Pollen Humidity Indicator of Jili Lake

The size of pollen source area depends on the size of the depositional basin, characteristics of pollen types and spatial distribution of the plant species (Jackson, 1990; Sugita, 1994). Sugita (1994) suggests that pollen assemblages of sedimentary basins with a radius larger than 750 m is mainly influenced by regional pollen rather than local pollen, and hence we considered the pollen assemblages in Jili Lake (~174 km^2) can reflect regional vegetation variations. Because of strong aeolian activity in Northern Xinjiang, we suggested pollen assemblages are a mixed signal to the regional vegetation in the basin. As modern vegetation types show there are less forest around Jili Lake except some specific planted poplar trees to protect farmlands (Xinjiang Comprehensive Investigation Team, Chinese Academy of Sciences, 1978), the tree pollen types in the lake could have been transported by wind and/or river from the southern slopes of the Altai Mountains.

The *Sparganium* is adapted to growing in wet conditions, and the high content of *Sparganium* might indicate a low lake level (Davis, 1999). The aquatic plants in JL18-02-A core from Jili Lake were mainly *Typha* and *Sparganium*, both of which are emergent plants. A previous study showed the higher content of aquatic pollen and lower total pollen concentration may indicate a shallower lake environment (Huang et al., 2010).

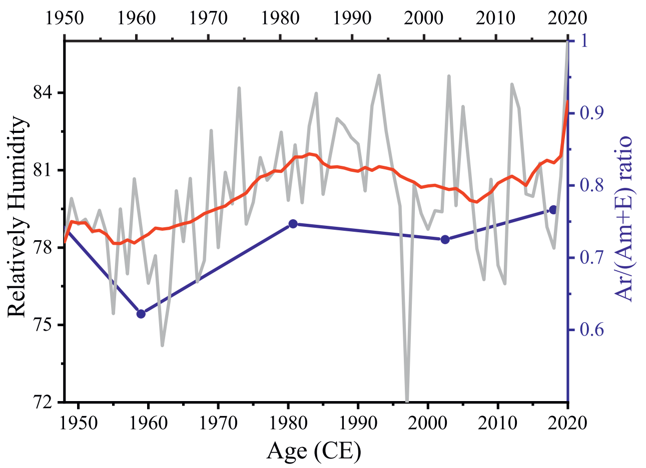

FIGURE 4 | Comparison of Ar/(Am + E) for the core JL18-02-A with various Relative Humidity records from the Fuhai station (data from https://psl.noaa.gov/data/index.html): grey line: relative humidity; red line: relative humidity result of 25-point smoothing; blue dot line: Ar/(Am + E) ratio.

To verify the reliability of Ar/(Am + E) ratio as an indicator of climatic humidity, we compared it to the relative humidity records from meteorological stations (**Figure 4**). It was demonstrated that the Ar/(Am + E) ratio fluctuations of JL18-02-A generally follow the relative humidity records from the Fuhai station, both showing an increasing trend in humidity during the 1950–2018 CE (**Figure 4**).Therefore, the Ar/(Am + E) ratio was a reliable indicator of humidity in this region, which is similar to A/C ratio used by many other previous studies (e.g., Huang et al., 2009; Zhang J. et al., 2018).

Comparison of Regional Moisture Changes in the Late Holocene

The moisture variations inferred from the Ar/(Am + E) ratio from Jili Lake (**Figure 4A**) over the last 2400 years is consistent with other regional records (e.g., Sayram Lake (**Figure 4C**) and Ebinur Lake (**Figure 4B**), and suggested that an increase in regional moisture, which is consistent with an increase in the average moisture index of Xinjiang towards the present (Wang et al., 2013). The nearby Lake Ulungur (**Figure 4I**) also showed an increase in moisture prior to 1450 CE, but then decreased sharply (Liu et al., 2008).

