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REVIEW
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Reviewing the Palaeoenvironmental Record to Better Understand Long-Term Human-Environment Interaction in Inner Asia During the Late Holocene

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The Middle to Late Holocene spread of agropastoralism throughout Eurasia not only subjected domesticated taxa to stressors associated with novel environments but also induced changes in these environments following the introduction of these social-ecological systems. The mountainous region of Inner Asia comprises various steppe, meadow, and forest landscapes where zooarchaeological evidence suggests occupation by herding populations as early as 7,000 years Before Present (BP). Recent archaeobotanical findings indicate the introduction of cropping and the development of agropastoralism around 4,500 BP. Here, we review and synthesize palaeoenvironmental studies and data to examine anthropogenic impacts and modifications of these landscapes. From around 4,000 BP, we find significant changes in palynomorph, charcoal, sediment, and other proxy data, related to the introduction of agriculture to the region, with later intensifications in land use indicators at around 2,000 and 1,000 BP. We note that these impacts are not uniform or continuous through and across the records and may be evidence of shifting phases of occupation and landscape management. This temporal and spatial variability may also be a response to shifts in moisture availability due to long-term Holocene changes in the intensity of the summer monsoon and Westerly circulation systems. Changes in arboreal pollen indicate the development of intensified use of forest resources in the region, which we identify as a topic for future investigation. Based on these data, we stress the long-term human paleoecology in the study area and argue that traditional agropastoralist systems should be considered in future programs of landscape conservation in the region. This study also emphasizes the importance of future local scale multiproxy studies into past anthropogenic changes within the Inner Asian landscape.

Keywords: Holocene, Central Asia, paleoecology, agro-pastoralism, Anthropocene

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INTRODUCTION

Proponents of "deep time" Anthropocene hypotheses have drawn on archaeological and palaeoenvironmental proxies to position humans as drivers of irreversible changes in terrestrial ecosystems from the Early Holocene (Stephens et al., 2019) and elevated levels of CO_2 and CH_4 emissions from the Middle Holocene (Ruddiman et al., 2020). While these studies have at times emphasized the negative impacts or feedback loops of past human populations on the environment, they have also allowed a critique of assumptions within modern conservation policy and practice regarding "pristine" pre-industrial or pre-colonial environments (Bliege Bird and Nimmo, 2018; Fletcher et al., 2021). Recent evaluations of the "deep time" Anthropocene have argued that mosaics of traditional land use incorporating diverse patterns of agriculture, pastoralism, and hunting-gathering often allowed positive feedback loops between ecosystem enrichment and resilient human social-ecological systems (Boivin and Crowther, 2021). It has been argued that modern processes of colonization and industrial or agricultural intensification have broken down traditional social-ecological systems, leading to the current global environmental crises (Ellis et al., 2021). This study reviews the published palaeoenvironmental research and data to investigate the evidence for long-term human management and modification of landscapes of Central Asia in sedimentary archives. Our geographic focus is on the mountain chain comprising the Altai, Tien Shan, and frequently referred to as the Inner Asian Mountain Corridor (IAMC; Frachetti, 2012), as well as the Western Himalaya-Hindu Kush.

Across Central or Inner Asia, human–environment interaction and adaptation have been in the past presented or understood as a traditional "steppe and sown" dichotomy between irrigated or oasis agriculture in desert river basins and nomadic pastoralist adaptations in open steppe or mountain areas (Brite et al., 2017). More recently, bioarchaeological and geoarchaeological studies located in desert areas have presented a more complex picture of human–environment interaction (Dodson et al., 2015; Brite et al., 2017; Markofsky et al., 2017). Research priorities in steppe and mountain areas (**Figure 1**) have presented an array of localized adaptations to environmental conditions, comprising diverse patterns of herding and cultivation that call into question the divisions between nomads and farmers (Doumani et al., 2015; Hermes et al., 2019; Motuzaite Matuzeviciute et al., 2019; Spengler et al., 2021). While this diversity in social-ecological systems arises partly in response to variability in topography, soil landscape, water availability, or vegetation resources, it is also recognized that past populations have actively and passively driven processes of environmental niche modification across Central Asia (Spengler, 2014; Ullah et al., 2019; Ventresca Miller et al., 2020).

These processes may include cultivation practices and their influence on soil formation, changes to vegetation communities, such as the conversion of forest to pasture or changes in herbaceous diversity, impacts of fire regimes on regional biogeography, and stresses associated with the movement of domesticated herds and crops into novel environments. Examination of these processes contributing to an early Anthropocene in Central Asia has typically been examined through archaeological data, including geoarchaeological, botanical, and faunal studies (Ventresca Miller et al., 2020). This study reviews diachronous changes in sedimentary records indicating early anthropogenic impacts on Central Asian environments and the long-term coevolution of humans and landscape in the region. These processes may be indicated through multiple palaeoenvironmental proxies including pollen and non-pollen palynomorphs, charcoal influx, and sediment properties that may indicate processes of herding, cultivation, or land clearing and modification associated with various forms of agropastoralism.

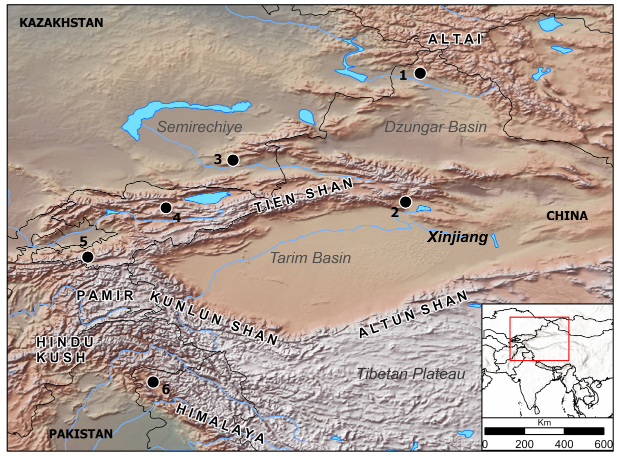

FIGURE 1 | Regional geography, points indicate significant early agropastoralist archaeological sites. (1) Tongtian Cave (Zhou et al., 2020), (2) Xintala (Zhao et al., 2013), (3) Begash (Frachetti et al., 2010) and Tasbas (Doumani et al., 2015), (4) Chap (Motuzaite Matuzeviciute et al., 2019) and Aigyrzhal (Motuzaite Matuzeviciute et al., 2017), (5) Obishir (Taylor et al., 2021), and (6) Pethpuran Teng (Yatoo et al., 2020) and Kanispur (Pokharia et al., 2018).

METHODS

Archived palaeoenvironmental data and their associated publications were searched in the online repositories Pangea and Neotoma, (Williams et al., 2018) using a search box bounded by 66.27°–98.8° E and 30.2°–52.79° N. An additional search of relevant journals (*The Holocene*; *Quaternary International*; *Quaternary Science Reviews*; *Vegetation History and Archaeobotany*; and *Palaeogeography, Palaeoclimatology, Palaeoecology*) was undertaken using strings of keywords including "Central Asia," "Inner Asia," "Holocene," "Human Impacts," "Kazakhstan," "Kyrgyzstan," "Tajikistan," "Uzbekistan," "Pakistan," "Xinjiang," "Tien Shan," "Pamirs," and "Hindu Kush." A search of the same keyword strings was also undertaken in Scopus and Google Scholar. Where possible, supplementary data were inspected in association with publications. Several publications (Beer et al., 2007, 2008; Beer and Tinner, 2008) where associated repository data were available (Ammann et al., 2021a,b,c,d; Heiri et al., 2021;

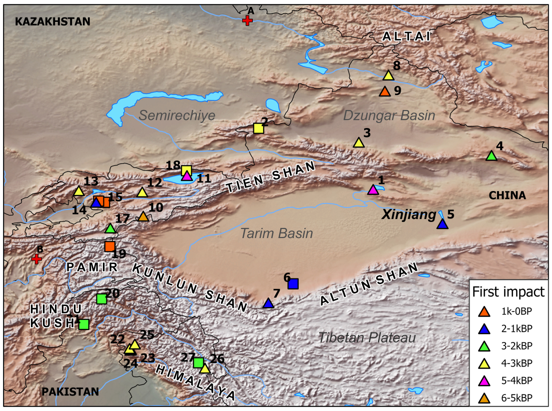

FIGURE 2 | Locations of proxy records examined here and timing of first anthropogenic impacts. Numbers refer to records in **Table 1**. Triangles indicate multi-proxy and squares indicate single-proxy records. Red crosses indicate additional climate records, as described in **Figure 3**: (A) Ozerki Swamp (Tarasov et al., 1997) and (B) CSM loess section (Gao et al., 2019).

