Human activity induced asynchronous dune mobilization in the deserts of NE China during the late Holocene

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ABSTRACT

Studies of dune mobilization during the last 3 kyr in the deserts of NE China indicate that the area of desert expanded, and associated dust storms increased in the affected regions downind. However, uncertainty about the timing and origin of episodes of late Holocene dune mobilization has resulted in the failure to provide information about dust-related processes that can be used in atmospheric dust models. Here, we present a detailed regional compilation of dune mobilization and human activity in the deserts of NE China and the adjacent regions spanning the last 3 kyr. The results show that human activity and dune mobilization intensified synchronously at ~2.5 ka in the Mu Us and Hobq deserts, at ~1.5 ka in the deserts of NE China, and at ~0.5 ka in the Horqin and Hulun Buir deserts. A comprehensive analysis indicates that a northward trend of intensified human activity, with the main contribution from cultivation and a secondary contribution from grazing, was responsible for the asynchronous pattern of dune mobilization in these deserts during the late Holocene.

1. Introduction

The deserts of NE China are a dust source area of global significance (Sun et al., 2001). In spring, abundant dust derived from the region is transported downwind and the resulting dust storms have substantial implications for human welfare because they likely cause a substantial increase in lagged non-accidental and cardiovascular mortality (Crooks et al., 2016). Successful prediction of future dust storm occurrences in the affected areas requires comprehensive knowledge of the processes of dust emission, transport and deposition. Xu et al. (2018) suggested that periods of increased dust occurrence in lake sediment records were consistent with episodes of dune mobilization within the dust source area during the late Holocene, and that dust transport was related to the Siberian High. Understanding the episodes of late Holocene dune mobilization in these deserts, and its driving mechanisms, is important for the development of atmospheric dust models capable of evaluating possible future dust storm occurrences in the affected areas downwind (Shao and Dong, 2006).

Multiple mechanisms are responsible for Holocene dune mobilization in the deserts of NE China, including early Holocene aridity (Mason et al., 2009; Lu et al., 2011), an irreversible regional hydrological event

at ~4.2 ka (Yang et al., 2015), climatic deterioration at ~4.0 ka (Guo et al., 2018), the combination of climatic deterioration and intensified human activity since ~2.3 ka (Sun, 2000; Li and Sun, 2006; Huang et al., 2009; Yang et al., 2017), and intensified human activity since ~2.0 ka (Yang et al., 2016). The driving mechanisms of early to middle Holocene dune mobilization can be established using continuous high-resolution sedimentary records with well-constrained chronologies, together with a comprehensive compilation of dune activity in the region. However, conclusions regarding the occurrence and causes of late Holocene dune mobilization are limited by the fact that data on dune activity are typically only available for a single desert. Although late Holocene records indicating climate change are of relative abundance in the region, there is limited documentary evidence of changes in human activities. This lack of knowledge of dust-related processes hinders the development of computer models that can predict future climate trends (Shao and Dong, 2006; Zhao et al., 2006). Thus, an increased number of reliable late Holocene records of dune activity and intensified human activity are needed in the region.