From 400 BCE-400 CE, there is lower water level and lower effective moisture recorded in Jili Lake, which is also seen in other records. For instance, climate conditions were drier at Sayram Lake (**Figure 4C**) and Ebinur Lake (**Figure 4D**) during this period (as interpreted from a low A/C ratio). This period of drying is coincident with strong solar activity (**Figure 4J**), and the known warming associated with the Roman Warm Period (RWP, 0–400 CE) (Biintgen et al., 2011). In low-elevation areas in northern Xinjiang, there are many sites that suggest a dry climate during the RWP (Feng et al., 2017). In the Aral Sea area, there was a period of low lake level from 1 CE to 425 CE (Sorrel et al., 2006), and at Bosten Lake, a period of high salinity and lower lake level occurred from 280 to 480 CE (Fontana et al., 2019; Li et al., 2021). Historical documents show that in the 4th Century, the city of the Loulan Kingdom experienced a severe drought (Li et al., 1991), which might also have been recorded in Jili Lake, as indicated by a lower PHI at 300–400 CE (**Figure 4A**). The results of lithological and grain-size analyses from Jili Lake suggest the lake was shallower before 400 CE, hence the hydrodynamics caused by wave action on the lake was relatively strong (Lang, 2020). We interpret the low pollen concentration as evidence of strong hydrodynamics and/or drier conditions. There are also differences in the records of humidity at different altitudes in the Xinjiang region. From 400 BCE to 400 CE, a decrease in moisture occurred in high altitude areas [e.g., Tielishahan Peat (Zhang et al., 2016) and Narenxia Peat (Zhang D. et al., 2018), Yushenkushi Peat (Yang et al., 2019), and Sayram Lake (Lan et al., 2020)], while a slight increase in moisture occurred in low altitude areas [e.g., Jili Lake (**Figure 5A**), Ulungur Lake (**Figure 5B**) and Ebinur Lake (**Figure 5D**)]. In addition, during this period moisture records from Bosten Lake in the southern Tienshan Mountains (**Figure 5H**; Huang et al., 2009) showed a slight decreasing in moisture during this period, which is inconsistent with low latitude lakes in northern Xinjiang.

From 400 CE to 850 CE [Dark Ages Cold Period (DACP)], the PHI indicates an increase in regional moisture, overlain by fluctuations in wet and dry phases at a centennial scale. The water level in Jili Lake began to increase, likely reaching its present-day level after c. 400 CE (Lang, 2020). Similarly, the moisture record from Ebinur Lake (**Figure 5D**) shows an increase in regional moisture, and pollen records from Kanas Lake suggests an increase in effective humidity from 550–1050 CE (Huang et al., 2018).

During the MWP (850–1200 CE), the climate was warm and dry. Although warm climatic conditions prevailed in the Northern Hemisphere (**Figures 5I, J**), the PHI suggests relatively dry conditions in the Jili Lake region. These drier conditions may be related to a period of higher evaporation at Bosten Lake (**Figure 3G**), and also coincided with a glacial retreat event recorded at Karakuli Lake (Liu et al., 2014). During this period, there is a higher content of coarse grain sizes (40–200 μm) from Jili Lake suggests an intensification of storm activity at Jili Lake (Lang, 2020). Likewise, the increased coarse fraction in the record from Harnur Lake (**Figure 5E**) and decreased A/C ratios at Ebinur Lake (**Figure 5D**) corroborate this interpretation.

During the Little Ice Age (LIA: 1200–1850 CE), there was an increase in moisture from 1200 CE (**Figure 5A**), consistent with the A/C ratios of Sayram Lake (**Figure 5C**), Ebinur Lake (**Figure 5D**) and Harnur Lake (**Figure 5E**). Cold climate also recorded in Manas Lake (Song et al., 2015) and Bosten Lake (**Figure 5G**) during this period. This period is not characterized by uniform wet conditions. For example, the period 1560–1700 CE was relatively dry with a lower PHI, though the regional climate was still wetter than the period prior to 1200 CE (**Figure 5A**). At Jili Lake the abundance of aquatic pollen (*Typha* and *Sparganium*) peaked at 1665 CE, with a brief interval of lower water level at 1600–1855 CE. Other regional records also attest to relatively dry conditions during 1560–1700 CE: Sichanghu peatland, Hutubi River Basin, Manas Lake, Kesang Cave and Dalong Pond (Chen F. et al., 2015; Song et al., 2015; Cai

