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Vegetation and fire anomalies during the last ~70 ka in the Ili Basin, Central Asia, and their implications for the ecology change caused by human activities

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Abstract: Changes in vegetation characteristics and fire occurrence during the last glacial period offer an opportunity to better understand paleoclimate change and past human activities as well as the relationships among them. However, in central Asia, records of both vegetation and fire have rarely been obtained from the same profile. Here, for the first time, we present pollen and microcharcoal data collected together from the wind-blown loess Nileke section, representing the past ~70 thousand years (ka) in the Ili Basin, Northwest China, Central Asia. These records enable investigation of the pollen-based vegetation and microcharcoal-based fire proxies as well as their possible relationships with ancient human activities. The results show that the temperate herbaceous taxa remained at relatively low levels before 36 ka, whereas the temperate woody taxa, especially Cupressaceae, were abundant. At the same time, the fire frequencies were relatively low. After 36 ka, herbaceous taxa abruptly replaced Cupressaceae and the fire occurrence gradually increased. We named this change as the local vegetation degeneration event, because no equivalent changes have been identified anywhere else across Eurasia. Prior to the event, a period of intensified fire activity occurred between 47.5 and 36 ka, although the background fire activity was relatively low. We argue that the intensified local fire activity was the primary factor causing the vegetation event and was mainly driven by human activity. Following migrations from Africa after 200 ka, humans began to colonize the Ili Basin at least 47.5 ka ago, bringing their skills of fire control and consequential destruction of woody vegetation. Future analysis of first-hand archeological sites in this area will be an important step in supporting our hypothesis.

Keywords: Vegetation; Fire; Ecology; Human activities; Last glacial period

1. Introduction

The climate, vegetation, fire and human activities, as well as the relationships among them over the late Quaternary, especially the last glacial period, provide basic insights by which to understand the future (e, g., Behling and Safford, 2010; Cheng et al., 2012; Li et al., 2013; Hubau et al., 2015; Varela et al., 2015). High-resolution stalagmite (Wang et al., 2001; Cheng et al., 2016), ice core (Thompson et al., 1997; Petit et al., 1999; Augustin et al., 2004) and loess (e.g., Chen et al., 1997; Hao et al., 2012; Sun et al., 2012) analysis has yielded highly reliable, integrated paleoclimate records. These are characterized by a series of strong fluctuations, named cold Heinrich or warm Dansgaard-Oeschger events, as well as a warm middle Holocene (e.g., Bond et al., 1997). At the eastern margin of Central Asia, precipitation has followed the same patterns as these events: lower precipitation during the cold events and vice versa (e.g., Rao et al., 2013). Vegetation is regarded as one of the most sensitive proxies for climate change, and a limited number of complete vegetation records have been obtained to show how the terrestrial ecological landscape responded to climate change (e.g., Guiot et al., 1993; Allen et al., 1999; Jiang et al., 2011). Fire is another sensitive proxy used for reconstructing climate (e.g., Filion, 1984; Bird and Cali, 1998; Bowman et al., 2009). Besides climate, records of vegetation and fire are also unique indicators of human activities, owing to the impact of human activities such as vegetation cutting and burning (e.g., Patterson et al., 1987; Whitlock and Larsen, 2002; Huang et al., 2006; Aranbarri et al., 2014; Miao et al., 2016b; Sirocko et al., 2016); however, most relevant studies have been limited to the late Holocene, especially at archeological sites. Few studies have attempted to reconstruct the last glacial period, despite this period being considered as a key period of

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migration: the human migration from Africa started at around 200 ka (Templeton, 2002; Sun et al., 2012). Furthermore, studies of vegetation and fire within the same profile (section or core) are helpful in understanding the vegetation, fire and climate, as well as human activities (e.g., Zhao et al., 2010; Xiao et al., 2013; Miao et al., 2016a; b).