Here, we present a detailed regional compilation of dune activity in the deserts of NE China over the last 3 kyr, which we compare with contemporaneous records of human activity in the deserts and the
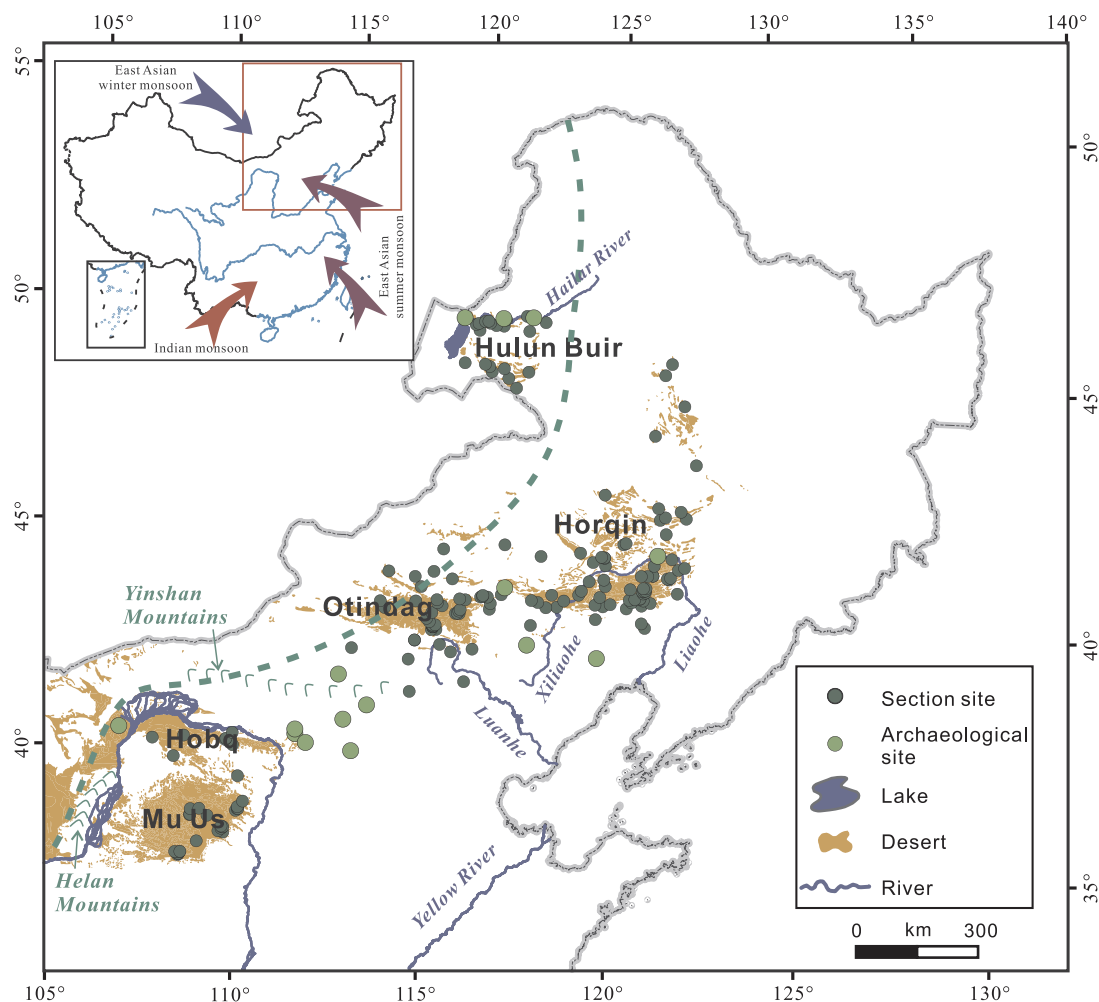
Fig. 1. Distribution of deserts (Hulun Buir, Horqin, Otindag, Hobq and Mu Us) and study sites (sections and archaeological sites) in NE China. The green dashed line indicates the front of the East Asian summer monsoon. The desert data set is provided by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China, http://westdc.westgis.ac.cn.

adjacent regions. Our regional compilation of dune activity and human activity is based on previously published data. Our principal aim is to explore the timing of the episodes of late Holocene dune mobilization in the region and to determine the main causal mechanisms.

2. Study region

The deserts of NE China are located on the northern margin of the region of influence of the East Asian summer monsoon (EASM) and consist of the Hulun Buir, Horqin, Otindag, Hobq and Mu Us deserts (Fig. 1). The modern climate of these deserts is semi-arid, with mean annual precipitation increasing from 200 mm in the northwest to 400–500 mm in the southeast (Ren et al., 1985). East Asian summer monsoon precipitation accounts for 65–75% of total annual precipitation (Liu, 2010). The dunes in the region are mainly stabilized and semi-stabilized at present, except for the dunes in the Hobq desert that are mainly active and semi-stabilized.

Grasses, mainly Needlegrass (*Stipa* sp.), Chinese wild rye (*Aneurolepidium chinense*) and *Cleistogenes squarrosa*, comprise the predominant natural vegetation, and they are favored by grazing animals. In addition, water from several rivers enables the relative flourishing of irrigation agriculture in cultivated areas, especially in riparian zones and inter-dune lowlands. Local agricultural activity can be traced back to the Hongshan culture (the middle Holocene), when agriculture from the Central Plain spread to the region (Han, 2012; Liu and Chen, 2012).

3. Data and methods

Previous research has documented the history of agricultural activity in the deserts of NE China and the adjacent regions (e.g., Han, 2012; Zhang et al., 2015a), and the findings are relevant to the present study. In addition, a regional compilation of dated Holocene records from sub-aerial sedimentary deposits in the desert can be used to characterize the spatiotemporal pattern of dune activity (Li and Yang, 2016; Guo et al., 2018). Paleosols, lacustrine, and peat deposits are the sources of dated records indicating a stable dune state, while eolian sand and loess are the sources of dated records for a mobile dune state (Guo et al., 2018). In practice, a mobile dune state is characteristic of a dry climate, mainly due to the increased aridity resulting from a deficit of EASM precipitation, and/or from the intensification of human activity. By contrast, abundant EASM precipitation favors plant growth and the development of paleosols and lakes, corresponding to a stable dune state.