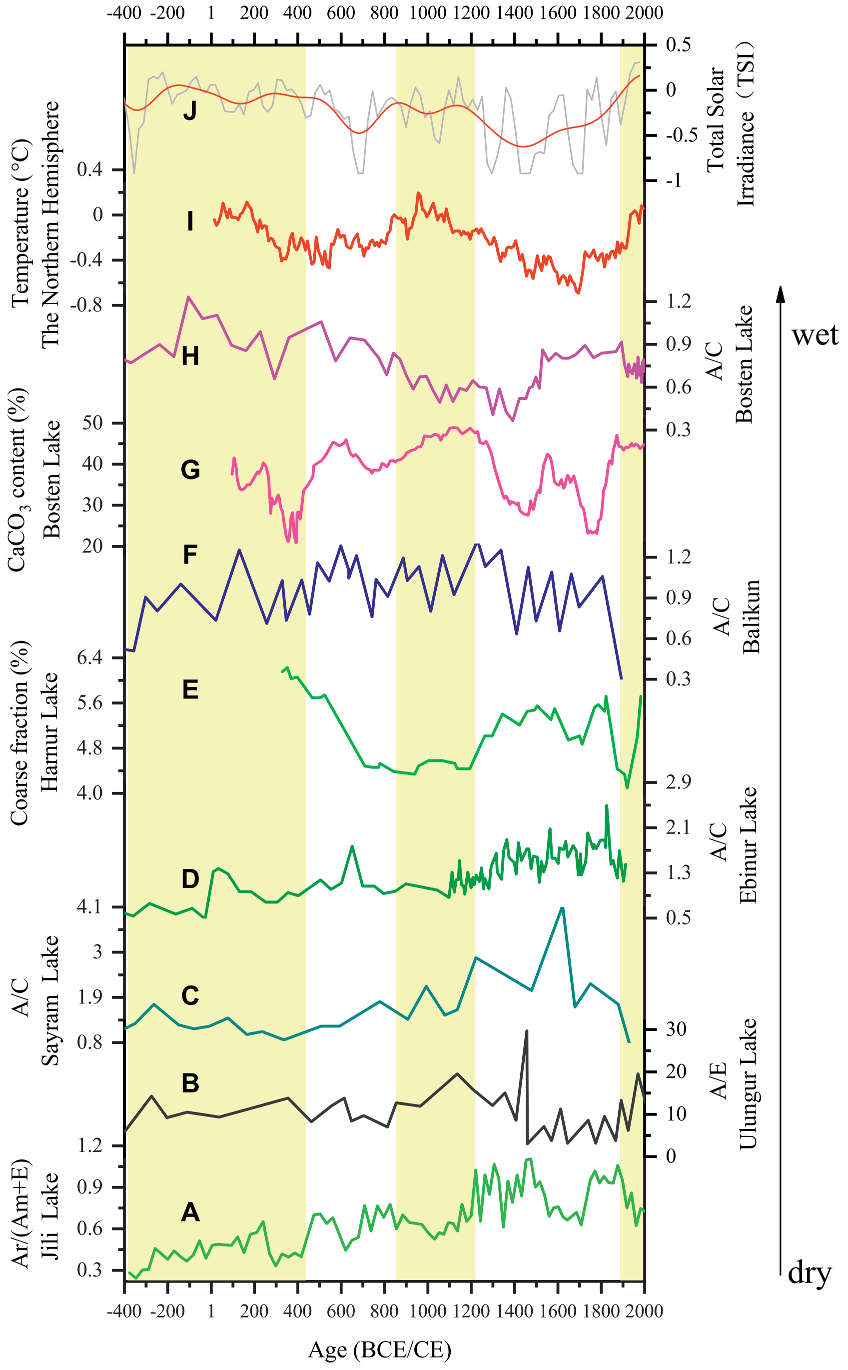

FIGURE 5 | Comparison of Ar/(Am + E) for the core JL18-02-A with various paleoclimatic records: **(A)** Ar/(Am + E) ratio from Jili Lake (this study); **(B)** A/E ratio from Ulungur Lake (Liu et al., 2008); **(C)** A/C ratio from Sayram Lake (Jiang et al., 2013); **(D)** A/C ratio from Ebinur Lake (Wang et al., 2013); **(E)** Coarse fraction from Harnur Lake (Lan et al., 2018); **(F)** A/C ratio from Balikun Lake (Tao et al., 2010); **(G)** $CaCO_3$ content from Bosten Lake (Fontana et al., 2019); **(H)** A/C ratio from Bosten Lake (Huang et al., 2009); **(I)** Temperature in the Northern Hemisphere (Ljungqvist, 2016); **(J)** Reconstructed Total Solar Irradiance (TSI) (Steinhilber et al., 2012).

et al., 2017; Lan et al., 2019; Ren et al., 2019). At Bosten Lake, the carbonate content (**Figure 5G**) suggests an interval of high evaporation during 1550–1700 CE; higher temperatures are recorded at the same times [e.g., at Manas Lake (Song et al., 2015) and Belukha glacier (Eichler et al., 2011)], suggesting that temperature was the main driving force of decreased moisture during this period. After 1850 CE, the