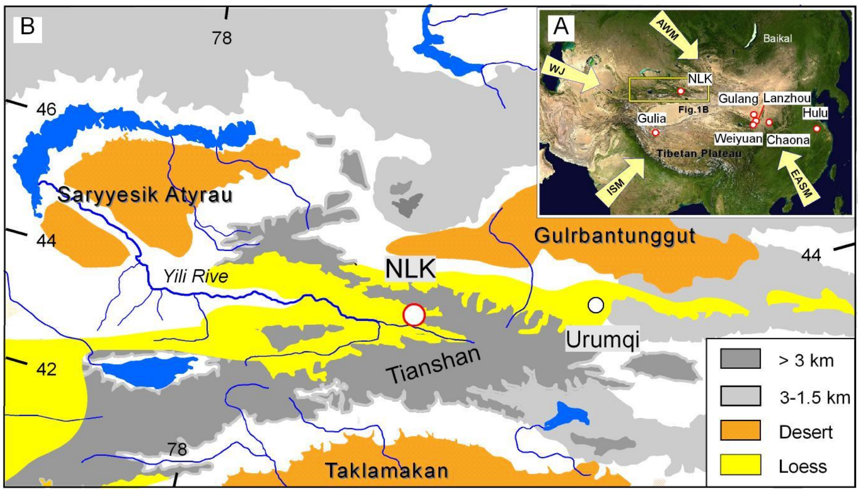

Figure 1. A. Asian morphological map with climate systems showing the NLK (Nileke) section location and climatic proxy sites covering the past 70 ka. These sites include the Gulia glacial core (Thompson et al., 1997), Gulang wind-blown sediments (Sun et al., 2012), Chaona (Wang et al., 2016), Hulu stalagmite oxygen isotope records (Wang et al., 2001), Weiyuan summer precipitation reconstruction (Rao et al., 2013) and Lanzhou pollen analysis (Jiang et al., 2011). B. A morphological map showing the location of the Nileke section in this study.

Central Asia is dominated by a dry climate (Figure 1A), which is very sensitive to any climate changes (fluctuations or abnormality) and human activities. In this study, we firstly present pollen and microcharcoal results from a wind-blown loess sediment section (Figure 1B) to reveal how vegetation and fire activity have changed during the past 70 ka; we then analyze the mechanisms underlying these changes.

2. Materials and methods

2. 1 Lithostratigraphy and chronology

The Ili Basin is surrounded by the Tianshan orogenic belt in east Central Asia, with gentle topography to the west. The basin opens to the west and funnels winds and cyclonic disturbances,

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often associated with prevailing westerly winds, down its axis (Ye, 2001). The Ili Basin has a temperate, continental, arid climate with a mean annual temperature that varies from 2.6 ℃ at 1850 m to 10.4 ℃ at 660 m; the mean annual precipitation varies correspondingly from 512 to 257 mm (Ye et al., 1997; Ye, 2001). The surface soils are a sierozem (aridosols) with widely distributed desert steppe vegetation. The vegetation coverage is <50%, mainly comprising *Artemisia* spp. and Chenopodiaceae spp. (Ye et al., 2000). There are no obvious accumulations of organic matter in the surface horizon of the modern soil.

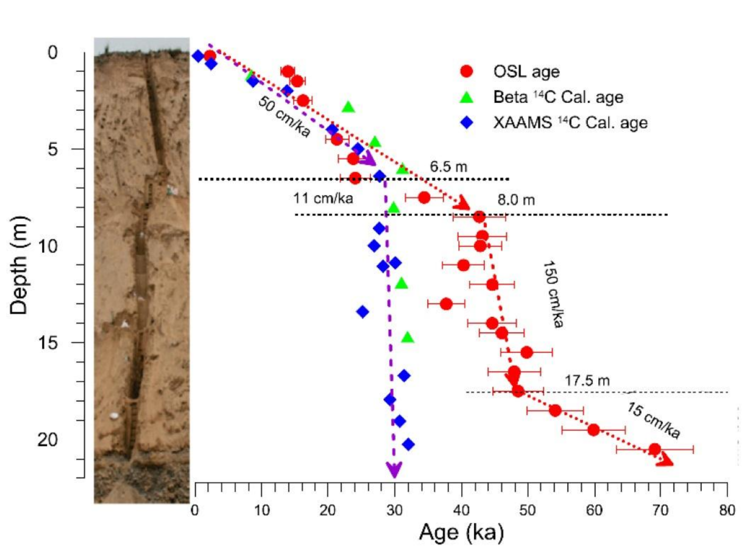

Figure 2. Stratigraphy and dating for the Nilke Section (for more detail see Song et al. 2015).

To the west of the Ili Basin are the vast central Asian Gobi Deserts, such as Saryesik-Atyrau Desert (Figure 1B), the probable source of dust for Late Pleistocene loess deposits. The loess deposits are widely distributed across the piedmont of the Tianshan Mountains, river terraces and desert margins. The loess thickness ranges from several meters to approximately two hundred meters, and there are two primary depocenters: around Sangongxiang in the northwest and Xinyuan in the east Ili basin (Song et al., 2014). Most of the loess appears to have been deposited since the last interglacial period (ca. 130 ka; Ye, 2001; Song et al., 2010; 2014; Li et al., 2016).