Tinner and Beer, 2021) used linear chronologies based on older radiocarbon calibration curves. In these cases, new Bayesian age-depth models based on the Intcal20 curve were produced using the Bacon package in R (Blaauw and Christen, 2011; Reimer et al., 2020) prior to data examination (**Supplementary Data**). Ecological impacts of agropastoralism in the study regions observed by the authors during fieldwork also form an interpretive background to this study (Leipe et al., 2014a,b; Motuzaite Matuzeviciute et al., 2019; Spate et al., 2022). We also review several key palaeoclimate studies to contextualize human activity across the study region. Our case studies have been grouped into the following subregions: Xinjiang (the Xinjiang Uighur Autonomous Region of China, including the Eastern Tien Shan, Altai, and Kunlun Shan ranges); Central and Western Tien Shan, and Pamirs (the entire territories of Kyrgyzstan and Tajikistan and mountainous regions of eastern Uzbekistan); Western Himalaya-Hindu Kush (eastern Afghanistan, Khyber Pakhtunkhwa province and the territories of Gilgit-Baltistan and Azad Kashmir in Pakistan, the Union Territories of Jammu and Kashmir, and Ladakh in India).

RESULTS

We identified a total of 29 single- or multi-proxy studies from 27 sites as having potential indicators of human impact across the Inner Asian mountains (**Table 1** and **Figure 2**). While a small number of these studies were targeted toward exploring human impacts in the past, the majority were directed toward the exploration of past climate dynamics, particularly between the Westerly, Siberian Cyclonic, and Summer Monsoon systems. Despite this, these studies often contained one or more proxy indicators of possible past human impacts on the landscape.

Xinjiang

A sediment core from Bosten Lake in the Yangqi Basin in the southern Tien Shan covers a temporal span of around 8,500 years (Tarasov et al., 2019). The authors interpret low levels of human perturbations at around 4,500 Before Present (BP), indicated by reductions in arboreal pollen, influxes of charred grass stems, and cereal-type pollen (>37 μm). The authors note the morphological overlap of some domestic and wild grass pollen in the study area and this pollen taxon alone cannot be taken as evidence of agriculture. After 4,000 BP, stronger evidence for human impact includes *Xanthium*-type and *Cannabis* pollen, typically associated with anthropogenic disturbances and also common in archaeobotanical assemblages from the neighboring Turpan and Hami Basins, where they are interpreted as medicinal plants (Jiang et al., 2015; Zhao et al., 2019; Wang et al., 2020). Increased *Glomus* spores after ca. 4,000 BP in the Bosten record (Tarasov et al., 2019) are contemporaneous with the establishment of the agriucltural settlement at Xintala (Dodson et al., 2013; Zhao et al., 2013). While *Glomus* spores must be interpreted cautiously in peat bog records, they may generally be considered a reliable indicator of higher erosional input in lake records (Kołaczek et al., 2013) and could possibly relate to an agricultural clearing in the lake basin. Macrobotanical records from the archaeological trench Xintala (Zhao et al., 2013) indicate that barley, wheat, and millet were cultivated around the site. High relative abundances of Asteraceae pollen (to 42%) are contemporaneous with the first increases of *Xanthium* in the Bosten record (Tarasov et al., 2019). Elsewhere in the Yangqi Basin, geoarchaeological evidence indicates the damming of mountain runoff in foothill areas in the first few centuries CE (Li et al., 2019a). This has been interpreted as a system for the trapping of sediments and water, by which agropastoralist populations enriched foothill ecotopes and enabled cultivation. This period of the Bosten Lake record sees the first presence of *Rumex* pollen (Tarasov et al., 2019), a nitrophilous colonizer typically associated with agropastoralist land use across Inner Asia (Spengler, 2014).

The Bortala Valley in the central Tien Shan holds a number of agropastoralist sites (Jia et al., 2018), including the settlement at Adunqiaolu, comprising several large stone structures where the occupation of one house is dated to ca. 3,800–3,500 BP (Jia et al., 2017). Archaeobotanical remains from this structure indicate a pastoral economy based on seasonal movement and grazing rather than local cultivation (Tian et al., 2021); however, large quantities of *Astragalus* seeds that appear to be stored may indicate foddering of local vegetation. A core from the Wenquan wetland, around 40 km east of Adunqiaolu, has been assessed for human impact among pollen and charcoal proxies (Li and Wang, 2020; Li et al., 2020). The pollen record indicates a steady decline in shrubby taxa (primarily *Ephedra*) and the expansion of upland herbs from ca. 7,500 BP onward, likely resulting from the onset of more humid conditions (Li et al., 2020). While avoiding overly deterministic explanations, it has been argued that further increases in humidity after ca. 4,000 BP enabled the pastoralist settlement in the valley; however, across the pollen spectrum, there is no indicator of

TABLE 1 | Locations, general proxy descriptions, and references for palaeoenvironmental records reviewed here.

No.	Name (region)	Site Type	Lat.	Long.	First impact (years BP)	Secondary impacts (years BP)	Single/multi proxy	Notes	References
1	Bosten (Xinjiang)	Lake	41.931	86.804	5–4k	4–3k	Multi (Pollen, NPP, charcoal)	Reduction in forest, charred grass and low levels indicator pollen c. 4.5 kBP. Post 4 kBP increase in *Glomus*, ruderals, charred remains and *Xanthium*	Tarasov et al., 2019
2	Wenquan (Xinjiang)	Wetland	44.97373	81.03134	4–3k		Single (Charcoal)	Grassland fire activity after 4 kBP. Interpreted as regional environmental change allowing occupation of area. Authors also raise possibility of human–fire relationship	Li and Wang, 2020; Li et al., 2020; Dodson et al., 2021
3	Chaotanhu (Xinjiang)	Wetland	44.3054	86.0804	4–3k	0.5k–0	Multi (Charcoal, pollen, TOC, sediment size)	Charcoal influxes, anthropogenic pollen, increased TOC and coarse sediment ca.3.5 k BP; 500 BP to present	Zhang et al., 2015
4	Balikun (Xinjiang)	Lake (saline/dry)	43.64428	92.77133	3–2k		Multi (Pollen, TOC)	Expansion of meadow vegetation after 2.3 k BP. LOI indicates higher organic fraction, sediment size indicating low lake levels. Interpreted as result of irrigated agriculture.	An et al., 2012
5	Lop Nur (Xinjiang)	Lake bed (dry)	40.20806	90.29972	2–1k		Multi (Sediment size, isotope, ostracod)	Aeolian layer indicating desiccation resulting from irrigation. Lake drying out of synch with regional lake high stands and δ18O indicators of wetter environment	Liu et al., 2016; Mischke et al., 2017
6	Niya (Xinjiang)	River terrace/dried wetland	37.14374	82.76689	2–1k		Single (Pollen)	Increased Poaceae pollen intrepreted as agricultural activity in cold-wet climate phase	Zhong et al., 2007
7	YC (Xinjiang)	Loess section	36.21911	81.52056	2–1k		Multi (Sediment size, magnetics)	Mag. susc., hematite, particle size. Accelerated weathering and dust circulation attributed to rapid population growth and climate deterioration after 2 kBP	Zhang et al., 2021
8	Alahake (Xinjiang)	Lake (saline)	47.68908	87.5785	4–3k	1k–0	Multi (Pollen, charcoal)	Increased fire activity and expansion of herbs at c. 1.7 k BP. Sharp decrease in trees, increased herbs and fire activity 0.5k-present	Li et al., 2019b
9	Jili (Xinjiang)	Lake	46.87831	87.39447	1k–0		Multi (Pollen, charcoal)	Cereal-type pollen and charcoal influx increase after c. 400 BP. Aquatic pollen types indicate low lake level, interpreted as anthropogenic water draw off during Qing period agricultural expansion	Xiao et al., 2021
10	Chatyr Kol (C. and W. Tien Shan)	Lake	40.58633	75.21097	6–5k		Multi	Fecal biomarkers – humans and herbivores present. Gradual reduction in arboreal pollen	Schroeter et al., 2020
11	Issyk Kol (C. and W. Tien Shan)	Lake	42.62903	77.41453	5–4k	4–3k	Multi (Pollen, NPP, charcoal)	Pollen, coprophagous spores, charcoal; *Glomus* spores 5–4k; 4–3k BP; 1 k BP-present	Leroy and Giralt, 2021

(Continued)

TABLE 1 | (Continued)