The localities on the northern margin of the agro-pastoral ecotone, which have existed for the last 3 kyr, and which are described in Han (2012), are a major concern of the present study. These localities are plotted in Fig. 2, and environmental changes in these areas mainly resulted from local human activity. The nature of the paleodiet of the ancient inhabitants during the interval of 3–0 ka has been investigated using a compilation of stable isotope data from animals (cattle, sheep and horses) and humans from 15 archaeological sites in NE China (Fig. 1; Zhang, 2006; Zhang et al., 2006, 2008, 2012a,b, 2015a,b, 2018;
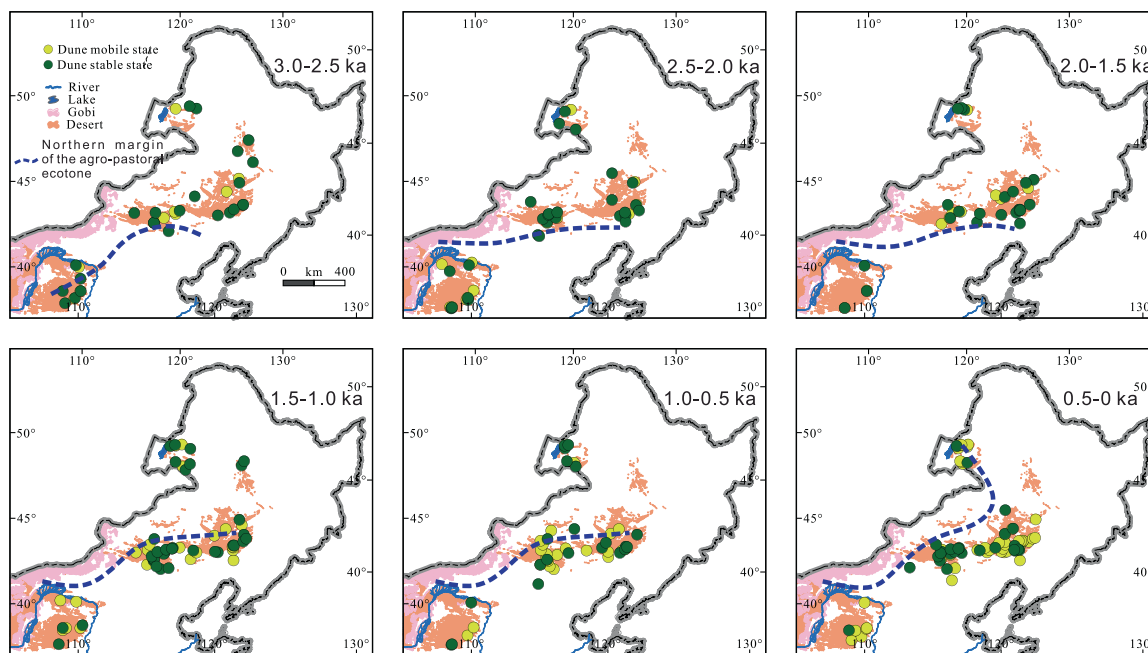
Fig. 2. Spatiotemporal distribution of dated records of sub-aerial sedimentary deposits in the deserts of NE China over the last 3 kyr. Also shown are the locations of the northern margin of the agro-pastoral ecotone in NE China. These dated records of mobile and stable dune states (Guo et al., 2018) reveal trends in late Holocene dune activity. The location information is described in Han (2012). In all maps, the extent of the deserts only reflects their modern status.

Dong et al., 2007; Gu, 2007). The ages of the stable isotope data are constrained by historically documented archaeological material. The stable isotope data are stacked and placed on a common timescale and subsequently we use it to review the diet of animals and humans during the interval of study. In addition, based on a compilation of late Holocene human activity in the study region, we determine the timing of episodes of human activity and explore its relationship to dune activity.

To determine the timing of episodes of dune activity in the deserts of NE China during the late Holocene, we compiled a total of 362 published dated records over the last 3 kyr from sub-aerial sedimentary deposits in these deserts (Fig. 2; Table 1). The records are illustrated using ArcGIS 10.2 with a bin width of 500 y. The records (179 dated records indicating mobile dune states and 183 dated records indicating stable dune states) are documented in Guo et al. (2018). They are selected using three criteria described in Guo et al. (2018) and Wang et al. (2014). First, all selected published actual ages were determined by radiocarbon or luminescence methods; second, the ages were in stratigraphic order; third, we selected a single dated record when multiple ages or similar ages were measured from the same layer at a site. Uncalibrated radiocarbon ages were calibrated to calendar years using the Calib Rev 7.0.4 radiocarbon age calibration program (Stuiver and Reimer, 1993) with the IntCal13 curve (Reimer et al., 2013). The data quality is determined by the application of these three criteria, and by the uniform calibration of the radiocarbon ages (Guo et al., 2018; Wang et al., 2014). For most of the luminescence and radiocarbon ages

compiled here, the error was less than 10% of the measured value; thus, we infer that the uncertainty is ∼10%, which will have only a minor effect on conclusions about environmental changes on a millennial timescale.