The Nileke section (83.25 °E, 43.76 °N, 1253 m a. s. l) is located on the second terrace of the Kashi River, a branch of the Ili River, in the east Ili Basin (Figure 1B). The loess sequence is 20.5

m thick, largely homogeneous in appearance with two diffuse paleosols at depths of 5-7.5 m and 15.5-18.5 m identified by the extent of rubification (Figure 2) (Song et al., 2015). The loess sequence rests conformably on fluvial sand and gravels. The contact between the loess and fluvial sediment is abrupt with no obvious lag, erosion or pedogenesis. The loess is composed of 70%-84% silt and 3%-17% very fine sand (63-100 mm), with the remaining fraction being clay. A high-resolution quartz optically stimulated luminescence (OSL) chronology has already been established (Yang et al., 2014; Song et al., 2015). Based on OSL ages, two intervals of higher mass accumulation rate occurred at 49-43 ka and 24-14 ka (Song et al., 2015).

2.2 Pollen and charcoal collection

A total of 104 samples of 49-56 g weight were taken at 20 cm intervals from the Nileke section for palynological analysis. The samples were treated with standard palynological methods: acid digestion (treatment with 10% HCl and 40% HF acid to remove carbonates and silicates, respectively) (Li et al., 1995) and fine sieving to enrich the spores and pollen grains. The prepared specimens were mounted in glycerol for identification. All samples were studied at the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS), by comparison with official published pollen plates and modern pollen references. Each pollen sample was counted under a light microscope at 400× magnification in regularly spaced traverses. More than 150 spores and pollen grains were counted within each sample. A known number of *Lycopodium clavatum* spores (batch # 27600) were initially added to each sample for calculation of pollen and microcharcoal concentrations (Maher, 1981).

The concentration of pollen or microcharcoals can be calculated according to the following formula: $C=N_x/L_x\times 27600/W_x$

C: concentration; N: identified number of charcoals; L: number of *Lycopodium clavatum*; W: sample dry weight; x: sample number; 27600: grain numbers of *Lycopodium clavatum* per pill.

For the microcharcoal identification, four particle size units were defined as follows: <30 μm, 30-50 μm, 50-100 μm and >100 μm (Miao et al., 2016a), then the total microcharcoal concentrations (MC) were obtained by summing over all sizes and using the above formula. As the residual matter from the incomplete burning of vegetation, charcoals are usually characterized by either spherical bodies without structure or particles with some original plant structures preserved.

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3. Results and analysis

In the pollen assemblages, dominant palynomorphs originated mainly from herbaceous taxa such as Chenopodiacaee, *Artemisia*, Ranunculaceae, Asteraceae and Rosaceae. Woody taxa were Cupressaceae, *Pinus*, *Betula*, Ulmaceae and Tamaricaeae; the other temperate taxa with low percentages were *Quercus*, *Picea*, *Cedrus* and *Broussanetia* etc.

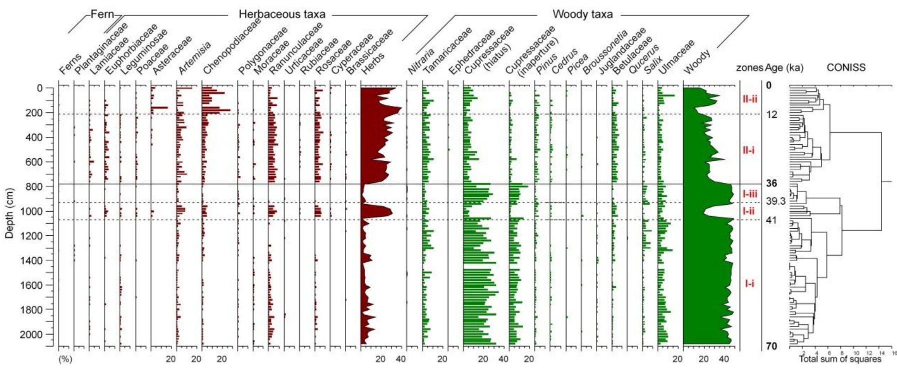

Figure 3. Pollen percentage diagram for the Nileke section, Ili Basin.

The pollen diagram was divided into two pollen assemblage zones based on variations in the percentages according to stratigraphically-constrained cluster analysis (CONISS) carried out using Tilia software (E. Grimm of Illinois State Museum, Springfield, Illinois, USA) (Figure 3) and concentrations of the dominant taxa, from the older to the younger samples. The two zones are as follows.