PHI derived from the Jili Lake record suggests a drier climate, which is consistent with the records of other lakes in northern Xinjiang (Huang et al., 2009; Feng et al., 2016; Li et al., 2017; Yang et al., 2019; Yang et al., 2020).

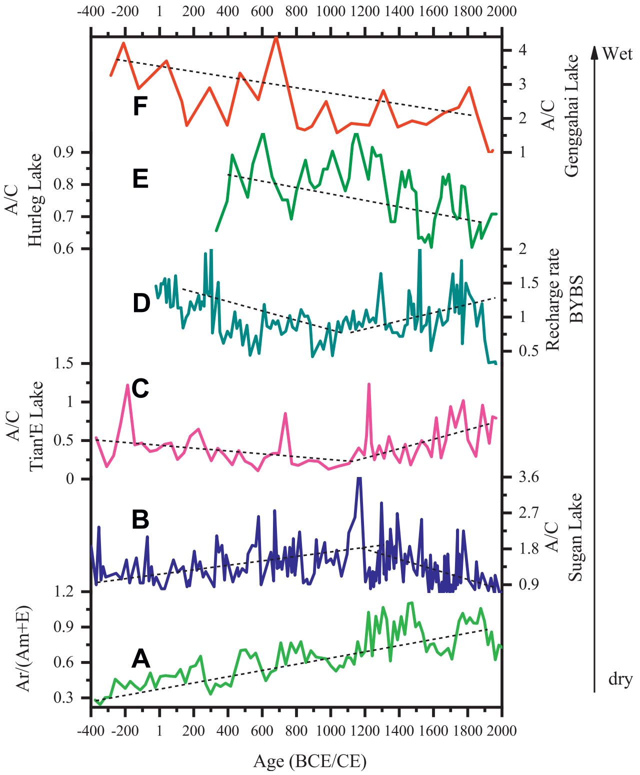

FIGURE 6 | Comparison of Ar/(Am + E) ratio for the core JL18-02-A with various paleoclimatic records in the monsoon marginal region: **(A)** Ar/(Am + E) ratio from Jili Lake (this study); **(B)** A/C ratio from Sugan Lake (Li, 2020); **(C)** A/C ratio from Tian'E Lake (Zhang J. et al., 2018); **(D)** Recharge rate from BYBS profile (Ma et al., 2009); **(E)** A/C ratio from Hurleg Lake (Zhao et al., 2010); **(F)** A/C ratio from Genggahai Lake (Liu et al., 2016).

Previous studies from northern Xinjiang showed that the region alternated between "cold-wet" and "warm-dry" during the late Holocene (Feng et al., 2006). Combining the Northern Hemisphere temperature (**Figure 5B**) with the PHI derived from the Jili Lake record, there is support for the climate model of "warm-dry" and "cold-wet" (Chen et al., 2019), overlain by a millennial timescale wetting trend from 1 CE to 1550 CE.

