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Desertification in China: An assessment

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ABSTRACT

Arid and semiarid China have experienced multiple arid phases throughout the Quaternary, and over the past five decades, there have been several periods with relatively high or low rates of desertification and rehabilitation. The causes of these changes and their historical trends have been debated by scientists because of their potentially huge significance for China, as well as for the global ecology and food supply. This paper reviews recent studies of desertification in different regions of arid and semiarid China. In general, the results of systematic monitoring, and analyses of the causes of desertification and the contemporaneous human impacts, suggest that desertification in China has been primarily caused by climate change, and particularly by strong wind regimes (with high sand transport potential) accompanied by decreased spring precipitation. Unfortunately, although numerous scientists have claimed that desertification in China is primarily due to human impacts; there is surprisingly little unassailable evidence to support this claim. The review presented in this paper show that desertification in China is likely to be controlled by climate change and geomorphological processes, even though human impacts have undeniably exacerbated their effects. Our arguments for both climate change and human activity as factors responsible for the observed changes in desertification rely primarily on inferences based on correlations between trends, thus future research must seek stronger and more direct evidence for the causal relationships that we have proposed as possibilities. This improved information is essential to provide a firm basis for future policy decisions on how best to combat desertification.

1. Introduction

Arid and semiarid areas of modern China, which have experienced multiple arid phases throughout the Quaternary, usually lie in regions above 35° N and have an annual rainfall of <450 mm. These areas stretch from central Asia in the west to northeastern China in the east, covering an area of more than 1.6 million km^2 (Z. Zhu et al., 1980; Z. Zhu and Chen, 1994; T. Wang et al., 2006). At present, more than 60% of this area is being managed using traditional pastoral and agricultural systems that could be seriously endangered, jeopardizing the existence of nearly 200 million people, if climate change or human activities continue to trigger land degradation in this region (Z. Zhu, 1998; Su et al., 2006; X. Wang et al., 2007, 2008). In arid and semiarid China, the most dominant form of land degradation involves the reactivation of anchored or semi-anchored dunes, and the degradation of arable land and grassland under conditions that lead to sand transport is exacerbated by decreases in vegetation cover or increases in sand transport (T. Wang and Zhu, 2001; X. Wang et al., 2005a). Over the past five decades, sandy lands and deserts have gone through several periods with high or low rates of dune reactivation and degradation of arable land and grassland, with corresponding occurrences of desertification and rehabilitation. The causes of these changes have interested Earth scientists and sociologists because of their potentially huge significance for China, as well as for the global ecology and food supply.

In China, desertification has usually occurred in regions in and around gobi (exposed surfaces comprising intricate mosaics of coarse particles, set on or in deposits of sand, silt or clay) areas and deserts with mobile sand in which cultivation and grazing take place; the resulting adverse changes have been defined as land degradation characterized by wind erosion, mainly as a result of a lack of coordination between human impacts and natural conditions in arid, semiarid, and some subhumid regions (Z. Zhu, 1998; T. Wang and Zhu, 2003). Although other land degradation processes, such as water erosion and salinization, have also occurred in arid and semiarid China, their areas account for no more than 16% of the total areas of degraded land (SFAC, 2005); therefore, the main form of desertification is referred to as "sandy" desertification

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because changing soil stability (i.e., dune mobility) is the dominant process responsible for land degradation in this region. During the past five decades, the area of desertification reached its maximum during the 1970s to the early 1980s, then decreased continuously from the late 1980s to the present.

The origin, causes, and processes of desertification, its impacts on climate change, and the methods available to combat desertification in arid and semiarid China have been discussed at great length. Based on field investigations and the results of remote sensing, researchers have reported classifications of desertification (e.g., Z. Zhu et al., 1980, 1981), its causes (e.g., W. Wu et al., 1997; B. Wu and Ci, 1998, 2002; W. Sun, 2000; W. Sun and Li, 2002; Runnström, 2003), its trends (e.g., T. Wang et al., 2002, 2003, 2004a,b), and its effects on climate (e.g., Ci and Yang, 2004), and have attempted to forecast its trends (e.g., Z. Zhu, 1985; Ci et al., 2002). Although the classifications of desertification in China are now nearly consistent, the causes are still being disputed. For instance, X. Wang et al. (2005a, 2006a) have proposed that desertification in the Mu Us and Otindag deserts and their adjacent regions was caused by climate change, and this hypothesis is supported by archaeological evidence (e.g., Y. Zhao, 1981; W. Wang, 2002; Han, 2003), even though others have argued that human activities were responsible (e.g., W. Wu, 2001; T. Wang et al., 2003, 2004b).