4. Results

4.1. Episodes of late Holocene dune mobilization

As shown in Figs. 2 and 3, there is a substantial increase in the number of dated records indicating mobile dune states (Guo et al., 2018) in the deserts of NE China at ∼1.5 ka, and the values remain relatively high thereafter. In addition, the number of mobile state records in the Horqin and Hulun Buir deserts increases again at ∼0.5 ka. However, in the Mu Us and Hobq deserts the increase occurs earlier, at ∼2.5 ka, and there are relatively few dated records thereafter (Fig. 3). Thus, our compilation of dated records from the deserts of NE China (Figs. 2 and 3) clearly reveals the occurrence of a phase of major dune mobilization in the Mu Us and Hobq deserts at ∼2.5 ka, and that dunes in these five deserts were also intensively mobilized at ∼1.5 ka. In addition, in the Horqin and Hulun Buir deserts the latest phase of major dune mobilization commenced at ∼0.5 ka. This result demonstrates that dune mobilization in these deserts during the late Holocene was asynchronous.

4.2. Shifts of the northern margin of the agro-pastoral ecotone

Three northward shifts of the northern margin of the agro-pastoral ecotone are evident in Fig. 2, suggesting that the intensity of agricultural activity increased northwards over the last 3 kyr. The first shift was in the southern part of the region, from Longmen-Jieshi during the Spring and Autumn period (770–476 BCE) to the Yinshan Mountains during the Qin and West Han dynasties (221–24 BCE). The second shift is recorded in central-southern Inner Mongolia, and involved an extension of the zone to the northern Xiliaohe drainage basin during the interval from the late North Wei (386–534 CE) to the Sui and Tang dynasties (581–907 CE). During the Ming and Qing dynasties (1368–1911 CE), the location of the northern margin of the agro-

Table 1
Distribution of luminescence and radiocarbon ages for the deserts of NE China.

Region	OSL	Radiocarbon dates	Total	Number of sites
Hulun Buir	41	5	46	20
Horqin	133	32	165	72
Otindag	81	18	99	46
Hobq	11	1	12	8
Mu Us	28	12	40	24
Total	294	68	362	170

Note: '-' indicates no data.
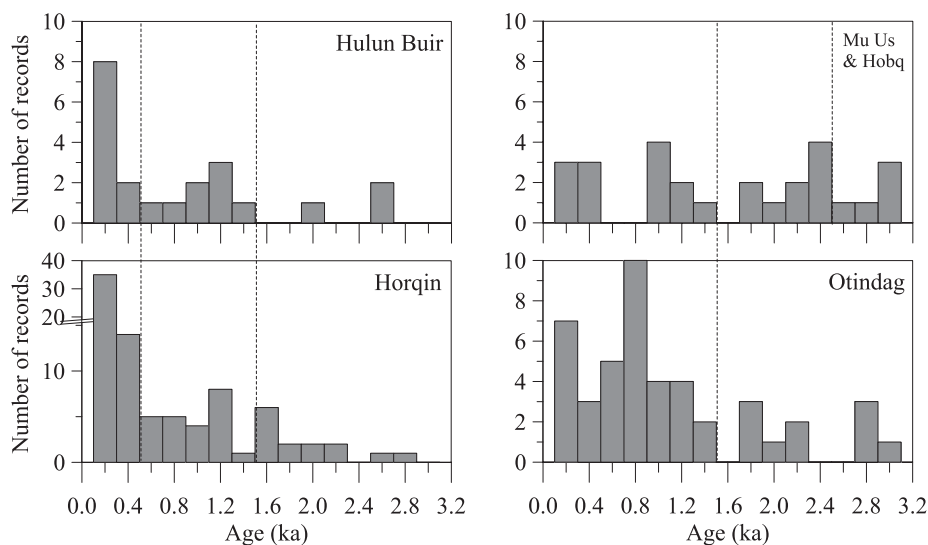OSL, Optically stimulated luminescence

Fig. 3. Histogram of dated records of mobile dune states, with a bin width of 200 y, in the deserts of NE China over the last 3 kyr. The dashed line shows the initiation of a phase of drastic dune mobilization.

pastoral ecotone reached its northernmost limit.

4.3. Stable isotope data from animal and human remains

The compilation of stable isotope data for the study region shows that the mean bone collagen $\delta^{13}C$ ($\delta^{15}N$) values of animal and human remains are -15.99 ± 3.04‰ (+9.60 ± 1.79‰) and −10.35 ± 2.30‰ (+6.46 ± 1.19‰), respectively (Fig. 4). In addition, the period of relatively high $\delta^{13}C$ values is consistent with that of relatively low $\delta^{15}N$ values, and vice versa.