No.	Name (region)	Site Type	Lat.	Long.	First impact (years BP)	Secondary impacts (years BP)	Single/multi proxy	Notes	References
12	Son Kol (C. and W. Tien Shan)	Lake	41.80092	75.16181	4–3k		Multi (NPP, diatom)	2 spikes in coprophagous spores c. 3.7k and 2.5 k BP. Increased algal *P. boryanum* after 4 k BP associated with human impact.	Mathis et al., 2014; Sorrel et al., 2021
13	Bakaly (C. and W. Tien Shan)	Mire	41.86734	71.96008	4–3k	2–1k	Multi (Pollen, charcoal)	Low level perturbations in pollen, char. influx and coprophagous spores c. 4–3 k BP. Regeneration of alpine trees and shrubs to 2 k BP. Sharp increase in grazing indicators after 2 k BP. *Juglans* after 2 k BP. *Platanus* and *Morus* pollen after 1 k BP.	Beer et al., 2008
14	Ak Terek (C. and W. Tien Shan)	Mire	41.2815	72.83431	2–1k		Multi (Pollen, charcoal)	Clearing of Juniper scrub, charcoal influx and increase in *Juglans*, *Morus*, and *Platanus* pollen after 2 k BP	Beer et al., 2008
15	Ortok (C. and W. Tien Shan)	Lake/mire	41.24565	73.26452	1k–0		Single (Pollen)	*Juglans*, *Morus*, and *Platanus* pollen after c. 1 k BP. Coprophagous spores, grazing weeds also present.	Beer et al., 2008
16	Nizhnee and Verkhnee (C. and W. Tien Shan)	Lake	41.30935	72.96399	1k–0		Single (Pollen)	*Juglans*, *Morus*, and *Platanus* pollen after c. 1 k BP. *Plantago* pollen also present.	Beer et al., 2008
17	Kichikol (C. and W. Tien Shan)	Lake	39.98767	73.55193	3–2k	2–1k	Multi (Pollen, charcoal)	Grazing/ruderal herbs from c. 3 k BP. *Juglans*, *Morus*, and *Platanus* pollen from c. 2 k BP, steadily increasing grazing pollen and charcoal influx.	Beer et al., 2007
18	Karakol (KG) (C. and W. Tien Shan)	Lake	42.83889	77.3925	4–3k	1.5k–0	Single (Pollen)	Grazing-associated pollen, *Podospora* and *Sporormiella*-type spores 4–3 k BP. Discontinuation then increase after 1.5 k BP. *Juglans*, *Morus*, and *Platanus* after 1 k BP	Beer and Tinner, 2008
19	Karakul (TJ) (Pamirs)	Lake	39.0176	73.5327	1k–0		Single (Pollen)	Expansion of alpine steppe vegetation. Increases in *Plantago*, Poaceae and Asteraceae interpreted as gazing impact	Heinecke et al., 2018
20	Shukan (Western Himalaya-Hindu Kush)	Swamp	36.38333	73.11667	3–2k	1k–0	Single (Pollen)	Possible anthropogenic replacement of *Pinus* forest with open landscape after c. 3 k BP. Increases in Poaceaea, grazing, and ruderal weeds. Stronger pollen evidence for grazing after 1 k BP.	Miehe et al., 2009
21	Kabal (Western Himalaya-Hindu Kush)	Swamp	35.1	72.21667	3–2k	0.6k–0	Single (Pollen)	Fungal spores and herbs interpreted as grazing related 2.4 k BP onward. Increased indicators after 0.6 k BP	Jan et al., 2019
22	TM01 (Western Himalaya-Hindu Kush)	Mire	33.92117	74.5188	4–3k	2–1k	Multi (Pollen, NPP, charcoal, sediment size)	Clearing subalpine vegetation, increased pollen and coprophagous spores, coarse sediment and charcoal influx after c. 3.7 k BP. All indicators steadily increase after 2 k BP.	Spate et al., 2021, 2022
23	PH03 (Western Himalaya-Hindu Kush)	Swamp	33.87481	74.58159	3–2k	2–1k	Multi (Pollen, NPP, charcoal, sediment size)	Low level pollen indicators, charcoal, sediment and coprophagous spores c. 2.5 k BP. Cereal pollen, increased fire activity and grazing indicators at 2.2 k BP onward	Spate et al., 2022

(Continued)

TABLE 1 | (Continued)

No.	Name (region)	Site Type	Lat.	Long.	First impact (years BP)	Secondary impacts (years BP)	Single/multi proxy	Notes	References
24	SG02 (Western Himalaya-Hindu Kush)	Mire	33.83455	74.57271	1k-0		Multi (Pollen, NPP, charcoal, sediment size)	Palynomorph, sediment and charcoal data indicating opening of forest pocket c. 0.5 k BP onward.	Spate et al., 2022
25	Anchar (Western Himalaya-Hindu Kush)	Lake	34.14377	74.78636	4–3k	0.5k–0	Multi (Pollen, geochemical, TOC)	Cereal and *Plantago* pollen after c. 4 k BP. *Juglans* and *Morus* pollen between c. 2.6 and 1.2 k BP. Coarse sediments, C/N and OM indicating higher terrestrial input and anthropogenic overprinting ca. 500 BP to present.	Agrawal, 1992; Lone et al., 2019
26	Tso Moriri (Western Himalaya-Hindu Kush)	Lake	32.92944	78.32333	4–3k	2–1k	Multi (Pollen, NPP, charcoal)	Low levels of grazing weeds, charred grass influx c. 3.7 k BP. Increases in grazing indicators after 1.8 k BP	Leipe et al., 2014a,b
27	Tso Kar (Western Himalaya-Hindu Kush)	Lake	33.16667	78	3–2k		Single (Pollen)	Cereal and cannabis-type pollen c.2.5 k BP. Interpreted as regional signal rather than local impact.	Demske et al., 2009

anthropogenic vegetation change (Dodson et al., 2021). The period following 4,000 BP also sees a higher fire frequency and intensity in the charcoal accumulation rate (Li and Wang, 2020), interpreted as the result of higher herbaceous burn-off related to humid conditions and higher available biomass. The study authors note the possibility that this higher fire intensity is of anthropogenic origin, supported by the archaeologically visible expansion of pastoralist settlements in the valley at this time. Stepwise increases at 8,000 and 4,000 BP in the CHAR record from Wenquan (Li and Wang, 2020) contrast with the Sayram Lake record (Jiang et al., 2013), also in the Bortala Valley around 30 km south of Wenquan, where stepwise reductions in charcoal concentration at ca. 10,000 and 5,000 BP are attributed to climate-driven reductions in biomass, supported by lower pollen concentrations.

Anthropogenic fire regimes as drivers of vegetation change have also been considered in pollen, charcoal, and mineral sediment records from the Caotanhu wetland, on the north facing slopes of the Tien Shan in the south of the Dzungar Basin (Zhang et al., 2015). Pollen including Poaceae, Asteraceae, Apiacaeae, and *Polygonum*-types were identified to be associated with disturbances by agriculture in modern pollen surface samples. Peaks in three size classes of macro- and micro-charcoal at around 3,500 BP are associated with an increase in these anthropogenic pollen types and a decline in arboreal taxa, interpreted as evidence of forest clearing and cultivation in the mountain foothills. This period sees an expansion of Bronze Age sites in the Dzungar Basin; however, with the exception of the agropastoral Luanzagangzi site (Zhang et al., 2017), excavated sites are primarily cemeteries, from which social-ecological systems are poorly understood (Jia et al., 2011). At Caotanhu, these apparent anthropogenic indicators again increase significantly after 700 BP, as does the sand fraction of mineral sediment, possibly indicating a more recent intensification of land clearing and cultivation (Zhang et al., 2015).

On the north side of the Dzungar Basin, the relationship between humans, fire, and vegetation change has also been raised in the examination of preliminary pollen and charcoal data from Alahake Lake in the foothills of the Altai north of the Irtysh River (Li et al., 2019b), where increases in all charcoal size classes have been tentatively associated with the decline of arboreal taxa, particularly *Betula* and *Larix* in the periods of ca. 3,500–2,500 BP and 700 BP–present. Archaeobotanical remains from the Tongtian cave on the south side of the Irtysh (Zhou et al., 2020) include wheat and barley remains dated to ca. 5,200 BP. Archaeological charcoals indicate the burning of *Betula* and *Larix* between ca. 5,000 and 3,500 BP, while pollen from cave sediments indicates the local presence of these taxa after only 3,500 BP. While Li et al. (2019b) note that forest composition and timber line are also sensitive to climatic shifts, the data from Alahake and the archaeological record at Tongtian indicate that the variability in forest taxa, particularly *Betula* and *Larix,* may be potential indicators of human impact. Later impacts near Alahake Lake may be evident in the Jili Lake record (Xiao et al., 2021) where after ca. 400 BP marshy *Typha* and *Sparganium* pollen indicate a low lake stand, out of synch with regional moisture patterns. The study authors have interpreted this as evidence of anthropogenic water withdrawal for irrigation. Through this period relative abundances of cereal-type Poaceae pollen and concentrations of macro-charcoals also increase.