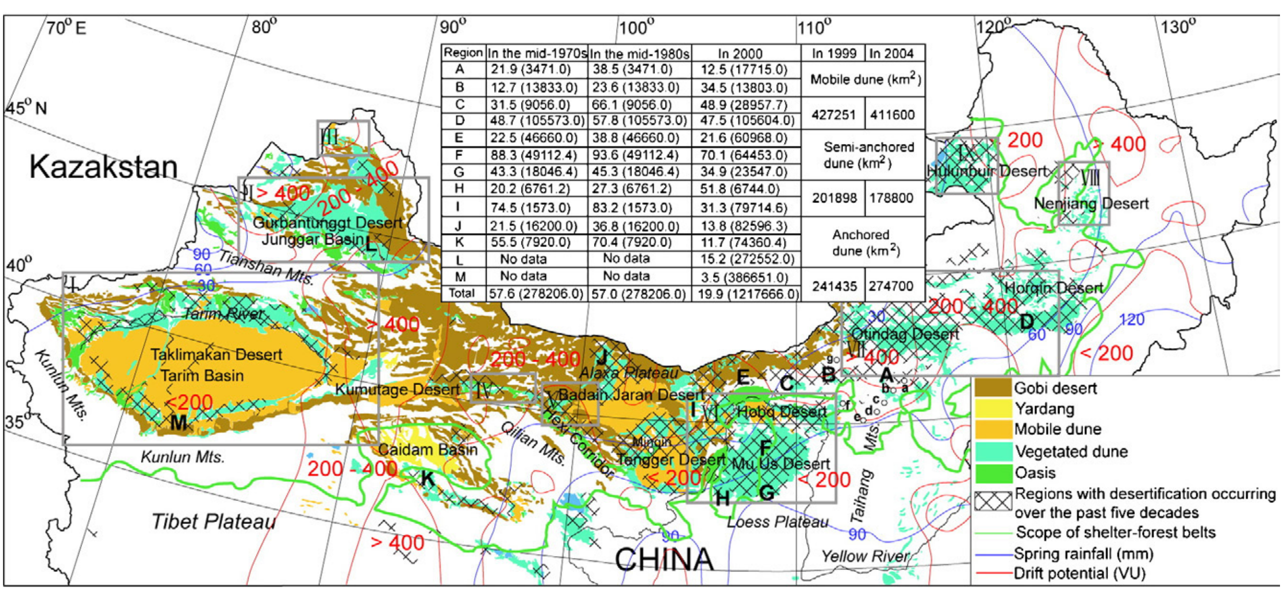
However, although there have been remarkable advances in Chinese desertification research in recent decades, and numerous scientists have claimed that desertification is primarily due to human activities, its dynamics are governed by the potential impacts of surface erodibility and atmospheric erosivity (Thomas et al., 2005; Thomas and Leason, 2005), and these dynamics are still not well understood. In the present paper, based on a review of previous studies and our own research, we have reviewed the geomorphological, geological, and ecological characteristics of desertification, reported its trends, and discussed the most likely causes of modern desertification in China.

2. Climatic, geological, and geomorphological backgrounds of desertification in China

In China, desertification has usually occurred in arid and semiarid regions, with annual precipitation <450 mm and spring precipitation <90 mm. Key areas include the regions around the Taklimakan, Badain Jaran, and Kumutage Deserts, some parts of the Tengger, Ulan Buh, and Hobq Deserts, and most parts of the Gurbantunggut, Mu Us, Otindag, Horqin, Hulunbuir, and Nenjiang Deserts (Fig. 1). The pattern of desertification in arid and semiarid China can be divided into two parts by a line drawn at around 100° E longitude: East of this line, the eastern part of the study area is significantly affected by precipitation, wind activity, and other climatic factors. Desertification west of this line is affected by the same factors, but in addition, terrestrial water (overland flow and rivers, controlled by glacier ablation, ice, and snow thawing) plays a major role in desertification or rehabilitation because most glaciers and continental rivers have developed in this region, where they act as major sources of water.

In addition, the occurrence of desertification or rehabilitation in arid and semiarid China has always had a close relationship with the local geomorphological types. Over the past five decades, desertification and rehabilitation have usually occurred in alluvial and flood plains or on plateaus where huge deposits of sandy materials developed (e.g., Z. Li et al., 2002). Under the control of these parent materials, the dominant soils are aeolian sands, brown soils, cinnamon soils, gray cinnamonic soils, chernozems, and kastanozems (Fig. 2C), which are highly vulnerable to wind erosion (e.g., Yang, 1985; L. Liu et al., 1998) and as a result, are highly vulnerable to degradation. In addition, desertification west of 100° E is closely related to oasis development and degradation due to changes in river channels and other bodies of surface water. This has occurred in the regions surrounding the Taklimakan, Tengger, and Badain Jaran Deserts (Z. Zhu et al., 1981; Xie et al., 2004, B. Li, 1998).

The vegetation types in regions where desertification or rehabilitation has occurred always include succulent halophytic small sub-shrub communities, steppes, savannas, and some herbaceous vegetation (Fig. 2D) that developed on aeolian sands and other soil types vulnerable to wind erosion. Dune activity is significantly inhibited by vegetation cover, increased soil moisture, and a low degree of exposure to wind activity. In arid and semiarid China, the dunes and sand sheets are usually anchored when the vegetation cover exceeds 40%, but the dunes and sand sheets become semi-anchored between 15 and 40% cover, and they become mobile at cover levels under 15% (Z. Zhu et al., 1980; D. Zhong, 1998). However, the threshold vegetation cover depends strongly on the nature of the surface soil, and some deposits are vulnerable to erosion even at relatively high vegetation



Region	In the mid-1970s	In the mid-1980s	In 2000	In 1999	In 2004
A	21.9 (3471.0)	38.5 (3471.0)	12.5 (17715.0)	Mobile dune (km^2)	
B	12.7 (13833.0)	23.6 (13833.0)	34.5 (13803.0)		
C	31.5 (9056.0)	66.1 (9056.0)	48.9 (28957.7)	427251	411600
D	48.7 (105573.0)	57.8 (105573.0)	47.5 (105604.0)		
E	22.5 (46660.0)	38.8 (46660.0)	21.6 (60968.0)	Semi-anchored dune (km^2)	
F	88.3 (49112.4)	93.6 (49112.4)	70.1 (64453.0)		
G	43.3 (18046.4)	45.3 (18046.4)	34.9 (23547.0)		
H	20.2 (6761.2)	27.3 (6761.2)	51.8 (6744.0)	201898	178800
I	74.5 (1573.0)	83.2 (1573.0)	31.3 (79714.6)		
J	21.5 (16200.0)	36.8 (16200.0)	13.8 (82596.3)	Anchored dune (km^2)	
K	55.5 (7920.0)	70.4 (7920.0)	11.7 (74360.4)		
L	No data	No data	15.2 (272552.0)		
M	No data	No data	3.5 (386651.0)	241435	274700
Total	57.6 (278206.0)	57.0 (278206.0)	19.9 (1217666.0)		