5. Discussion

5.1. Possible driving mechanisms of the late Holocene dune mobilization

Drought is regarded as the dominant driving mechanism of dune mobilization during the early and middle Holocene (Mason et al., 2009;

Fig. 4. Compilation of bone collagen $\delta^{13}C$ (a) and $\delta^{15}N$ (b) values of animal (n = 34) and human remains (n = 197) from archaeological sites in NE China over the last 3 kyr (see Fig. 1 for the location of the sites) (Zhang, 2006; Zhang et al., 2006, 2008, 2012a,b, 2015a,b, 2018; Dong et al., 2007; Gu, 2007).

Lu et al., 2011; Guo et al., 2018), while for the late Holocene, climatic deterioration, coupled with intensified human activity, has been implicated (Sun, 2000; Li and Sun, 2006; Huang et al., 2009; Yang et al., 2017). However, although late Holocene dune mobilization is recorded in several eolian sand-paleosol sequences, the limited number of dated records of dune activity from a single desert has resulted in the failure to determine the episodes of dune activity at a larger scale in the study region. This problem limits our understanding of the role of climatic deterioration and intensified human activity in dune mobilization in these deserts during this interval.

Although our compilation of dated records was provided by Guo et al. (2018), the principal aim of that study was to investigate the nature of mid-Holocene human-environment interactions in the deserts of NE China. The main difference between the present study and the previous research is that here we use a regional compilation of dated records documenting mobile and stable states with a bin width of 500 y to characterize the spatiotemporal distribution of dune activity in the study region during the late Holocene. Moreover, our conclusions differ from many previous studies of late Holocene dune mobilization (e.g. Sun, 2000; Li and Sun, 2006; Huang et al., 2009; Yang et al., 2016, 2017), because our compilation of dated records from the five deserts in NE China enables a more precise definition of the episodes of dune activity (Li and Yang, 2016; Guo et al., 2018). Thus, the driving mechanisms of late Holocene dune mobilization in the study region need to be reconsidered.