By comparison of regional moisture changes with records in monsoon marginal region (**Figure 6**), it was found that there was an increasing trend in moisture at Jili Lake (**Figure 6A**) during 400 BCE-2000 CE, which is in contrast to records from Hurleg Lake (**Figure 6E**) and Genggahai Lake (**Figure 6F**). The reason for these differences may be the climate of Hurleg Lake and Genggahai Lake being mainly driven by the Asia Summer Monsoon (Liu et al., 2016; Zhao et al., 2010). Records from Tian'E Lake (in the Qilian Mountains) and BYBS profile (in the western part of the Badain Jaran Desert) show a decrease in moisture during 400 BCE-1100 CE and an increase in moisture from 1100 BCE to 1800 CE, which was in antiphase to the moisture record at Sugan Lake (**Figures 6B, C, E**). An increase in moisture during 1100–1800 CE at Tian'E Lake and BYBS profile may be due to the weakening of the Asian Summer Monsoon caused by the reducing solar radiation (Steinhilber et al., 2012; Gao et al., 2020). In general, a wetting record from Jili Lake over 2400 years (**Figure 6A**) is obviously different from that in the monsoon marginal region.

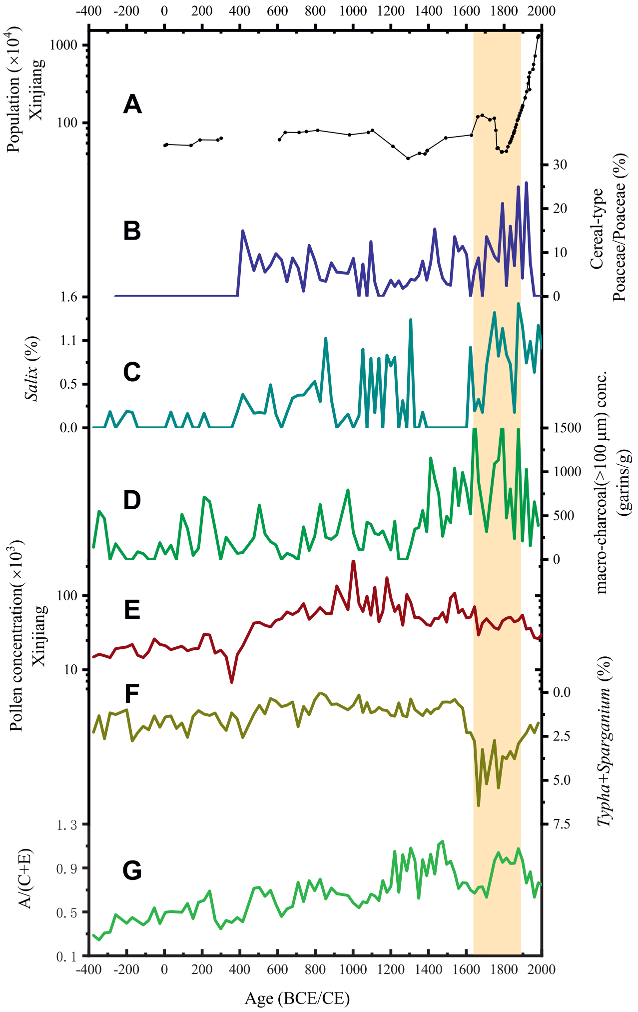

FIGURE 7 | Comparison of Ar/(Am + E) ratio for the core JL18-02-A with population in Xinjiang: **(A)** Ar/(Am + E) ratio from Jili Lake (this study); **(B)** The percentage of *Typha* and *Sparganium* from Jili Lake (this study); **(C)** Macro-charcoal (>100 μm) concentration from Jili Lake (this study); **(D)** Pollen concentration form Jili Lake (this study, c: Y-axis is a log scale); **(E)** Ce/Po from Jili Lake (this study); **(F)** Population in Xinjiang, a: Y-axis is a log scale (Zhao and Xie, 1988). The orange area indicates a population growth period.