Fig. 1. Map of dune systems in 2000 and desertification trends from the 1970s to 2000 in arid and semiarid China. Numbers outside and inside brackets indicate (respectively) the extent of desertification (% of the monitoring area) and the monitoring area (km^2). Sand drift potential and the distribution of spring precipitation are also shown. The map was compiled based on data from IGFDR (1974), CAREERI (2005), T. Wang et al. (2003), SFAC (2005), and X. Wang et al. (2007,2008).

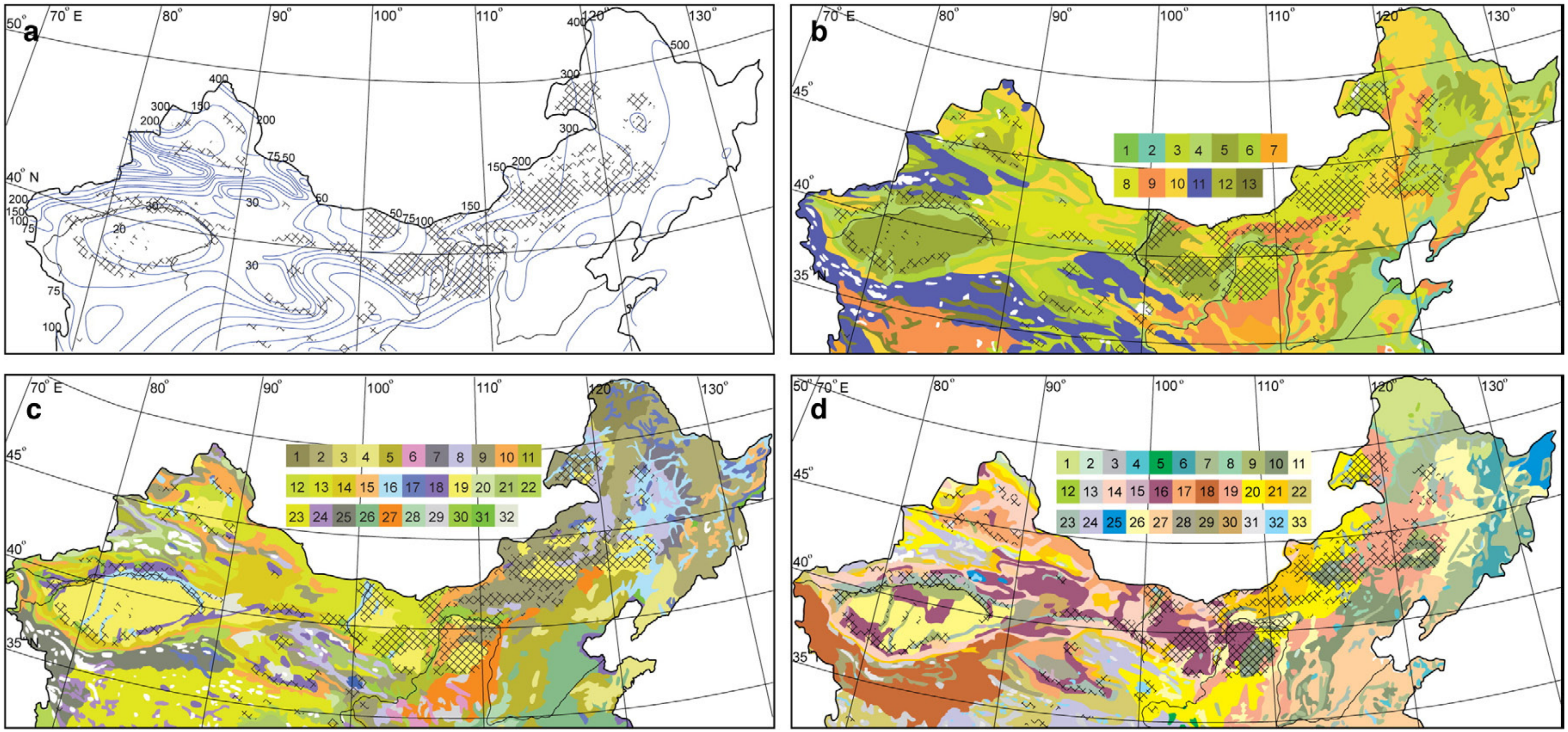


Fig. 2. (a) Annual mean precipitation (mm), (b) geomorphological setting, (c) soil type, and (d) vegetation type distributions in arid and semiarid China. Areas covered by diamonds indicate regions in which desertification has occurred over the past five decades. Data were compiled from Sinomaps Press (1998). Legend for 2-b: 1, fan delta; 2, marine-origin plain; 3, lacustrine plain; 4, alluvial plain; 5, flood plain; 6, dip plain; 7, terrace; 8, piedmont plain; 9, hill; 10, low and medium mountains; 11, alpine; 12, saline plain; 13, frost melting plain. Legend for 2-c: 1, brown coniferous forest soil; 2, brown forest dark soil; 3, gray forest soil; 4, brown soil; 5, cinnamon soil; 6, gray cinnamonic soil; 7, phaeozem; 8, chernozem; 9, kastanozem; 10, brown calcic soil; 11, sierozem; 12, gray desert soil; 13, gray-brown desert soil; 14, brown desert soil; 15, Baijiang soil; 16, meadow soil; 17, bog soil; 18, solonchak; 19, aeolian sandy soil; 20, subalpine meadow soil; 21, alpine meadow soil; 22, subalpine steppe soil; 23, alpine steppe soil; 24, alpine frost desert soil; 25, alpine desert soil; 26, fluvo-aquic soil; 27, loess soil; 28, manured loessial soil; 29, Heilu soil; 30, irrigation-silting soil; 31, paddy soil; 32, salt crust. Legend for 2-d, 1, cold-temperate and temperate mountain deciduous coniferous forest; 2, cold-temperate and temperate mountain evergreen coniferous forest; 3, temperate steppe and sandy land evergreen coniferous woodland; 4, temperate evergreen coniferous forest; 5, subtropical and tropical mountain evergreen coniferous forest; 6, temperate deciduous broadleaf and evergreen coniferous mixed forest; 7, temperate (subtropical) deciduous broad-leaved forest; 8, temperate mountain deciduous microphyll forest; 9, temperate deciduous microphyll woodland; 10, temperate deciduous thicket; 11, tropical shrubs; 12, temperate alpine undershrub tundra; 13, alpine cushion little sub-shrub plus sparse alpine herbosa vegetation; 14, temperate little sub-shrub desert; 15, temperate succulent halophytic little sub-shrub desert; 16, temperate shrub and sub-shrub desert; 17, temperate semi-arbor desert; 18, temperate alpine trailing little sub-shrub desert steppe and savanna; 19, temperate grass and weed steppe; 20, temperate bunchgrass steppe; 21, temperate little bunchgrass and sub-shrub steppe; 22, temperate and subtropical alpine steppe; 23, temperate meadow; 24, temperate and subtropical alpine meadow; 25, temperate herbaceous marsh; 26, food crop with one cropping; 27, continuous cropping and deciduous fruit tree garden with two crops; 28, salt crust; 29, detritus in alpine peak; 30, gobi; 31, snow, ice, and glacier; 32, water body; 33, desert.

covers. Consequently, significant variations in aeolian sand transport and rainfall can strengthen or weaken the vegetation, leading to evolution of the dunes between the mobile, semi-anchored, and anchored forms. Depending on the direction of the evolution, desertification or rehabilitation took place.

In general, desertification in arid and semiarid China has occurred in the alluvial and flood plains or on plateaus where continental rivers developed and huge deposits of sand have formed. On these geomorphological types, shrubs or small trees grew and extensive nebkha dunes and mobile dunes developed. Under the control of climatic changes and geomorphological processes, or under the influence of human impacts, both dune types have evolved between mobile and anchored.