Irrigation intensive agriculture has also been interpreted as a driver of low lake levels at Balikun Lake (An et al., 2012) in the eastern Tien Shan and Lop Nur in the eastern Tarim Basin (Mischke et al., 2017), both at around 2,000 BP. At Balikun, sedimentary proxies indicate a low lake level and high relative abundances of Cyperaceae pollen, showing that marshy conditions are in disagreement with regional records indicating wetter climatic conditions (An et al., 2012). At Lop Nur, a sediment layer composed of very poorly sorted sand (mean grain size 218–226 μm) dated to around 1,800 BP (Mischke et al., 2017) indicates a shift from fluvial to aeolian dominated deposition, while increases in soluble salts, shifts in ostracod assemblages (Liu et al., 2016), and $\delta^{18}O$ ‰ (Mischke et al., 2017) indicate salinization and desiccation. As this shift in lake conditions also appears out of phase with regional climatic conditions, Mischke et al. (2017) attribute this to excessive water withdrawal during the Han Dynasty that may have ultimately had a role in the collapse of the Loulan Kingdom. Environmental degradation due to intensive or maladapted agricultural systems has also been indicated after ca. 2,000 BP in the YC loess section of the southern Tarim Basin (Zhang et al., 2021), where fluctuations in sediment size have no linear relationship with magnetic or mineral data and are partially interpreted as anthropogenic dust disturbance relating to river draw off and lake desiccation. This is also contemporaneous with an increase in Poaceae pollen and fine and coarse sands in the Niya River section (Zhong et al., 2007), in a former desiccated wetland. The study authors also attribute these changes to the intensification of agriculture during the Han and Jin Dynasties.

In the southwest of the Tarim Basin, only a few pre- and proto-historic settlements are known, with an agricultural settlement of Wupaer in the Pamir foothills having the only published archaeobotanical data (Yang et al., 2020). The $\Delta^{13}C$ values of wheat grains at the site indicate a shift from non-irrigated to irrigated agriculture between the early (ca. 3,500–3,300 BP) and late (ca. 3,200–2,600 BP) phases at the site; however, this is interpreted to have been managed through gravity-fed mountain runoff rather than intensive river/oasis agriculture as described in the eastern Tarim Basin. Pollen data from an incised river section also at Wupaer (Zhao et al., 2012) do not indicate any significant anthropogenic impact on vegetation at this time.

Central and Western Tien Shan and Pamirs

Diverse forms of agropastoralist settlement along the Tien Shan foothills and Semirechiye basin of southeast Kazakhstan are evident throughout the Bronze and Iron Ages ca. 4,500–2,000 BP (Frachetti et al., 2010; Doumani et al., 2015; Chang, 2018; Hermes et al., 2021). Despite the extensive archaeological record during this period, most palaeoenvironmental reconstructions have focused on the Late Pleistocene and Late Holocene (Blättermann et al., 2012; Chiba et al., 2016), with the Middle Holocene period of early land use intensification being less investigated. Geomorphological and geoarchaeological studies (Blättermann et al., 2012; Macklin et al., 2015; Ullah et al., 2019) have described fluvial and aeolian processes driving the development of a soil landscape suitable for cultivation. It has been argued that agricultural systems may have further enriched these soil landscapes (Ullah et al., 2019) through systems of floodwater farming which may be comparable to those in the Yanqi Basin further to the east (Li et al., 2019a). There remains some scope for investigating more broad patterns of human landscape modification using palaeoenvironmental data from this region.

In the Kochkor Valley of north-central Kyrgyzstan, substantial evidence for the anthropogenic creation of a high-altitude agropastoralist niche comes from archaeological, archaeobotanical, and aerial survey data indicating the presence of a number of settlement sites, corral structures, water management features, and the cultivation of cereal crops at elevations above 1,900 m above sea level (ASL), dating from ca. 4,500 BP onward (Motuzaite Matuzeviciute et al., 2019, 2020; Rouse et al., 2022). The first phase of occupation at the site of Chap (ca. 4,500–4,000 BP) indicates the development of mainly bread wheat and naked barley agriculture, with weed seeds from the archaeobotanical assemblage probably resulting from both crop processing and burning dung of domestic herbivores (Motuzaite Matuzeviciute et al., 2020). During the second phase of occupation (ca. 3,000–2,800 BP), the agricultural package expands to include peas, summer millets, and hulled barley (Motuzaite Matuzeviciute et al., 2019). Animal bones in both phases provide direct evidence of livestock herding. To the west of the Kochkor Valley, peaks of summed coprophagous spores in the Son Kol lake record at ca. 3,700 and 2,500 BP have also been interpreted as evidence of phases of intensified herding (Sorrel et al., 2021) while increased occurrences of *Pediastrum boryanum* after ca. 4,000 BP in another core from Son Kol have also been interpreted as evidence of human impact (Mathis et al., 2014).

Chap II represents the first agropastoral communities moving into the landscape of Central Tien Shan at ca. 4,500 BP (Motuzaite Matuzeviciute et al., 2019, 2020). The site comprises houses and waste pits dug almost into the bedrock, likely indicating the period of first agropastoral settlement followed 1,000 years of slow postglacial sedimentation, suggesting a stable and low-erosion environment. Between the Chap II occupation and the Chap I occupation phase ca. 1,500 years later, 1.4–1.7 m of aeolian sediment had been accumulated (Motuzaite Matuzeviciute et al., 2020), while the Chap I occupation was also buried by 1–1.5 m of sediment following abandonment (Motuzaite Matuzeviciute et al., 2019). This rapid sedimentation was possibly the result of human-induced landscape disturbances *via* grazing and agricultural activities leading to sediment mobilization (Motuzaite Matuzeviciute et al., 2020). A similar situation was also observed at the Aigyrzhal-2 mound located in the middle of the Naryn River canyon in Central Kyrgyzstan (Motuzaite Matuzeviciute et al., 2017). Aigyrzhal-2 contains both a 12,000 BP Mesolithic occupation and a later Bronze Age occupation dated to ca. 2,000 BP, separated by a 30-cm-thick loess horizon. Following the Bronze Age, the sedimentation rate at Aigyrzhal-2 increases dramatically covering the occupation horizon with a sediment bedding over 1 m thick, possibly reflecting anthropogenic erosion processes following the initiation of agriculture in the area.

This interpretation may be supported by a lake core on the north side of Issyk Kol, in a large basin east of the Kochkor Valley, where the highest abundances of *Glomus* spores are between ca. 4,500 and 2,700 BP (Leroy and Giralt, 2021). This period in the Issyk Kol record also has the highest abundances of coprophagous spores (*Sporormiella*, *Podospora*, and *Sordaria*-types) and pollen types that may be associated with grazing including Asteraceae, *Rumex, Polygonum*, and *Plantago*, while a peak in micro-charcoal influx may be possible evidence of anthropogenic burning. After 2,700 BP, these indicators are generally present at low but fluctuating levels until 1,000 BP when increased abundance and influx may be evidence of intensified human impact. New survey data from the south of the Issyk Kol basin (Chang et al., 2022) indicates occupation of the area from 4,000 BP onward, with significant expansion during the Qarakhanid period after ca. 1,000 BP, roughly consistent with changes in the lake core data.

These patterns in land use may also be apparent in a smaller lake record from Karakol (Beer and Tinner, 2008), a subalpine lake (2,350 m ASL) located in the mountains around 23 km north of the Issyk Kol coring site. At ca. 3,600 BP, arboreal and shrubby pollen types reach a minimum, while Poaceae (to 60%), various Asteraceae (>10%), and other meadow vegetation increase, and a maximum charcoal influx is recorded. *Podospora* concentrations reach their highest values, and *Sordaria*-types are also present. Other pollens indicating disturbance, including *Plantago* and *Urtica,* are also present. After ca. 3,000 BP, these indicators decline until ca. 1,000 BP when peaks of coprophagous spores, charcoal influx, disturbance indicators (*Plantago, Urtica*, and *Cannabis*), and other pollen types associated with grazing (*Rumex* and *Trifolium*) are all recorded. Notably, three pollen types that may be associated with "Silk Road" trees are present after ca. 500 BP—walnut (*Juglans regia*), mulberry (*Morus alba*-type), and plane tree (*Platanus orientalis*).