Zone I (2080-780 cm; 70-36 ka): the assemblages were characterized by high percentages of Cupressaceae (hiatus) (ca. 5.2%-68.7%, with an average of 42.4%) and Cupressaceae (inaperture) (ca. 1.4%-34.7%, average 14.0%), Ulmaceae (ca. 2.8%-26.1%, average 11.3%), Tamaricaceae (ca. 1.9%-20.9%, average 7.3%). In the herbaceous taxa, only *Artemisia* (ca. 0-14.8%, average 3.3%), Rannuculaceae (ca. 0-14.2%, average 3.0%) and Chenopodiacae (ca. 0-8%, average 1.8%) were dominant, and at much lower abundances relative to the woody taxa. In more detail, three subzones were identified according to the assemblages: I-i, I-ii and I-iii with divisions at 1070 and 930 cm, corresponding to ages of 41 ka and 39.3 ka. The subzones I-i and I-iii were both characterized by high Cupressaceae, whereas subzone I-ii was relatively dominated by herbaceous

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taxa.

In the pollen concentrations, the same zones were also identified at a depth of 780 cm. The woody taxa were dominant below this boundary, and those such as Cupressaceae (hiatus and inaperture), Ulmaceae and Tamaricaceae reached counts of around 1000 grains/g, 200 grains/g and 100 gains/g respectively. Others such as *Pinus*, Juglandaceae, *Betula* and *Salix* were also common. By contrast, all herbaceous taxa were very low (Figure 4). We also added the boundary at a depth of 780 cm to divide the MC assemblages. Below the boundary, the fluctuations in all different sizes and shapes were stronger, especially in Zones I-ii and I-iii (Figure 5).

Zone II (780-0 cm; 36-0 ka): the woody taxa were extensively replaced by herbaceous taxa, of which Cupressaceae (hiatus) (ca. 3.5%-51.0%, average 12.1%) and Cupressaceae (inaperture) (ca. 0-24.5%, average 2.9%), Tamaricaceae (ca. 1.5%-19.4%, average 8.9%) and Ulmaceae (ca. 0.5%-27.9%, average 5.6%) were dominant; *Betula* and *Pinus* increased slightly (ca. 0-12.6%, average 6.4% and ca. 0-8.6%, average 2.3%, respectively). In the herbaceous taxa, *Artemisia* (ca. 0.9-24.1%, average 7.1%), Chenopodiaceae (ca. 0-48.2%, average 9.0%), Rosaceae (ca. 0-15.0%, average 8.6%) and Rannuculaceae (ca. 0-14.2%, average 3.0%) increased obviously, and the rest remained broadly stable. In more detail, two sub-horizons were identified: II-i and II-ii, divided based on the Asteraceae and Chenopodiaceae increase at 210 cm, correlated to an age of 12 ka B.P. (Figure 3).

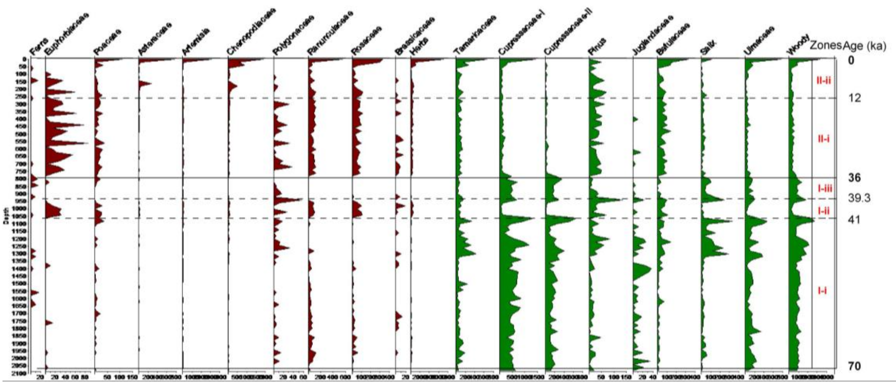

Figure 4. Pollen concentration diagram for the Nileke section, Ili Basin, China (zone divisions follow Figure 3).

The pollen concentrations in Zone II show that the woody Cupressaceae (hiatus and

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inaperture), Ulmaceae, Juglandaceae and Tamaricaceae decreased obviously while the herbaceous taxa such as *Artemisia*, Chenopodiaceae, Poaceae, Ranuculaceae and Rosaceae increased. At the sub-boundary of II-i and II-ii, Asteracea, *Artemisia* and Chenopodiaceae increased strongly (Figure 4). For the MC, all different shapes and sizes remained at generally stable and relatively low values in Zone II-i whereas in Zone II-ii the concentrations in all samples clearly started to increase, especially in the uppermost layers (Figure 5).