The results of our study suggest that dunes in the deserts of NE China were mobilized asynchronously, at ~2.5 ka in the Mu Us and Hobq deserts, at ~1.5 ka in all the deserts of NE China, and at ~0.5 ka in the Horqin and Hulun Buir deserts (Figs. 2 and 3). This scenario is supported by the complex pattern of late Holocene dune mobilization inferred from a regional compilation of dated records in the study region (Lu et al., 2005; Yang et al., 2010, 2012; Li and Yang, 2016). In addition, Sun (2000) suggested that in the Mu Us desert, dunes have been mobilized since ~2.3 ka. To the north, in the Hobq desert, the latest period of dune mobilization is OSL-dated to ~2.0 ka (Yang et al., 2016); in the Hulun Buir desert, the present dune mobilization is mainly the result of intensified human activity over the last 300 years (Li and Sun, 2006). These results all support our finding that an asynchronous pattern of dune mobilization occurred in the last 3000 years. After ~3.0 ka, dune mobilization in the deserts of NE China (Fig. 5a) gradually became dominated by climatic deterioration, because of the decrease in monsoon-driven precipitation (Guo et al., 2018) and the gradual increase in the strength of the East Asian winter monsoon
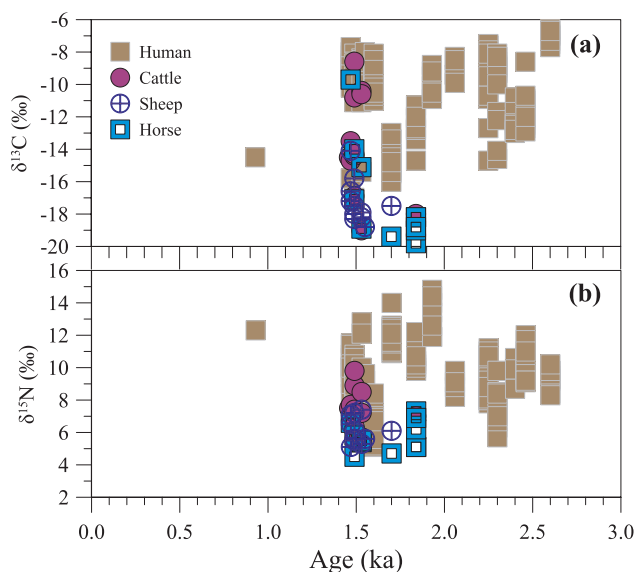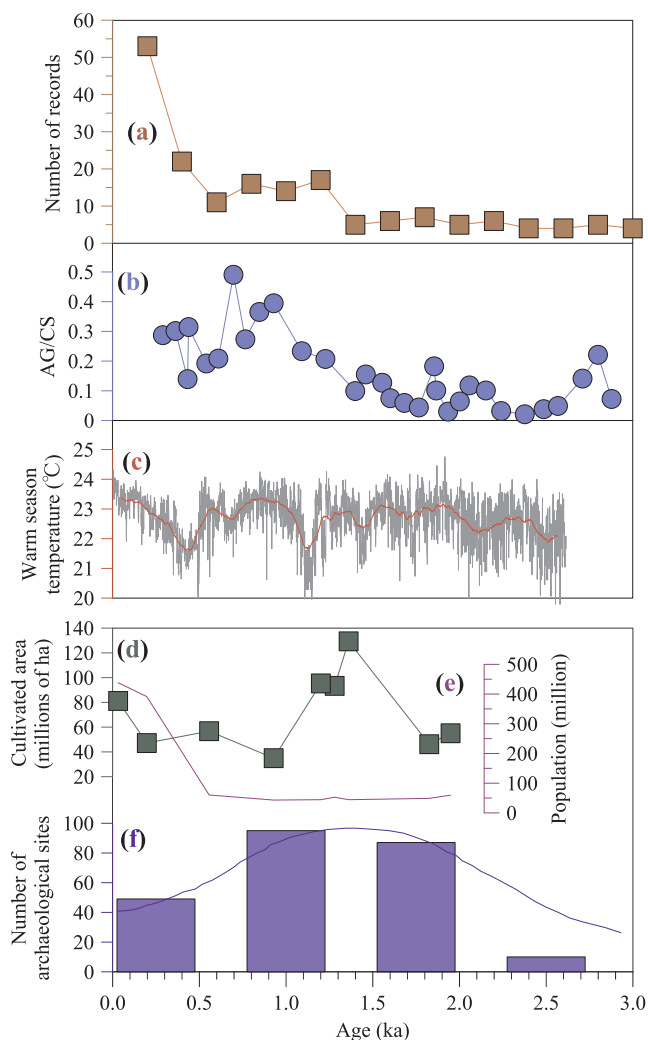
Fig. 5. Climatic archives (a and b) and historical documents indicating changes in land use (c–e) for the deserts of NE China and adjacent regions over the last 3 kyr. (a) Dated records of mobile dune states in the study region (Guo et al., 2018); (b) positive index of the strength of the EAWM inferred from the AG/CS (*Aulacoseira granulata/Cyclotella stelligera*) diatom ratio (Wang et al., 2012); (c) warm season temperature reconstruction from a stalagmite from Shihua Cave, Beijing (Tan et al., 2003); (d) national cultivated area and (e) population (Han, 2012); (f) number of archaeological sites in Horqin Zuoyihouqi, in the southeastern Horqin desert (Ren, 1999).

(Fig. 5b). The fluctuating nature of the late Holocene climate (Wang et al., 2005) resulted in the alternation of cold and dry and warm and humid phases in NE China (Fig. 5c). If the conclusion that late Holocene climate changes were responsible for dune activity in the region is correct, the changes in the episodes of dune mobilization should be synchronous. Although the climate in the study region may change slightly from south to north, temperature and precipitation both decrease northwestwards (Ren et al., 1985).

Consequently, the observed episodes of drastic but asynchronous dune mobilization in the study region are unlikely to have been caused by cyclical changes in climate, and instead they are likely to have been caused by changes in the intensity of human activity. The evidence for this conclusion is that our dated records clearly demonstrate that the periods of northward intensification of human activity correspond with the episodes of major dune mobilization (Figs. 2 and 3) and with documentary evidence of human land use changes (Figs. 2 and 5). Intensified human activity caused vegetation degradation which triggered the late Holocene dune mobilization in the deserts of NE China, while at the same time the gradually increasing strength of the East Asian winter

monsoon (Fig. 5b) increased the potential for dust transport in spring.

5.2. Timing of northward shifts in the intensity of human activity

Since ~2.5 ka, the Mu Us and Hobq deserts were located within the agro-pastoral ecotone (Fig. 2), suggesting that cultivation and grazing were responsible for triggering dune mobilization. In addition, there were three main phases of human migration from the Central Plain of China to the deserts and adjacent regions over the last 2.3 kyr (Sun, 2000; Han, 2012). Statistical analysis of the historical literature shows that the size of the total immigrant population, including soldiers and farmers, was potentially several millions. Consequently, the major administrative center of Sufangjun was established in the region to control the Han military and to stimulate the regional economy (Wang, 1991). Furthermore, the construction of the Great Wall in the Mu Us and Hobq deserts and adjacent regions after ~2.5 ka likely triggered substantial soil erosion which was responsible for the decreased number of radiocarbon records in the region (Fig. 2).