3. Modern desertification trends in China

Using aerial photos (1:50 000) obtained from the mid-1950s, mid-1960s, mid-1970s, and mid-1980s, Landsat TM images obtained in 2000, and field surveys in 2005, extent of desertification from the 1950s to 2005 in China were assessed. Based on this analysis, the area of desertification in 2000 in arid and semiarid China totaled 38, 57, 00 km^2 (T. Wang et al., 2002, 2003, 2004a), located at the margins of deserts and in some steppe regions (Fig. 1). In addition, D. Zhong (1998) reported that from the mid-1950s to the mid-1990s, desertification was being reversed in most deserts of arid and semiarid China (Table 1). Compared with the areas of deserts in the mid-1950s, the area of desert with mobile dunes decreased by 422 km^2, and the area in which mobile dunes became anchored increased by 17 820 km^2 for China as a whole (D. Zhong and Qu, 2003); this, combined with the fact that all deserts in Table 1 showed a larger increase in rehabilitated area than in desertified area, suggests that rehabilitation has occurred from the mid-1950s to the mid-1990s. In addition, the area of sandy desertification in 1999 had decreased by 33 673 km^2 by 2004 (SFAC, 2005). This suggests that rehabilitation has occurred continuously from the 1990s to the present in arid and semiarid China.

There were significant differences in the desertification trends in the western and eastern parts of arid and semiarid China: In the western parts, the major forms of desertification and rehabilitation involved changes in dune activity, including the evolution of anchored and semi-anchored dunes into mobile dunes in some areas and the evolution of mobile dunes into anchored and semi-anchored dunes in other areas. In the eastern parts, the same changes in dune activity occurred, but extensive nebkha dunes also developed.

From the mid-1950s to the early 2000s, desertification passed through several phases in arid and semiarid China. Rapid desertification occurred from the 1970s to the early 1980s, when the areas of desertification amounted to 57.6 and 57.0% of the total monitoring area, respectively; in contrast, desertified land covered only 19.9% of the area in 2000 (T. Wang et al., 2003, 2004a, Fig. 1). From the 1970s to the early 1980s, desertification in eastern areas included the reactivation of dunes and the development of nebkha dunes in the alluvial and flood plains. The nebkha dunes that originated during this period persisted despite the extensive rehabilitation that occurred from the late 1980s to the present. The desertification in this region also included coarsening of the soils in some grasslands due to severe wind erosion leading to the loss of finer particles during this period. In the western areas, the desertification that occurred during this period mainly involved activation of anchored or semi-anchored dunes, whereas the rehabilitation always involved anchoring of mobile or semi-anchored dunes.

Monitoring and field investigations (e.g., D. Zhong, 2003) revealed that although human impacts such as over-reclamation contributed to desertification from the mid-1950s to the mid-1990s, a period when the area of arable land increased significantly in this region, most of the reclaimed lands did not become desertified during this period. Therefore, it is questionable whether the desertification that occurred during this period was mainly due to over-reclamation, as previous studies have suggested (e.g., W. Wu et al., 1997; B. Wu and Ci, 1998, 2002; W. Sun, 2000; S. Qiu, 2004).