In summary, there are clear divisions at a depth of 780 cm, corresponding to an age of 36 ka. Prior to this change there was a high percentage of woody taxa, but subsequently the herbaceous taxa became more dominant, especially after 12 ka. The assemblages of pollen concentrations and MC can also be divided into two periods, with a transition at 36 ka.

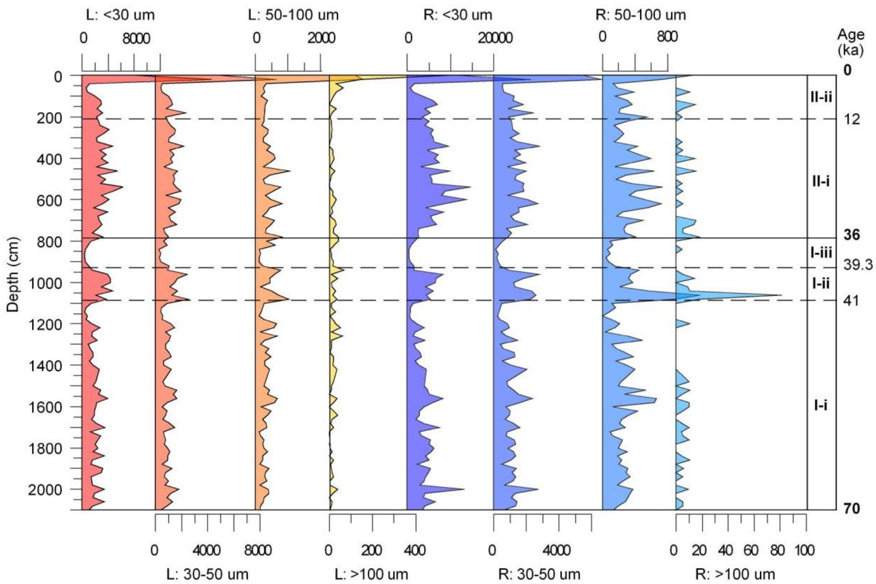

Figure 5. The MC records for different sizes and shapes in the Nileke section (unit: grains/g; L: elongated; R: zone divisions follow Figure 3).

4. Discussion

The modern climate in Central Asia is controlled by the East Asian summer monsoon, Indian summer monsoon, Asian winter monsoon and Westerlies (Figure 1A). In the Ili Basin, meteorological records indicate that strong surface winds from the west, northwest and southwest which occur frequently from April to July play the dominant role in the transportation of dust, suggesting that the wind-blown sediments in the Nileke section are driven by the Westerlies. Therefore, the grain size of the sediments can be regarded as a basic proxy for the intensification of the Westerlies (Li et al., 2015; Li et al., 2016). Furthermore, the Ili Basin is surrounded by the Tianshan Mountains to the south, east and north (with elevations exceeding 3-4 km) but low elevations (~800-1600 m a. s. l) to the west. Consequently, most of the precipitation reaching the basin will have been transported by the Westerlies during the last glacial period. Here, we try firstly to estimate changes in the vegetation and fire characteristics in the Ili Basin, secondly to discuss the overall climate change across Eurasia over the past 70 ka, and finally provide some speculation regarding the differences.

4.1 Vegetation and fire records at Nileke

The pollen dataset can be regarded as a reliable proxy for investigating the vegetation change in the study area. In the Nileke section, during 70-36 ka, the pollen assemblages show a relatively woody taxa-dominated landscape: during this time, the woody taxa reached their highest levels of the whole section (Figure 6). After 36 ka, the vegetation deteriorated markedly, as evidenced by the rapid disappearance of woody taxa following strong fluctuations during 41-36 ka. This was especially notable for Cupressaceae. In more detail, no obvious fluctuations were noted during these two periods except for the interval between 41 and 36 ka. The pollen concentrations also follow a similar trend, according to the pollen percentages. Overall, the most obvious vegetation change according to the pollen data was at around 36 ka ago, as indicated by the sharp change in vegetation assemblages. A similar transition has not been observed in Europe (e.g., Guiot et al., 1993; Allen et al., 1999) or elsewhere in Asia (e.g., Jiang et al., 2011).