A series of targeted cores from mires and small lakes have investigated the origins of walnut forests around the rim of the Ferghana Valley in northeast Kyrgyzstan (Beer et al., 2008). At Bakaly, a minor peak in charcoal influx ca. 4,000 BP may be associated with a sharp decline in an arboreal (*Picea* and *Betula*) and shrubby *Juniperus* pollen types. There is an apparent opening of the landscape, indicated by various Asteraceae types, and *Podospora, Sordaria*, and *Sporormiella*-type spores reach peak concentrations. These perturbations may be evidence of anthropogenic clearing of the landscape and initiation of herding. These indicators decline between 3,000 and 2,000 BP while arboreals and shrubs recover before a similar pattern is repeated and other disturbance indicators including *Plantago* and *Urtica* also increase. *Juglans* and *Platanus* pollen are present in low levels after 2,000 BP, and *M. alba*-type after 1,000 BP. All three types of trees increase sharply after 500 BP. At Ak Terek, *Juniperus* pollen decreases after 2,000 BP, possibly related to an increase in charcoal influx. Indicators for grazing disturbances including *Plantago* and *Urtica* pollen and all three types of coprophagous spores also increase after 2,000 BP, and *Juglans* is present at low levels, before increasing sharply after 1,000 BP. *M. alba* and *Platanus* types are infrequent after 1,000 BP. Increases in these three tree pollen types and pollen and fungal spore indicators for grazing are also recorded after 1,000 BP in a lake/mire core at Ortok and two lake cores at Nizhnee and Verkhnee.

A recent zooarchaeological study of remains from contexts 1 and 2 at the Obishir V site in southern Kyrgyzstan indicates the herding of domestic sheep as early as 8,000–6,000 BP, at an elevation of 1,700 m ASL (Taylor et al., 2021) and in the mountains of eastern Uzbekistan (Nishiaki et al., 2022). The latter dates from these sites appear to be contemporaneous with a small spike in the summed human (coprostanol, epicoprostanol, and cholesterol) and herbivore (5b-stigmastanol) fecal biomarkers at ca. 5,900 BP, from an alpine (3,535 m ASL) lake core at Chatyr Kol in central Kyrgyzstan (Schroeter et al., 2020). A more significant increase in these biomarkers appears ca. 5,000–4,000 BP before declining sharply, with a final minor peak at ca. 2,300 BP. The study authors correlate these spikes in biomarkers with regionally drier conditions, which may have driven the use of higher altitude ecological niches. The authors also note that the Chatyr Kol pollen assemblage is dominated by non-arboreal taxa and exhibits no significant variation; however, we note that there is a stepwise reduction in arboreal pollen, averaging 7.8% of the assemblage between ca. 8,000 and 6,000 BP; 5.8% between 6,000 and 4,000 BP; 2.9% between 4,000 and 2,000 BP and 2.6% from 2,000 BP to the present (Schroeter et al., 2020). While these reductions may be the result of natural Holocene processes, they also appear to coincide with other data indicating human impacts on the landscape. A lower elevation lake sediment record from Kichikol in southern Kyrgyzstan records a reduction in *Betula* and *Juniperus* and increases in *Plantago, Cannabis*, *Urtica* pollen, and charcoal influx after 3,000 BP, possibly indicating early land clearing (Beer et al., 2007). After 2,000 BP, *Juglans, Morus*, and *Platanus* tree pollens are present. Within this region, minor impacts on the landscape have also been inferred from pollen indicators, indicating an expansion of steppe herbs and increases in Asteraceae and *Plantago* from the Karakul alpine lake in Tajikistan (Heinecke et al., 2018), dated shortly after 1,000 BP.

Western Himalaya-Hindu Kush

A pollen record from a heavily grazed Cyperaceae swamp, adjacent to a high-altitude summer settlement at Shukan (3,360 m ASL) in the Eastern Hindu Kush, Pakistan, has been studied to investigate human impact on the landscape (Miehe et al., 2009). While the site area has relict patches or stands of *Pinus wallichania* and *Betula utilis,* the landscape today is primarily open pasture. Based on a sharp reduction of *Pinus* pollen and monolete fern spores, the study authors argue for an anthropogenic opening of the landscape by ca. 3,000 BP. Long-distance transport and the recorded overrepresentation of *Pinus* pollen in the temperate Himalayas (Quamar and Kar, 2020) may support this interpretation. Increases in other indicator pollen including *Rumex, Urtica*, and *Plantago* after ca. 1,000 BP may indicate an intensification of land use after this period. Other evidence for intensified patterns of grazing comes from fungal spore indicators between ca. 2,400 and 1,500 BP in a core from Kabal in the Swat Valley (Jan et al., 2019). These single-proxy studies present promising early results for examining long-term agropastoralist ecology in a region where little data are available.

In the Kashmir Valley, India, three cores taken from middle- to high-altitude pastures investigated the impacts of agropastoralism on the landscape (Spate et al., 2021, 2022). In the subalpine TM01 record, reductions in arboreal *Betula* and *Juniperus* pollen and the deposition of coarser, more poorly sorted sediment after ca. 3,700 BP are interpreted as clearing by herders, also indicated by increased influxes of charcoal, concentrations of coprophagous spores, increases in Poaceae, *Rumex*, and other grazing-associated herbs and reduction in grazing sensitive *Artemisia*. This period is contemporaneous with the expansion of agropastoralist settlements across lower elevations in the valley during the Late Neolithic (Betts et al., 2019). After ca. 2,000 BP, there is another stepwise reduction in arboreal pollen and a stronger signal for grazing in the earlier proxies. In the middle-altitude PH03 record, increases in charcoal influx, sediment size, and grazing-associated pollen and spores increase sharply at ca. 2,200 BP (Spate et al., 2022). Cereal-type pollens are interpreted as the movement of cultivation to middle altitudes, possibly in response to regionally drier climate conditions. These conditions may have also stressed sensitive populations of relict *Quercus* forest across the valley, possibly driven to extinction by human overuse, evidenced by the disappearance of *Quercus* pollen in sediment records (Spate et al., 2021) and charcoal at archaeological sites (Lone et al., 1993) after ca. 2,000 BP. Multiple proxies for grazing also increase in the SG02 core from a forest opening at 2,800 m ASL after ca. 500 BP (Spate et al., 2022). These discontinuous phases of land use also parallel changes in the pollen record from Anchar Lake on the valley floor, where the intensification of agriculture after ca. 4,000 BP is indicated by increases in *Plantago,* cereal-type, and other ruderal pollen (Agrawal, 1992). Changes in magnetic susceptibility indicating eutrophication of the lake, higher C/N ratio and organic input, and coarser sediment deposition have been interpreted as signals of anthropogenic control of Anchar Lake after ca. 500 BP (Lone et al., 2019).

East of the Kashmir Valley, an alpine lake core from Tso Moriri (Leipe et al., 2014a,b), had a moderate influx of charred grass epidermis and *Cannabis* pollen after ca. 3,700 BP, interpreted as a possible low-level human impact on the landscape. After ca. 2,700 BP, relative abundances of ruderal and other grazing-associated pollen types such as *Rumex*, *Urtica*, and *Plantago* increase. After ca. 1,000 BP, cereal-type and *Fagopyrum* pollen are also present, though the authors note the effects of altitude on Poaceae pollen size and the distribution of wild *Fagopyrum* in the Himalayas as confounding factors. Similarly, *Cannabis* and cereal-type pollen from Tso Kar (Demske et al., 2009) after ca. 2,500 BP have been interpreted as regional signals rather than local vegetation. Both lakes are surrounded by alpine (ca. 4,500 m ASL) meadows that are currently utilized by seasonal herders. Given the large size of the lake catchments, they may present a record of regional impacts rather than local modification of the environment by herders.

Holocene Climatic Variation

The available proxy data draw a spatiotemporally complex picture of the climate and environmental evolution in the study region during the Middle (8,200–4,200 BP) and Late (last 4,200 years) Holocene. Precipitation and moisture availability are mainly controlled by two atmospheric circulation systems—the Atlantic Westerlies and the Asian summer monsoon. While the monsoon influence dominates most parts of East, Southeast, and South Asia, the westerlies control large parts of West and Central Asia, including the western Eurasian steppes of southwest Siberia and Kazakhstan and the arid regions to the south. Xinjiang and the Western Himalayas represent transitional zones between both circulation systems, complicating the interpretation of palaeoenvironmental proxy records with respect to driving factors, especially with the awareness that the intensity of these circulation systems has changed during the Holocene.

The steppe and desert regions west of the Tien Shan experienced increased moisture availability during the Middle and Late Holocene. Representative evidence for the steppes of Kazakhstan and south-western Siberia is the fossil pollen-inferred continuous spread of tree taxa around the Ozerki swamp (Tarasov et al., 1997; **Figure 3A**). A similar pattern is revealed by the sediment properties of the CSM loess section in western Tajikistan, located west of the main Pamir ranges. The magnetic susceptibility record demonstrates that soil moisture was relatively stable until ca. 5,000 BP and gradually increased afterward (Gao et al., 2019; **Figure 3B**). Although several new proxy records have been published over the last decade, the moisture index curve based on palaeoenvironmental data synthesis by Ran and Feng (2013); **Figure 3C** remains a representative record for Holocene moisture availability in the Dzungar Basin, continuously increasing between ca. 8,000 and 1,000 BP. While the long-term trend of these records indicates increased moisture availability through the Middle to Late Holocene, there is an apparent minor downward fluctuation between ca. 3,000 and 2,000 BP.