Desertification generally reversed in most of arid and semiarid China by the 2000s, except for one or two regions. Significant changes mainly occurred in the central and eastern regions, where significant rehabilitation occurred. However, in parts of western China such as the Tarim Basin, no significant changes in desertification status occurred during the study period because the observed vegetation changes were not significant.

4. Desertification in different regions of arid and semiarid China

4.1. Desertification in the Horqin, Hulunbuir, and Nenjiang Deserts and adjacent regions

UNEP (1992) maps of regions of northeastern China with high risks of desertification include the Hulunbuir, Nenjiang, and Horqin deserts and adjacent regions (Fig. 3), where the dominant geomorphological types are anchored and semi-anchored dunes, and where there is relatively high annual precipitation (~450 mm) and huge sand deposits. From the mid-1950s to the early 2000s, the desertification trend revealed several distinct periods in these regions: desertification increased from the 1950s to the 1970s, it accelerated in the 1970s and decelerated in the early 1980s, and then rehabilitation has occurred since the late 1980s. For instance, the area of desertification increased from 51 384 km^2 in the mid-1970s to 61 008 km^2 in the mid-1980s, and then decreased to 50 198 km^2 in 2000 (W. Wu, 2003). From the 1990s to the 2000s, the area of desertification decreased by 10 866 km^2 in these areas (T. Wang et al., 2004a). Table 2 summarizes the decreases

Table 1
Evolution of dune systems from the mid-1950s to the mid-1990s in arid and semiarid China. The deserts in this table are identified in Fig. 1. Data were obtained from D. Zhong (2003)

Desert	Area (km^2)					
	Total	Desertification increased	Rehabilitation occurred	Dune mobility decreased	Dune mobility increased	No significant change
China (total)	808,860	12,840	42,280	422	24,460	729,280
Taklimakan	365,000	0	1450	7	510	363,050
Gurbantunggut	51,130	1030	1080	50	460	48,560
Badain Jaran	50,510	0	10	0	73	50,430
Horqin	50,440	7270	12,120	18	10400	20,650
Tengger	42,320	47	1570	1	600	40,100
Mu Us	38,940	190	6160	0	3420	29,170
Otindag	29,220	3500	4940	97	5290	15,500
Kumutage	21,970	0	0	0	0	21,970
Hexi Corridor	19,740	10	2050	6	280	17,400
Hobq	17,310	0	590	7	690	16,030
Caidam	14,940	0	100	0	90	14,750
Ulan Buh	10,760	0	270	0	680	9070