Charcoal particles remaining following combustion are entrained by the smoke and then carried by the wind. Following deposition, they remain as a direct proxy of fire activity. On the Loess Plateau, smaller charcoal particles can be easily transported over long distances by the wind, but the larger particles tend to travel only a short distance (Huang et al., 2006). Therefore, the charcoal particle size can be related to its distance from the fire (Patterson et al., 1987; Clark, 1988; Luo et al., 2006; Miao et al., 2016a; b), with smaller particles likely to have been transported further from the fire (Clark, 1988). Moreover, a rounder shape (long axis to short axis ratio <2.5) is more likely related to forest fires while elongated particles (long axis to short axis ratio >2.5)

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are more indicative of grass fires (Umbanhowar and Mcgrath, 1998; Crawford and Belcher, 2014). The charcoal assemblages in the Ili Basin show a relative low fire frequency/severity at regional and local scales, in forest and grass, before 36 ka; activities then increased gradually after 36 ka (Figure 6, 7). Superimposed on this general trend, the first notable anomaly occurred at 47.5-36 ka and was characterized by a high frequency of local grass and forest fires. Another similar anomaly occurred at the top of the profile (less than 6 ka) in the layer with the highest levels of regional and local grass fires as well as the highest regional forest fires (Figure 3-5).

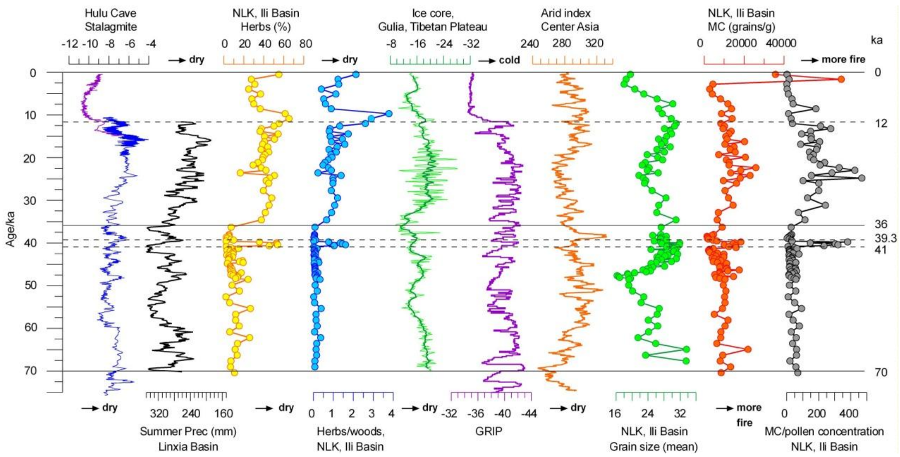

Figure 6. Comparison of climate proxies across the Northern Hemisphere and Nileke section. These are Hulu cave, Nanjing (Wang et al., 2001); summer precipitation reconstruction in the Linxia Basin (Rao et al., 2013); ice core, Gulia, Tibetan Plateau (Thompson et al., 1997); NGRIP (Andersen et al., 2004); and aridity index in central Asia (Li et al., 2013). Divisions follow Fig. 3. No anomalies occurred during 41-36 ka.

4.2 Climate in Eurasia

Here, multiple proxies from the terrestrial and marine sources have revealed the basic patterns of climate change during the last glacial period, characterized by abrupt, millennial-scale cold events (Petit et al., 1999; Wang et al., 2001; Augustin et al., 2004; Cheng et al., 2016) (Figure 6). These climate fluctuations are particularly pronounced in records of the East Asian monsoon system (Porter and An, 1995; Guo et al., 1996; Thompson et al., 1997; Wang et al., 2001; Sun et al., 2012).

The Greenland NGRIP ice core (Andersen et al., 2004) indicates that temperature variations in the high latitudes of the Northern Hemisphere are characterized by high-frequency fluctuations over the past 70 ka, with the most obvious change occurring at around 12 ka and no significant anomaly at 36 ka. At the same time, high-resolution summer precipitation variations in the western Chinese Loess Plateau were found to contain similar anomalies (Rao et al., 2013), yet with no obvious precipitation change at around 36 ka, despite their proximity to the Lanzhou loess sediments, where the shrubs and herbs reached the highest abundances after ~40 ka owning to the westerlies strengthening and supplying plenty of moisture to Northwest China (Jiang et al., 2011). In Europe the newest study shows that during 49-36.5 ka, the boreal forest of pine, birch and few spruce with little dust activity, however the charcoal indicates drought stress and frequent forest fires. During 36.5-28.5 ka, the steppe with grass, pine and birch enlarged. Dust storm increased. Spread of anatomically modern humans in the increasingly open landscape, where horse, reindeer and mammoth, the favored hunting preys, must have been abundant (Sirocko et al., 2016). This time is correlated with the time of early modern humans spreading into central Europe (Trinkaus et al., 2003; Mellars, 2006; Conard and Bolus, 2008; Klein, 2008; Hublin, 2012; Nigst et al., 2014).