An opposite moisture trend is demonstrated by proxy records from sediment archives in Xinjiang south of the Tien Shan or in its eastern extremity. Organic geochemical parameters from sediments in the hypersaline Lake Balikun indicate a long-term decline in moisture availability that started around 6,000 BP (Zhao et al., 2022). The moisture index derived from the deposits at Lop Nur agrees with this trend (Liu et al., 2016). The pollen record at Lake Bosten indicates that moisture availability declines between ca. 6,000/5,000 and 1,500 BP and then increases to the present (Tarasov et al., 2019; **Figure 3E**). A similar moisture pattern is found in palaeoenvironmental records from the north-western Himalayas located at the modern northern boundary of the Asian summer monsoon domain. Pollen-based reconstructions of moisture availability for the areas around the high-alpine (approximately 4,500 m ASL) lakes Tso Kar (Demske et al., 2009) and Tso Moriri (Leipe et al., 2014a; **Figure 3F**) show a continuous decline in annual precipitation from ca. 7,000 BP. This trend reversed from 1,500 calendar years BP, probably due to the increasing inflow of moisture derived from the west.

Precipitation and moisture availability in the extensive mountainous interior of the central and western Tian-Shan and Pamir appears to be more complex, lacking evidence for clear long-term trends. Several studies reconstructed a phase of increased or increasing moisture between ca. 5,000 and 4,000 BP including pollen spectra from Lake Karakul, north-eastern

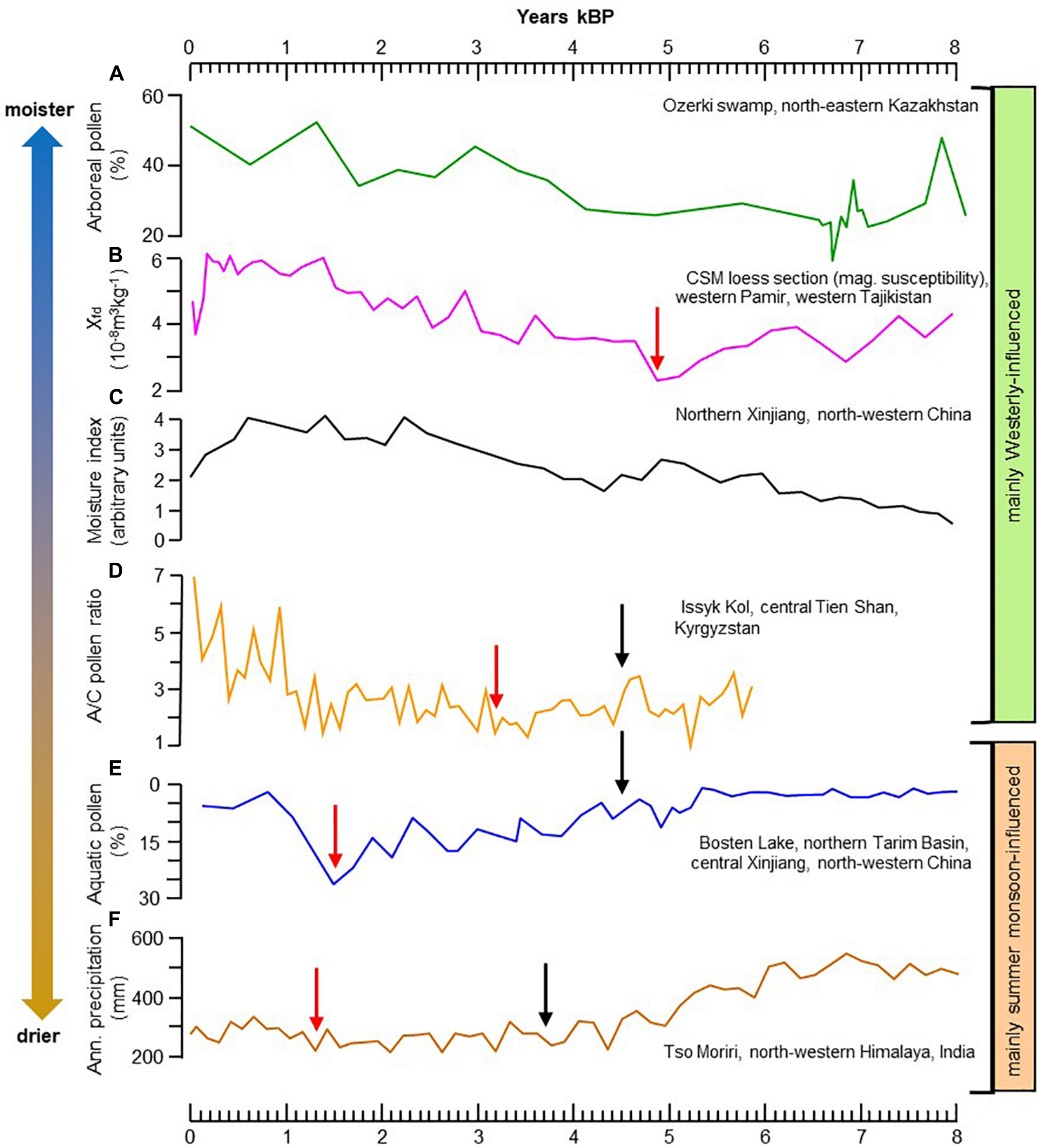

FIGURE 3 | Representative moisture records from Westerly and summer monsoon-controlled regions. **(A)** Tarasov et al., 1997; **(B)** Gao et al., 2019; **(C)** Ran and Feng, 2013; **(D)** Leroy, 2022; **(E)** Tarasov et al., 2019; **(F)** Leipe et al., 2014a. Red arrows mark the transition from summer monsoon-dominated to a Westerly-dominated moisture availability. Records without arrows represent regions that were consistently influenced by Westerly precipitation. Black arrows indicate human impacts in palaeoenvironment record for Central Tien Shan, Xinjiang and Western Himalayan regions.

Tajikistan (Heinecke et al., 2018), lithological properties, pollen and chironomid records from Lake Kichikol, south-western Kyrgyzstan (Beer et al., 2007), pollen spectra from Lake Issyk Kol, north-eastern Kyrgyzstan (Leroy and Giralt, 2021), and chironomid spectra from Lake Son Kol, central Kyrgyzstan (Laug et al., 2020). However, other records obtained from the same lakes or studies conducted at other sites in the region suggest contradicting moisture trends. Based on sediment geochemical parameters, Heinecke et al. (2017) inferred a Middle–Late Holocene drying trend around Lake Karakul. A multi-proxy study from Son Kol (Lauterbach et al., 2014) inferred a dry phase between 5,000 and 4,000 BP, followed by a progressive but weak decrease in moisture to the present. Another multi-proxy study from the same lake by Schwarz et al. (2017) found evidence for a dry climate interval ca. 6,000–3,800 BP. In contrast, Mathis et al. (2014) reconstructed warm and moist conditions around Son Kol before 4,500 BP, followed by arid conditions. This complicated spatiotemporal pattern of moisture evolution may be the result of an interplay between complex topography and shifts in atmospheric circulation patterns. The region is likely to represent a transitional zone between the Western and Asian summer monsoon systems and is therefore sensitive to short-term fluctuations and long-term changes in their intensity. Additionally, the mountainous environment potentially affected the hydrology of the lakes by changes in basin properties (endorheic, exorheic conditions) and/or more pronounced impacts of temperature changes leading to changes in meltwater supply and lake evaporation. We plotted the *Artemisia*/Chenopodiaceae (A/C) pollen ratio for Issyk Kol from available repository data (Leroy, 2022; **Figure 3D**) as a commonly used proxy for changes in moisture availability in arid and semi-arid environments (El-Moslimany, 1990). The data broadly indicate a drying trend from at least ca. 6,000 BP to 3,000 BP, possibly due to weakening summer monsoon precipitation. After 3,000 BP, increased Westerly control may have driven moister conditions, with minor drier fluctuations around 2,700 and 1,700 BP. A strong increase in the A/C ratio after ca. 1,500 BP coincides with increased Westerly precipitation around the Bosten (**Figure 3E**) and Tso Moriri (**Figure 3F**) lakes, previously dominated by the Asian summer monsoon system. All three records suggest an enhanced increase in Westerly-associated precipitation in the respective regions after ca. 1,500 BP.