At ~1.5 ka, the eastern agro-pastoral ecotone shifted northwards (Fig. 2), and the extent of the national cultivated area reached a maximum (Fig. 5d). Although the national population was relatively low during this period (Fig. 5e), the number of archaeological sites in the southeastern Horqin desert suggests that human activity intensified after ~2 ka, with a peak in activity at ~1.5 ka (Fig. 5f). This conclusion is evidenced by the development of millet agriculture (Zhang et al., 2015a) and animal husbandry (Table 2) in the deserts of NE China and adjacent regions during the late North Wei dynasty (386–534 CE). In addition, at 485 CE, the Equal Landship directly promoted the development of cultivation in the region (Han, 2012). Further evidence for intensified agricultural activity is provided by the occurrence of cereal pollen in the sediments of Gonghai Lake after ~1.6 ka (Chen et al., 2015). In the Hulun Buir desert, a minor increase in dated records of a stable dune state at ~1.5 ka may have resulted from the gradual development of cultivation (Yi, 1994). Overall, it is evident that human activity flourished in these deserts after ~1.5 ka.

After ~0.5 ka, the shift in the northernmost boundary of the agro-pastoral ecotone (Fig. 2), together with an increase in the national cultivated area and population (Fig. 5d and e), demonstrate a renewed intensification of human activity in the Horqin and Hulun Buir deserts. A possible explanation is that an increase in the demand for grain promoted the intensification of agricultural activity. This was reflected by the establishment by the Ming government of the centers of Liaodong Dusi and Nuergan Dusi for administering agriculture and other activities in the Horqin and Hulun Buir deserts and the adjacent regions (Yi, 1994); this is reflected by discoveries of numerous iron agricultural implements at archaeological sites dated to this period. During the early to late Qing dynasty, the government initially prohibited and then promoted land reclamation in the region; in practice, however, these policies stimulated the development of cultivation (Yi, 1994). Thus, cultivation was the foundation of the subsistence economy in the Horqin and Hulun Buir deserts since ~0.5 ka.

Table 2
Four state-owned pastoral areas during the North Wei dynasty (Wang et al., 2004).

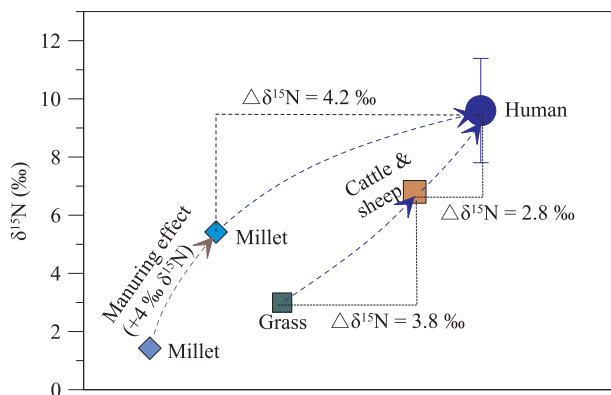| Name	Number	Function
Daijun pastureland	Horses (350,000), cattle and sheep (1,600,000)	Military
Monan pastureland	Horses, cattle and sheep (6,000,000)	Commerce
Hexi pastureland	Horse (2,000,000), camels (1,000,000), cattle and sheep (million)	Commerce
Heyang pastureland	Horses (100,000)	Military and commerce

Fig. 6. Differences in mean $\delta^{15}N$ values between two adjacent trophic levels ($\triangle\delta^{15}N$) in the agricultural economy of the deserts of NE China during the late Holocene. The effect of millet fertilization by animal manure (+4‰; Wang et al., 2018) is excluded. Mean $\delta^{15}N$ value of grass in the study region values is +3‰ (Xu et al., 2010). The $\delta^{15}N$ values of modern millet from China are from Wang et al. (2018).

5.3. Stable isotope evidence of the paleodiet of animals and humans

The compilation of $\delta^{13}C$ records suggests that at ~1.5 ka, cattle, sheep and horse were fed mainly on terrestrial C_3 plants and that humans relied on C_3/C_4-plant-based foods. The difference between the mean $\delta^{13}C$ values of the collagen of animal and human bones (~5–6‰) is much larger than that between prey and predators (0–2‰; Bocherens and Drucker, 2003), indicating that more C_4-plant-based foods were consumed by humans during the last 3 kyr.