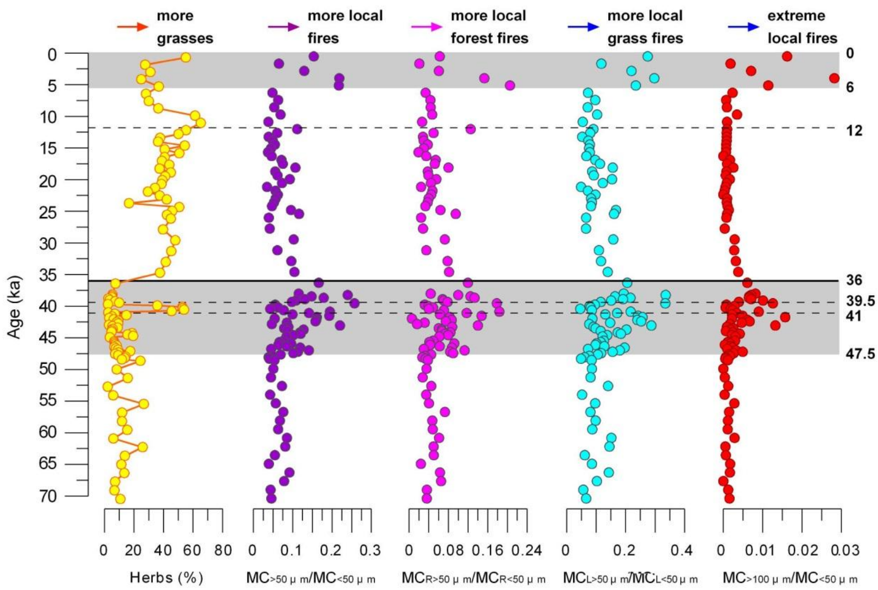

Figure 7. Vegetation versus fire anomalies identified in the Nileke section during 47.5-36 kyr. Gray rectangles show periods of intensified local fire activity during 47.5-36 and 6-0 kyr, which

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cannot be explained as the result of the climate change.

Therefore, we argue that the natural climate change at around 36 ka is not the main cause for the vegetation changes in the Ili Basin. Furthermore, the aridity index in Central Asia reveals that the change at ~36 ka did not shift the climate away from its generally arid classification (Li et al., 2013). Another potential factor to consider is the wind velocity change, however according to the grain-size distribution of the sediments in the Nileke section, there was no obvious change in the mean size and accordingly no significant variation in wind during that time (Figure 6).

4.3 Climate and fire anomalies and their driving forces

According to the oxygen isotope records from Greenland (Andersen et al., 2004) and Hulu Cave (Wang et al., 2001), as well as data from summer precipitation (Rao et al., 2013) and the aridity index established for Central Asia (Sun et al., 2012), the climate across Central Asia has maintained steady large-scale patterns with no substantial changes since 36 ka. Levels of CH_4 (Blunier and Brook, 2001) and CO_2 (Ahn and Brook, 2008) during this period remained within the bounds of normal fluctuations. So, large-scale climate change across Eurasia cannot be the primary factor explaining vegetation anomalies in the Ili Basin.

Excluding climate change, fire can be another factor causing changes to vegetation and land cover (Miao et al., 2016a), with potential for then causing a climate anomaly. In Figure 7, we compiled the microcharcoal data to investigate the fire intensity on a relatively regional scale ($MC_{>50\ \mu m}/MC_{>50\ \mu m}$), including local forest fire ($MC_{R>50\ \mu m}/MC_{R>50\ \mu m}$) and local grass fire ($MC_{L>50\ \mu m}/MC_{L>50\ \mu m}$) as well as extreme local fire events ($MC_{>100\ \mu m}/MC_{<50\ \mu m}$), according to the different shapes and sizes (see section 4.1). The results revealed two obvious fire anomaly periods: one during 47.5-36 ka, when local and extreme-local fires were markedly more intense, with a sharp decrease at 36 ka; the second was during 6-0 ka, again characterized by strong local and extreme-local fires.