The water vapor in ACA originates from the North Atlantic Ocean, the Mediterranean Sea, Caspian Sea, and regional water recycling within inland Asia, and is transported from west to east by the westerlies (Aizen et al., 2006; Chen et al., 2008). The southward shift of the westerly jet stream facilitates the infiltration of water vapor from the Indian Ocean to ACA and leads to more rainfall over northern Xinjiang (Yang and Zhang., 2008; Zhao et al., 2014). Solar activity plays an important role in atmospheric circulation (Reid, 1991; Steinhilber et al., 2012). Yan et al. (2019) suggesting that changes in solar activity and the intensity and location of the westerly jet stream are the dominant control on hydroclimatic variations in ACA. The stronger westerly and the southern migration of the westerly jet stream, which corresponds to lower total solar irradiance (TSI) and colder conditions, could favor more water vapor transport to ACA, and vice versa (Yan et al., 2019). During 400 BCE-400 CE and the MWP, the Jili Lake region had a warm-dry climate when the solar activity was higher (**Figures 5A, J**). During the LIA, there was a period of higher evaporation (1560–1700 CE) and an associated low moisture index.

Human Activity in the Region and Its Impact on the Lake Level of Jili Lake

Since 1700 CE, there were higher concentrations of macro-charcoal (>100 μm) (**Figure 7C**), accompanied by an increase in the Ce/Po ratio (**Figure 7E**). These indicators suggest that a period of intensified human activity played an important role in influencing the vegetation in the region, and this can be matched with local and state historical documents. The population of Xinjiang gradually increased during 1626–1760 CE (**Figure 7F**). Irrigation for agriculture in northern Xinjiang began in the early Qing Dynasty (from 1716 CE) (Zhao and Xie, 1988) with a rapid phase of development during 1749–1840 CE (Fang, 1989). After 1755 CE, there was an upsurge in urban construction in northern Xinjiang, driven by political, economic and military factors, as well as expended cultivation and trade development (Yang, 2018). Likewise, during the 1600–1850 CE, Jili Lake had a lower lake level as indicated by the higher percentage of aquatic pollen (*Typha* and *Sparganium*) (**Figure 7B**) and the lower pollen concentration (**Figure 7D**). Notably, the PHI derived from the Jili Lake sediments was relatively higher during 1700–1850 CE and indicated relatively wet conditions (**Figure 7A**), which is in contrast to the lower lake level. Therefore, the wetter climate during 1700–1850 can't explain the lower lake level and we infer that the lower water level in Jili Lake during 1600–1850 CE may have been caused by human activities or the more extensive exploitation of water resources. Similarly, the decline of water level in Ulungur Lake was likely caused by the greatly increased regional population and the associated development of oasis irrigation agriculture along the rivers in the lower basin during the Ming and Qing Dynasties (Liu et al., 2008; Tuerhong, 2011; Ni et al., 2021). Consequently, lower lake level may be mainly influenced by stronger irrigation agricultural activities during 1700–1850 CE.

CONCLUSION

The high-resolution pollen record from core Jl18-02-A reveals the evolution of vegetation in Jili Lake and its surrounding area over the last 2400 years in response to climate drivers and human impact. The comparison of moisture availability, as inferred by the Ar/(Am + E) ratios to other regional records suggest that the moisture in the northern Xinjiang region study area shows an increase of humidity from 1 CE to 1550 CE, corresponding to a long-term cooling in the Northern Hemisphere. Pollen assemblages indicated that regional vegetation dominated by desert gradually shifted into a desert steppe. The moisture was characterized by the "warm-dry" periods of RWP (c. 0 to c. 400 CE), MWP (c. 800 to c. 1200 CE) and CWP (since 1850 CE), and the "cold-wet" periods of DACP (c. 400 to c. 8000 CE) and LIA (c. 1400 to c. 1850 CE). Over the last 2400 years, the monsoon had little influence on moisture changes in the Jili Lake basin. Notably, during 1700–1850 CE, the increase of the percentages in aquatic pollen (*Typha* and *Sparganium*) and cereal-type Poaecea pollen reflecting anthropogonic impacts, and the rise of macro-charcoal and population may result from the intensified irrigation for agriculture in the catchment.(Fang, 1989; Zhang and Feng, 2018a).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

XH conceived this study. YX and LX identified the pollen. YX, LX, and XH wrote and revised the manuscript. KM, JZ, YL, and XC discussed the data. KM improved the language.

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