The compilation of $\delta^{15}N$ values indicates that humans may have had a mixed diet since ~2.5 ka (Fig. 6). The mean $\delta^{15}N$ value of modern millet from China increases from 1.42‰ to 5.42‰ (n = 179) when millet is fertilized with animal dung (Fig. 6). The difference between the mean $\delta^{15}N$ values of animal and human tissue is about 2.8‰, and that between fertilized millet and human tissue is up to 4.2‰. These values are consistent with the differences between prey and predators (3–5‰) (Bocherens and Drucker, 2003). Based on the difference in mean $\delta^{15}N$ values between the tissues of prey and predators, an increase in millet consumption by humans may have caused a decrease in the $\delta^{15}N$ values of bone collagen.

At ~1.5 ka, there is a negative relationship between $\delta^{13}C$ and $\delta^{15}N$ values of human bone collagen (Fig. 4), which can be explained by the flourishing of millet cultivation which provided an increased food source in the region (Zhang et al., 2015a). Thus, the results of the paleodietary analysis of animals and humans demonstrate that cultivation was flourishing in the deserts of NE China and adjacent regions at ~1.5 ka. In addition, several archaeological sites, dated from ~2.5 to 2.0 ka, are located within the agro-pastoral ecotone (Fig. 2). Consequently, the relatively low $\delta^{15}N$ values during the interval of ~2.5–2.0 ka suggest that the flourishing millet-based agricultural system was associated with a major phase of dune mobilization in the Mu Us and Hobq deserts.

5.4. Implications for climate modelling of dust-related processes

Combining the regional compilation of dune activity and human activity in the deserts of NE China and adjacent regions during the late Holocene, we speculate that climatic deterioration in the mid-Holocene was the initial cause of dune mobilization (Guo et al., 2018). Subsequently, however, human activity (mainly cultivation and grazing) intensified with a northward trend and induced drastic dune mobilization at ~2.5 ka in the Mu Us and Hobq deserts, at ~1.5 ka in all five deserts, and at ~0.5 ka in the Horqin and Hulun Buir deserts. Previous studies have suggested that the potential for dune mobilization in cultivated

areas is greater than in pastoral regions (Sun, 2000; Li and Sun, 2006). This inference is supported by the positive relationship between evidence for cultivation and flooding in the middle reaches of the Yellow River during the Holocene (Chen et al., 2012). In semi-arid regions, the roots of crops are removed in winter by farmers, causing the impairment of soil fertility; thus, long-term cultivation in deserts and adjacent regions increases the potential for soil erosion and dune mobilization.

Comprehensive knowledge of the processes of dust emission, transport and deposition is important for estimating the impact of dust on the Earth system (Shao and Dong, 2006; Schepanski et al., 2017). More recently, there have been substantial research efforts to investigate the processes of dust emission and its causes at an interannual scale (e.g. Zhao et al., 2006; Schepanski et al., 2009; Crouvi et al., 2012; Wagner et al., 2016). Past research on the causes of dust emission from source areas has focused mainly on natural factors, such as meteorological processes, dust sources, surface conditions, and the pattern of atmospheric circulation. Within many atmospheric dust models, human activity has attracted much attention from climate scientists, because it has important implications for the interpretation of atmospheric dust model simulations. However, the impact of intensified human activity on the processes of dust emission is not yet completely understood (Wagner et al., 2016). Here, the conclusion that a northward trend of intensified human activity induced asynchronous dune mobilization in the deserts of NE China during the late Holocene is evidenced by a detailed regional compilation of dune activity and human activity in the region. Intensified human activity leads to decreased vegetation cover and dune mobilization, and it likely causes an increase in long-term dust emission from the source area, which affects social and economic life in the affected regions downwind. Consequently, we speculate that without the implementation of sustainable agricultural practices, it will be the continued intensification of human land use in the dust source region, rather than the current global warming, that continue to result in dust storms in the affected areas downwind.

6. Conclusions

We have produced a comprehensive regional compilation of evidence for changes in dune mobility and the intensity of human land use in the deserts of NE China and adjacent regions over the last 3 kyr. Analysis of the data suggests the occurrence of several major phases of dunes mobility: at ~2.5 ka in the Mu Us and Hobq deserts, at ~1.5 ka in all the deserts of NE China, and at ~0.5 ka for the Horqin and Hulun Buir deserts. In addition, human activity and dune mobilization intensified synchronously in these deserts. Comparison of the results with regional climatic records indicates that the northward trend of intensified human activity (mainly cultivation and grazing) was the major driving mechanism of the asynchronous trend of dune mobilization in these deserts during the late Holocene. In addition, cultivation was a more important factor in late Holocene dune mobilization than grazing. The role of intensified human activity in influencing the episodes of late Holocene dune mobilization in the study region provides a potentially useful reference for the development and interpretation of atmospheric dust model simulations which incorporate ongoing global warming and the intensification of human land use, especially in semi-arid and arid regions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.aeolia.2018.08.003.

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