DISCUSSION

Assessing Long-Term Human Impacts

Many of the records examined here are drawn from lake studies focused primarily on broader patterns of Holocene climate or environmental change, with some proxies from these studies indicating varying levels of human impact. Several of the records drawn from high-altitude lakes (Demske et al., 2009; Heinecke et al., 2018; Schroeter et al., 2020) typically have proxies indicating the human presence and low-level impact through time, consistent with their altitudinal position and catchment size. Multi-proxy studies from large lakes located in regions more intensively inhabited by past populations provide strong evidence for long-term processes of environmental modification and impact by humans (Tarasov et al., 2019; Leroy and Giralt, 2021). A number of the studies were more specifically oriented toward understanding local patterns of anthropogenic environmental change, using multiproxy indicators to examine human impacts (Beer and Tinner, 2008; Beer et al., 2008; Zhang et al., 2015; Spate et al., 2022). Core samples in these studies were generally drawn from smaller swamps, wetlands, or mires with catchment sizes more suitable for understanding local patterns of human land use. One single-proxy pollen study (Miehe et al., 2009) from a similar sampling site also demonstrates promise for reconstructing anthropogenically driven environmental change.

The oldest evidence of the possible human presence in the studies reviewed comes from the biomarkers in the high-altitude Chatry Kol (Schroeter et al., 2020) lake in the Tien Shan (**Table 1** and **Figures 2**, **4**). These proxies do not indicate significant human impact and we approach them cautiously; however, they do appear to be temporally consistent with archaeological evidence for early herding and hunting populations in the mountain environment (Taylor et al., 2021; Nishiaki et al., 2022). Currently, there is no archaeological evidence for agriculture in the study region at this period; however, given the presence of Neolithic agricultural settlements in the adjacent Kopet Dag foothills of southern Turkmenistan (Harris, 2010), future archaeological testing for early agriculture is required. The most significant early impact are seen in pollen, spore, and charcoal proxies around 4,500 BP at Issyk Kol (Leroy and Giralt, 2021) and Bosten (Tarasov et al., 2019) and are closely associated with the first archaeological evidence for cereal cultivation and agropastoralism across the study region (Doumani et al., 2015; Hermes et al., 2019; Motuzaite Matuzeviciute et al., 2020). In the period 4,000–3,000 BP, 10 of the reviewed records indicated evidence for human impacts, primarily palynomorph, charcoal, and sediment proxies associated with agropastoralist land use across foothills and middle-altitude mountain zones. In the Issy Kol record, these proxies present before 4,000 BP also increase significantly in the following centuries (Mathis et al., 2014; Leroy and Giralt, 2021). The close association between these impacts and archaeological evidence for the expansion of agriculture and pastoralism (Motuzaite Matuzeviciute et al., 2020; Yatoo et al., 2020; Hermes et al., 2021; Tian et al., 2021) indicates a significant and rapid transformation of these environments. This suggests a divergence in land use impact between earlier herding-only populations and later agropastoralist ecologies.

Archaeological sequences from sites across the region indicate long-term settlement patterns at sites, comprising phases of occupation interspersed with centuries of abandonment (Frachetti and Mar'yashev, 2007; Doumani et al., 2015; Pokharia et al., 2018; Motuzaite Matuzeviciute et al., 2020; Hermes et al., 2021). The temporal variability of the human impacts in the records reviewed here may be broadly reflective of these patterns of land use. Variability in indicators for human impact in swamp/mire records may reflect localized patterns of settlement or land use as agropastoral populations shifted sites of economic or ecological focus. A deeper understanding of these patterns may require further data from local scale palaeoenvironmental studies and a close synthesis with an expanding archaeological record. The studies reviewed here typically indicate long-term, low-level perturbations suggesting that agropastoralist groups across the Inner Asian mountains maintained ecological niches through systems of locally adapted grazing and cultivation.

The variability in environments and climates across the study area likely drove differentiated human adaptations in land use in the past. Spengler et al. (2016) have suggested that the continuous trend toward higher moisture levels in the Westerly-dominated steppe regions west of the Altai Mountains improved the conditions for crop cultivation and thus promoted the spread of agropastoral populations in northern Central Asia. The progressive increase in moisture availability may have also facilitated the documented spread of pastoralist groups into the Dzungar Basin by the middle of the fifth millennium BP (Jia et al., 2020; Dodson et al., 2021) by providing suitable grazing lands in areas that have likely been too dry before. Similarly, d'Alpoim Guedes and Bocinsky (2018) have argued that changing thermal and moisture conditions stimulated the exchange of crops and diversification of agricultural systems as a buffer against risk in higher altitudes and latitudes in Asia. Weakening moisture availability in the Kashmir Valley after ca. 5,000 BP (Lone et al., 2019; Spate et al., 2021) may have driven the relatively early adoption of millet agriculture dated to ca. 4,400–4,200 BP (Yatoo et al., 2020). The intensification of herding and agriculture at

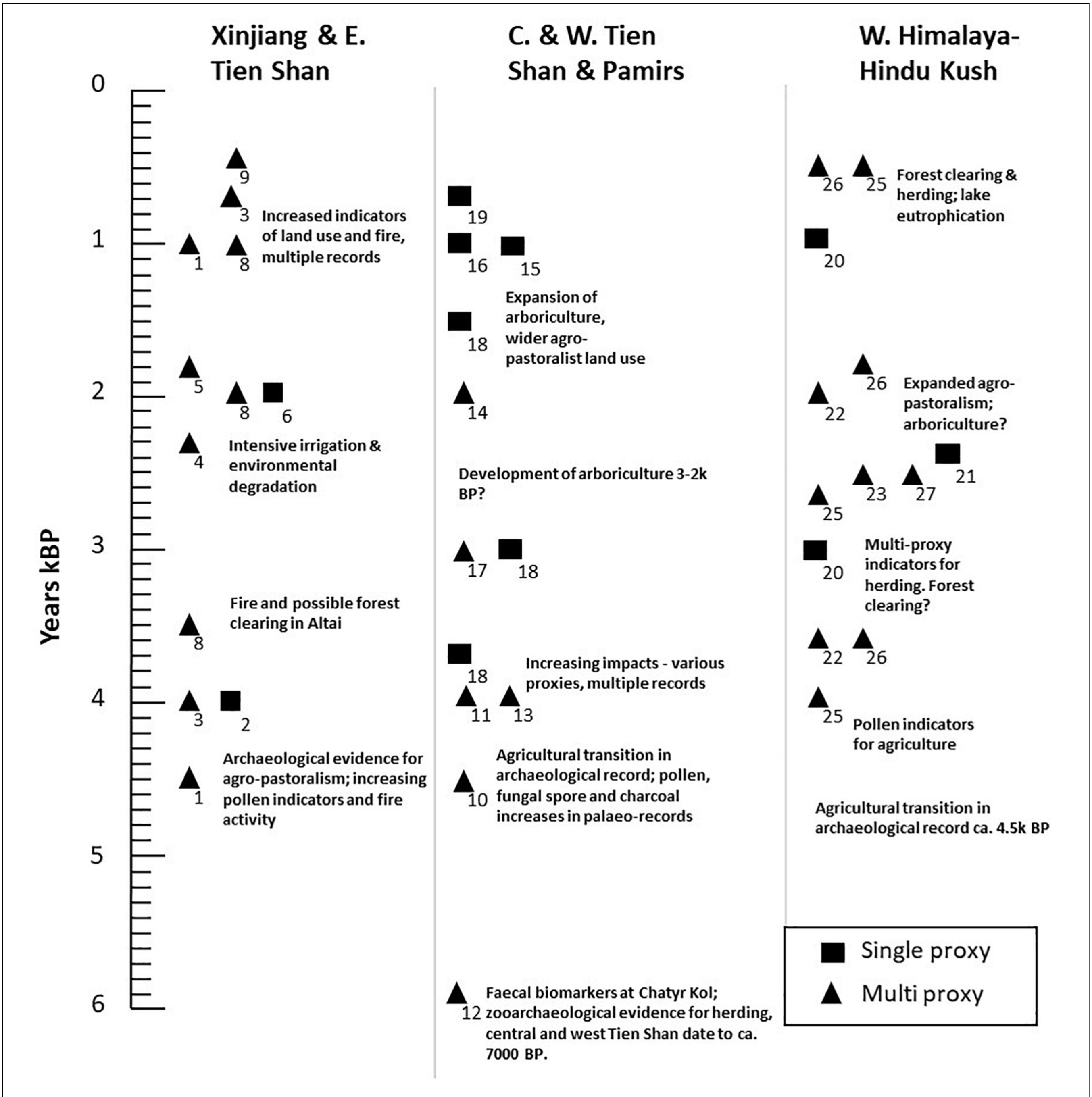

FIGURE 4 | The time scale of impacts identified in the studies reviewed here and described changes from available archaeological and environmental records. Numbers refer to records in **Table 1**.

higher altitudes on the Kashmir Valley flanks also appears to respond partly to the onset of more arid conditions on the floodplain of the valley floor around 2,000 BP (Spate et al., 2022). Isotopic data from Begash, Dali, and Tasbas at Semirechiye, indicating winter foddering of sheep and goats (Hermes et al., 2019) after ca. 4,700 BP, suggests the close integration of herding and cultivation. Interestingly, millets are not found in the early occupation phase at Chap (Motuzaite Matuzeviciute et al., 2020) and are only present after ca. 3,000 BP. While our review of Western precipitation records generally indicates increasingly wetter conditions through the late Holocene, however we note high variability and complex relationships between Western and monsoon systems in the Central Tien Shan records, complicating the understanding of human responses to climate change. The Issyk Kol record is the most proximal to Chap and indicates a phase of minimum moisture availability in the late Bronze

Age around 3,000 BP, as evidenced by low A/C pollen ratios (Leroy, 2022; **Figure 3D**). This more localized phase of low moisture availability may have been a driving factor in the delayed adoption of millet at Chap. At present, the archaeological record across the studied region suggested a flexible agropastoralist ecology that was able to draw on various patterns of herding and cultivation to respond to Holocene climatic perturbations.