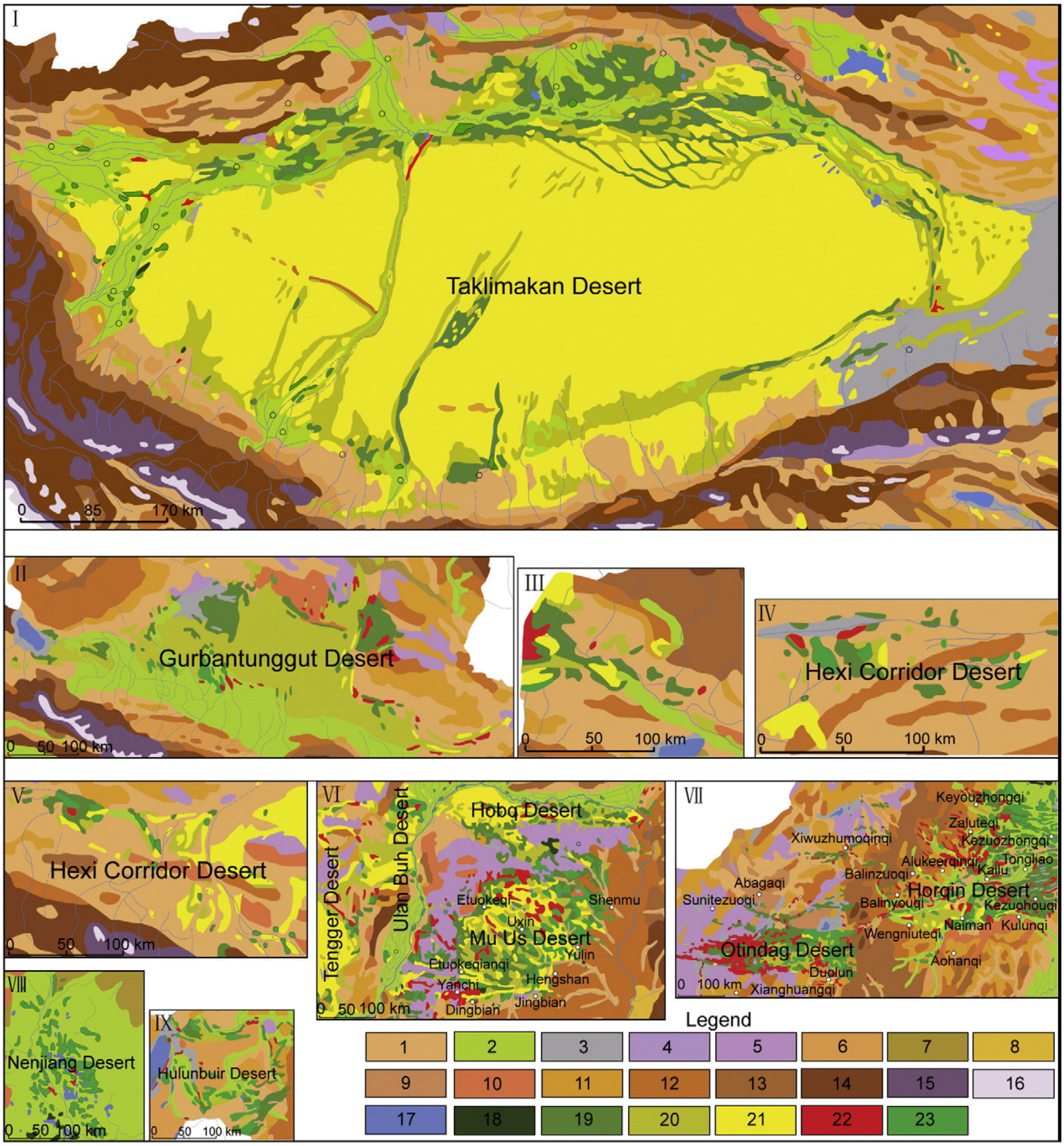


Fig. 3. Evolution of dune systems from the mid-1950s to 2000, and associated human and environmental parameters, in typical regions of arid and semiarid China. The extents of these regions are shown in Fig. 1. Data were compiled from D. Zhong (1998, 2003) and D. Zhong and Qu (2003). Legend: 1, flood plain; 2, alluvial plain; 3, lacustrine plain; 4, drift plain; 5, denudation plain; 6, diluvial plateau; 7, alluvial plateau; 8, loess upland; 9, lava plateau; 10, denudation plateau; 11, hills; 12, low mountains; 13, medium mountains; 14, high mountains; 15, alps; 16, glaciers; 17, body of water; 18, arable land; 19, anchored dunes; 20, semi-anchored dunes; 21, mobile dunes; 22, desertification occurred; 23, rehabilitation occurred.

for this and other regions. Although there have been no significant changes in dune activity from 2000 to the present, continuous rehabilitation has occurred (A. Li et al., 2006). From the mid-1950s to the mid-1990s, desertification occurred in only a few regions of the Hulunbuir and Nenjiang deserts, and during this period, extensive rehabilitation occurred in both regions. For instance, the area of mobile dunes in the Hulunbuir Desert increased from 5695 ha in the late 1980s to 8315 ha in the late 1990s, but the area of semi-anchored dunes increased from 14 161 ha to 21 808 ha and the area of anchored dunes increased from 308 303 ha to 453 025 ha (Lu et al., 2005).

In the Horqin Desert the major form of desertification was the development of nebkha dunes in the alluvial and flood plains of desert margins in the 1970s due to a decrease in groundwater levels (X. Wang et al., 2006b), but some anchored and semi-anchored dunes also evolved into semi-anchored and mobile dunes. In the Hulunbuir and Nenjiang deserts and their adjacent regions, the major form of desertification was the evolution of semi-anchored dunes into mobile dunes. Therefore, although extensive rehabilitation occurred after the late 1980s, usually expressed by decreases in dune mobility, the nebkha dunes that originated in the 1970s continued to develop, which shows that desertification processes may go through relatively long stages once aeolian geomorphology develops.

Although many researchers (e.g., H. Zhao et al., 2002; Qiu, 2004; T. Wang et al., 2004b; Chang et al., 2005) have claimed that over-

Table 2
Areas of desertification in different periods in various regions of the Horqin Desert and adjacent regions. The locations are identified in Fig. 3. Data from W. Wu (2003)

Location	Area of desertification (km^2)		
	In the mid-1970s	In the mid-1980s	In 2000
Balinzuoqi	No data	No data	1255.91
Balinyouqi	6131.7	5340.4	5205.22
Zaluteqi	5061.9	9051.5	3905.75
Wengniuteqi	6531.4	5665.9	5029.94
Aohanqi	No data	No data	771.71
Alukeerqinqi	5613.6	8322.4	7010.31
Naimanqi	5657.1	5409.6	4505.84
Kezuozhongqi	3616.9	5479.6	5570.49
Kezuohouqi	8400	9631.9	9056.79
Kailu	1527	2693.9	1535.66
Tongliao	No data	1489.8	624.64
Keyouzhongqi	1979.5	2827.4	3631.07
Kulunqi	2658.6	2327.1	2094.19

reclamation of land for agriculture and other activities accelerated desertification, the human impacts on desertification remain questionable even in regions with high densities of human activities. For instance, mobile dunes and semi-anchored dunes were reworked into arable lands in the Nenjiang Desert over the past five decades (Fig. 3), very little arable land was deserted because of desertification. In addition, two or three alternations between paleosols and aeolian sands from the start of the Holocene to the present and this shows that periods of desertification and rehabilitation alternated in the Horqin and Nenjiang Deserts (S. Qiu et al., 1992), largely in the absence of any human impacts during the early parts of this period. In addition, the occurrence of desertification after the Medieval Warm Period in this region appears to have resulted from the cold and windy climate in this region (P. Shi and Hasi, 2002). Therefore, from prehistorical times through historical times and to the present, the dynamics of desertification in this region appear to have been dominated by climate change, and although human activities may have played a role in desertification in more recent times, their significance must be considered more carefully in light of the strength of the long-term climatic cycles.