In nature, wildfire has existed since the vegetation began to colonize the land (Glasspool et al., 2004). According to Holocene fire records from the Northeast Tibetan Plateau (Miao et al., 2016b), as well as global records on orbital time scales (Bird and Cali, 1998; Luo et al., 2001), the climate change might have strongly driven the fire changes by changing humidity. Summer precipitation during 41-36 ka was at its highest level of the past 70 ka (Rao et al., 2013), which

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will have impeded burning. So, the precipitation change was not the key factor in the observed fire anomalies. Another possibility is that the fire was caused by human activities. The earliest human-controlled fire can be traced back to at least 0.8 million years in Israel (Goren-Inbar et al., 2004) or 0.4-0.5 million years for *Homo erectus pekinensis* in China (Weiner et al., 1998), which means that after that the humans have colonized the worldwide regions in the latest period of the Pleistocene e.g., the last glacial period with the skills of fire control. The Ili Basin, as one of most important passageways from Africa to high-latitude of Asia, e.g., Baikal Lake, can be burned during their colonization, thus the natural vegetation during their colonization should have been changed or destroyed strongly, especially including the arbors. Cupressaceae as one sensitive woody species in the mid latitude of Inner Asia grow slowly and, once destroyed, regrowth is very slow. This could explain why Cupressaceae disappeared so fast following human colonization.

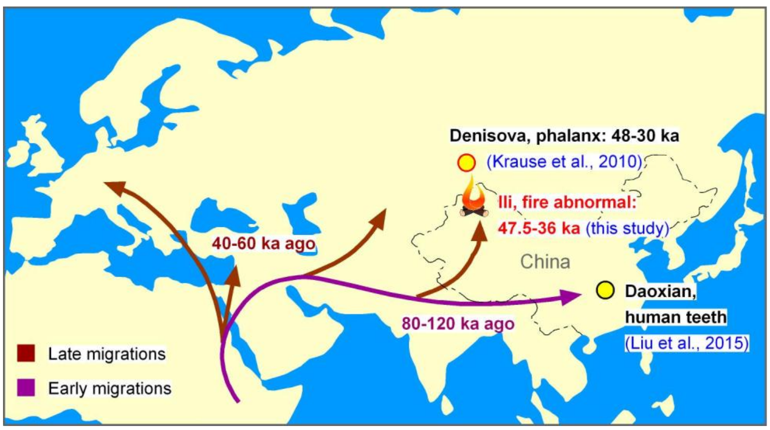

Figure 8. An early migration from Africa (adapted from Callaway, 2015). Finds in the Ili Basin dated to 47.5-36 kyr correlate with human fire activity (this study).

There is widespread evidence supporting human occupation of Central Asia during the Holocene (Huang et al., 1988; Wang and Zhang, 1988; Taklimakan Desert archaeology group, 1990; Yidilis, 1993; Lü et al., 2010; Zhang et al., 2011; Tang et al., 2013; Han et al., 2014). In the Ili Basin, although direct archeological sites are limited, the coeval local fire intensification supports human activity as a factor causing fire anomalies after around 6 ka. This relationship can be similarly extended to observed fire anomalies at 47.5-36 ka, when humans migrated into the Ili

Basin. Although direct archeological proofs of fire usage at this time are still lacking, human colonization of mid-to high-latitude Eurasia occurred after 200 to 80 ka (Wu et al., 2015) and extended to Central Asia after around 60-40 ka (Callaway, 2015), for example, In Denisova Cave, the Altai Mountains, Russia. The phalanx was found in a stratum dated to 48–30 ka ago (Krause et al., 2010) (Figure 8). So, it is not difficult to link the local fire anomalies during 47.5-36 ka in the Ili Basin to human activities: the increased occurrence of local fires (for cooking, or burning the uncultivated land) quickly destroyed the vegetation, causing the observed vegetation degeneration. If this is the case, the modern vegetation may have originated since around 36 ka. In future the use of a massive and sustained ecological program of vegetation rehabilitation in the arid and semiarid region should reduce the risk of destructive fire in order to avoid a similar local vegetation disaster to that which occurred at 36 ka.

5. Conclusions

In the Nileke Section, Ili Basin, the pollen assemblages show a sharp change at ~36 ka characterized by herb increase and Cupressaceae decrease, which is difficult to be explained in terms of a Eurasian climate anomaly and instead is attributed to local vegetation degradation caused by local fire intensification. Human activities during 45-36 ka are inferred as the main driving force of this change, although direct archeological proofs are still lacking. In future, new archeological sites in this area are required to investigate the extent to which ancient human activities influenced the vegetation. This will provide further insights into the relationships between human fire activity and local vegetation and even climate change.

Acknowledgements

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