Forest Use and Mining?

While proxy indicators for cultivation and pastoralism identified here are primarily changes among herbaceous pollen and coprophagous spores, reductions in arboreal pollen and charcoal influxes may indicate forest clearing and the opening of landscapes (Miehe et al., 2009; Li et al., 2019b; Spate et al., 2022). At Chap, the early phase of occupation has high concentrations of wood charcoal, while during the later phase dung burning appears to be the major fuel source (Motuzaite Matuzeviciute et al., 2021). The present-day site environment is an open landscape and the change between these fuel sources may partially result from the exhaustion of forest resources around the site. Currently, shifts in *Picea* pollen concentration at Issyk Kol (Leroy and Giralt, 2021) and influx at Son Kol (Beer and Tinner, 2008) have been interpreted as related to climate-driven shifting of the tree line. REVEALS modeling (Cao et al., 2019) applied to data from the studies of Beer et al. (2007, 2008) and Beer and Tinner (2008) based on relative pollen productivity (RPP) estimates from analogous Chinese and European plant taxa do indicate a reduction in conifer forests sometime around 2,000 BP; however, Cao et al. (2019) note that the temporal resolution of the original studies fails the binning of time slices in the model. In the Kashmir Valley, anthracological data indicate a broadening use of timber fuels through time (Lone et al., 1993). Two charcoal types identified as *Quercus* during the Kushan period (ca. 2,000 BP) indicate the use of oaks, absent in the valley today. Pollen records (Spate et al., 2021) also indicate the disappearance of *Quercus* at ca. 2,000 BP, during a period of weak summer precipitation, possibly evidence of a climate and anthropogenic extinction of oaks in Kashmir. As with the Central Tien Shan data, interpreting land-cover change in the Western Himalaya-Hindu Kush based on pollen records is complicated by the high productivity and long-distance transport of coniferous pollen (Quamar and Kar, 2020). As a result of these circumstances, there is good potential for land-cover modeling based on RPP and pollen fall speed estimates for local taxa in the future.

Our review indicates that, in addition to processes of land clearing, instances of human management of forest stands are also evident, notably the potential anthropogenic afforestation of walnut in Kyrgyzstan (Beer et al., 2008). While Beer et al. (2008) have interpreted these increases as evidence for the introduction of walnut into the region, the genetic diversity of extant walnut forests in Central Asia (Pollegioni et al., 2014), and the presence of *Juglans* pollen in Pleistocene deposits from the Kashmir Valley (Agrawal, 1992) indicate an autochthonous postglacial distribution in the region. The increased abundance in pollen records from Kyrgyzstan may be rather indicative of an intensified human economic focus on this taxon.

In addition to increases in *Juglans* pollen, the presence of *Platanus* pollen suggests an aesthetic and economic investment into this landscape. Potts (2018) notes the mid-Holocene spread of *Juglans* and *Platanus* in pollen records across Iran, which precedes the deep cultural significance of walnut and plane trees in the later Persian and Islamic periods when pollen of both types expands in records from Iran (Saeidi Ghavi Andam et al., 2021). *Platanus* pollen is recorded in a Pleistocene loess-palaeosol record from southern Tajikistan (Dodonov and Baiguzina, 1995), however, in the topmost pedocomplex 1, dated relative to Marine Isotope Stage 5, it is poorly represented and also appears absent from other Early Holocene pollen records in the region. It is unclear when *Platanus* was reintroduced to Central Asia, though it is assumed to have been before the Islamic Period (Rix and Fay, 2017). *Platanus* and *Morus* charcoals have been identified in Early Historical (ca. 2,000 BP) contexts at Semthan and Burzahom in the Kashmir Valley (Lone et al., 1993), where in historical periods these two trees, along with walnut, were valued for their fruits and oils and prized as fuel and carving woods, particularly for the doors of Sufi mausoleums (Lawrence, 2005 [1895]). The close association between plane trees and Sufi shrines has been noted throughout Central Asia (Yasushi et al., 2013), and the Kyrgyzstan pollen records (Beer et al., 2008) provide early insights into the spread of these culturally significant taxa across Central Asia. The expansion of *Morus* pollen during the Medieval era may also be associated with the development of the silk industry in the Islamic period (Spengler, 2019).

Environmental impacts of mining and smelting in the study areas remain underexplored. Metallurgy has been identified as a parallel productive industry that pastoralists engaged in throughout the region, from the Bronze Age to the Medieval period (Frachetti, 2012; Maksudov et al., 2019). Copper mines with diagnostic Andronovo Bronze Age ceramics have been identified in the Ili Valley in Xinjiang (Wang et al., 2019), and tin mines also associated with Andronovo finds have been recorded in mountainous areas of eastern Uzbekistan and Tajikistan (Boroffka et al., 2002). Localized pollen records may be one method of exploring impacts on forests for fuel in these areas, while geochemical pollution accumulated in lake sediments or mires may provide an expanded record for anthropogenic perturbations related to mining, as has been demonstrated in other areas of the planet (Mighall et al., 2002; Pompeani et al., 2013; Martínez Cortizas et al., 2016).

Is There a "Tipping Point?"

The data we review typically do not indicate wholesale transitions from a "pristine" to a completely anthropogenic environment. In total, 10 of the records indicate the "secondary" or intensified impact after ca. 2,000 BP or later, becoming more pronounced again after ca. 1,000 BP (**Figure 4**). The synthesis of these studies generally indicates long-term management of landscapes, with "patchy" mosaics (Spengler, 2014) of managed pasture land. The most detrimental environmental impacts appear in the form of degradation induced by intensive irrigation agriculture (An et al., 2012; Mischke et al., 2017) in ecologically unsuitable regions.

This degradation of larger lake systems may be comparable to the withdrawal of water from Lake Balkhash tributaries in southeast Kazakhstan since the 19th century, which has had an impact on lake levels (Chiba et al., 2016; Mischke et al., 2020; Sala et al., 2020) where increased water consumption is correlated with urbanization in the region. The environmental impacts of urban expansion in more mountainous regions during the early historic and Medieval periods present an important area for future investigation (Maksudov et al., 2019). The onset of anthropogenic control at Anchar Lake (Lone et al., 2019) in 500 BP is likely associated with the expansion of the city of Srinagar in the immediate lake catchment, presenting preliminary evidence of the more intensive transformation of mountain environments across the region.

CONCLUSION

The studies under review indicate long-term processes of land management and modification in the foothills and mountain zones of Inner Asia. Evidence of early human presence may date as early as ca. 6,000 BP, constrained to high-altitude areas. This is in agreement with recent genetic and zooarchaeological evidence showing movements of small herding populations across the landscape in the absence of agriculture (Taylor et al., 2021; Nishiaki et al., 2022). Across the study region, there is evidence of human impact and disturbance of natural environments around 4,500 BP, with indications for intensification after ca. 4,000 BP. These changes correlate closely with archaeological data reflecting the beginning of crop cultivation and intensified herding activity, with the environmental record lagging the archaeological record by 500 years or less. We interpret this as indicating agropastoralism driving a rapid environmental change across landscapes of the study area. Following the introduction of agriculture, progressive impacts on environments are generally not evident; however, there may be some intensifications in land use by agropastoralists at ca. 2,000 and 1,000 BP as indicated in numerous records across all of the areas we examined. Interpretations of anthropogenic perturbation are best supported by multiproxy studies comprising biotic and abiotic data proxies, preferably with different pathways into the sedimentary record. We have identified areas for further research, particularly the potential for the quantitative study of changes in forest landcover of the study region. The apparent long-term stability of the study area landscapes indicates that traditional forms of agropastoralism may be a sustainable economy with a low impact on local ecologies and should be considered in the present and future programs of conservation and environmental restoration.

AUTHOR CONTRIBUTIONS

MS conceptualized the research. All authors undertook the research, reviewed and edited manuscript. MS drafted the manuscript with written inputs from CL and GM.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2022.939374/full#supplementary-material

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