4.2. Desertification in the Otindag Desert and adjacent regions

The Otindag Desert and its adjacent regions have sustained serious desertification due to over-reclamation and grazing during recent decades (e.g., T. Wang et al., 1991; J. Sun et al., 1994, 1999a,b; J. Wang et al., 1999; X. Liu et al., 2002; W. Sun and Li, 2002, Hai et al., 2002, 2003; Yu, 2003). Unfortunately, although previous studies have proposed that humans were responsible for the desertification, firm evidence to defend this assertion is lacking because none of these studies attempted to explain why desertification reversed during certain phases even though the stresses imposed by human activities continuously increased during the past five decades in this region (S. Liu and Wang, 2004; Xue et al., 2005; Table 3). As was the case in the Horqin Desert, rapid desertification occurred in the 1970s, and the major forms of desertification were the development of nebkha dunes (X. Wang et al., 2006a) and the activation of anchored dunes. Desertification in the 1970s covered the whole Otindag Desert and adjacent regions, whereas the rehabilitation that occurred after the late 1980s mainly occurred in the western Otindag as a result of anchoring of mobile dunes (Fig. 3); the nebkha dunes that developed during the desertification period could not be rehabilitated during a short period even when climate change promoted the rehabilitation of desertified land elsewhere in the region.

Since the start of the Holocene, this region has experienced several phases of desertification. X. Fang (1999), X. Liu et al. (2002), W. Qiu et al. (2005), Yang (1985), and Ha Si (1994) proposed that changes in precipitation and sand transport played major roles in desertification in this region. X. Wang et al. (2006a) provided a more comprehensive framework for the factors that controlled desertification in the Otindag Desert and adjacent regions (Fig. 4). The framework included trends in precipitation, evaporation, potential sand transport, numbers of livestock, arable lands, and the human population during different periods of desertification (1970s to 1980s) and rehabilitation (1980s to present) in this region. The results clearly show that the human impacts have no significant relationships with desertification and rehabilitation in this region.

4.3. Desertification in the Mu Us, Ulan Buh, and Hobq deserts

The Mu Us Desert, located in the Ordos Plateau, is well-known in China and around the world as a “human-made” desert, as the serious desertification that occurred in this area has been attributed primarily to human activity over the past 2000 years (e.g., Hou, 1973; S. Wang, 1985; Jing, 2000). Similarly, the desertification that has occurred in the Hobq Desert is considered to have resulted from human activities over the past several thousand years (M. Qiu and Liu, 1985). However, there is little evidence to support this hypothesis. For instance, based on historical records from ancient China and archaeological evidence, Zhao (1981), Niu and Zhao (2000), W. Wang (2002), and Han (2003) concluded that the modern Mu Us Desert existed at least 4000 years ago, long before large human populations lived in this area, and from that time to the present, this region has experienced several phases of desertification and rehabilitation that paralleled climatic changes. Bao and Zhang (1984) concluded that climate changes controlled desertification in the Ulan Buh and Hobq Deserts; they found no strong relationships between human factors and either reclamation or desertification in this region. On the contrary, they found that rehabilitation occurred even though human populations (and their associated activities) increased. Furthermore, at least 27 alternating cycles of deposition of aeolian dune sands and of fluvio-lacustrine facies or paleosols have occurred during the last 150 000 years (G. Dong et al., 1988; B. Li et al., 2000), and aeolian sequences have been deposited within this region for about 580 000 years (J. Sun et al., 1995, 1999a,b; J. Sun, 2000). From the mid-1950s to the present, the desertification rate in the Mu Us Desert has decreased steadily, to 68% in the mid-1970s, 63% in the mid-1980s, and 54% in 2000 (T. Wang et al., 2003). The main form of desertification was the evolution of anchored dunes into semi-anchored dunes, and the main form of rehabilitation was the evolution of mobile dunes into semi-anchored and anchored dunes (Fig. 3). Modern desertification processes also do not support the human-made-desert hypothesis. Although W. Wu (2001) and B. Wu and Ci (1998, 1998, 2002) proposed that the desertification occurring in this region resulted from high human impacts, they provided little evidence in their papers to support this hypothesis, and could not explain the several desertification and rehabilitation phases that have occurred during the past five decades in this region (Table 4).

Table 3
Area of desertification in the counties and regions in the Otindag Desert and adjacent regions. Regions are identified in Fig. 1 (letters a to f) and 2. Data are from Z. Zhu and Chen (1994), T. Wang et al. (2004a), Xue et al. (2005), and S. Liu and Wang (2004)

County	Area of desertification (km^2)		
	In the mid-1970s	In the mid-1980s	In 2000
Huade (b)	1117.31	1733.80	1122.60
Shangdu (c)	1887.50	2634.00	1668.90
Chayouhouqi (d)	765.00	1160.00	1025.10
Chayouzhongqi (e)	565.00	1880.00	798.95
Taipusiqi (a)	602.33	1629.73	854.62
Duolun	1067.87	1978.53	1717.70
Xianghuangqi	1354.33	1466.53	1295.21
Abagaqi	No data	No data	4597.05
Sunitezuoqi	No data	No data	7511.16
Suniteyouqi (g)	No data	No data	8117.50
Siziwangqi (f)	6537.50	10305.00	<1200
Xiwuzhumoqin	1065.86	4297.26	No data

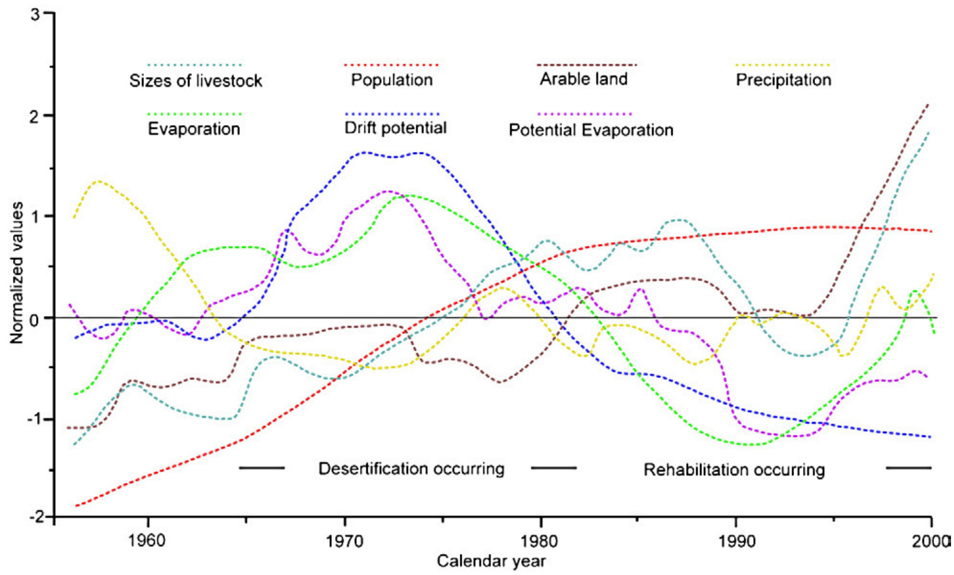


Fig. 4. Conceptual diagram of a framework illustrating the trends in the numbers of livestock, human population, the area of arable land, potential evaporation, evaporation, drift potential, and precipitation from the mid-1950s to 2000, and the relationship of these indices to desertification and rehabilitation in the Otindag Desert and adjacent regions. Data from X. Wang et al. (2006a).

Runnström (2003) and X. Wang et al. (2005a) have systematically discussed the causes of desertification based on both climatic factors and human impacts in the Mu Us Desert. After examining the factors that potentially controlled desertification in this region, they found that the over-reclamation and the large increase in the number of livestock during the 1980s did not result in desertification in this region (Fig. 5). For instance, the number of livestock (sheep and goats) and the human population have increased continuously over the past 50 years in this region, but significant rehabilitation occurred after the 1980s despite these increases. In addition, from the mid-1950s to the mid-1990s, over-reclamation occurred in this region, but few areas of arable land became desertified during these periods. However, the trends for desertification and rehabilitation are consistent with that for potential sand transport. Therefore, Runnström and Wang concluded that the significant decrease in potential sand transport was the key factor that controlled desertification in this region because the soils of this region are very sensitive to wind erosion, and sand-driving wind activity may still have occurred even with a vegetation cover of 50 to 60% (Huang et al., 2001). Consequently, human activities may have had some impacts on desertification in this region, but climate change was the key factor.

4.4. Desertification in the Hexi Corridor Region

The Tengger, Badain Jaran, and Hexi Corridor deserts developed in the Western Helan Mountains. Although most areas of the Badain Jaran and Tengger deserts are covered by mobile dunes, which have shown no significant changes in their activity in recent decades, desertification in the Hexi Corridor Desert, which has developed on the northern side of the Qilian Mountains, occurred rapidly due to significant variations in the region's water supply and wind activity, accompanied by the degradation of oases. Over the past five decades, rehabilitation has generally exceeded desertification in this region, largely due to a decrease in wind activity and increase in the water supply (J. Wang et al., 2002; Fig. 3). In contrast with desertification in other regions of China, the water supply (which is controlled by glaciers and snow in the Qilian Mountains) was the key factor that controlled desertification in this region (Xie et al., 2004).

Over the past thousand years, periods of desertification and rehabilitation have alternated in this region, but the areas of oases have not decreased; on the contrary, the areas of oases increased in some regions as a result of the diversion of rivers and an increase in this region's water supply (B. Li, 1999, 2001). For instance, an extensive oasis developed during the Han (206 B.C. to 220 A.D.) and Tang (618 to 907 A.D.) dynasties in the Hexi Corridor region, but were deserted due to a reduction in the region's water supply and a natural change in its river channels (Fig. 6), but new oases were developed adjacent to modern river channels (B. Li, 1998, 1999). However, if there are significant changes in the region's water supply, the areas of desertification will change significantly once again.

At present, the Minqin Oasis in the Hexi Corridor is regarded as a typical region in which rapid desertification is occurring, and this has been

Table 4
Area of desertification (km^2) in the Mu Us Desert in the mid-1970s, mid-1980s, and 2000. The area of desertification represents the percentage of the total monitoring area in the region that is classified as desertified. The locations are identified in Fig. 3. Data are from T. Wang et al. (2003)

Location	In the mid-1970s			In the mid-1980s			In 2000		
	Monitoring area	Area of desertification	%	Monitoring areas	Area of desertification	%	Monitoring areas	Area of desertification	%
Yulin	6551.0	5729.8	87.5	6551.0	5248.1	80.1	6891.0	4360.0	63.3
Hengshan	2584.0	1596.5	61.8	2584.0	1292.4	50.0	4219.0	782.5	18.6
Dingbian	4493.0	2093.5	46.6	4493.0	1729.8	38.5	6847.0	2295.0	33.5
Yanchi	6761.0	1369.0	20.2	6761.0	1846.0	27.3	6744.0	3495.0	51.8
Etuoke	5251.0	4721.0	89.9	5251.0	4165.0	79.3	20245.0	13,103.0	64.7
Jingbian	3485.0	1917.5	55.0	3485.0	1815.5	52.1	4972.0	1227.0	24.7
Shenmu	4463.0	3772.9	84.5	4463.0	3345.8	75.0	7509	3195.0	42.5
Uxin	11,645.0	10,164.0	87.3	11,645.0	9561.0	82.1	11,627.0	10,779.0	92.7
Etuokeqianqi	7713.0	6321.0	82.0	7713.0	6306.0	81.8	12321.0	11,426.0	92.7

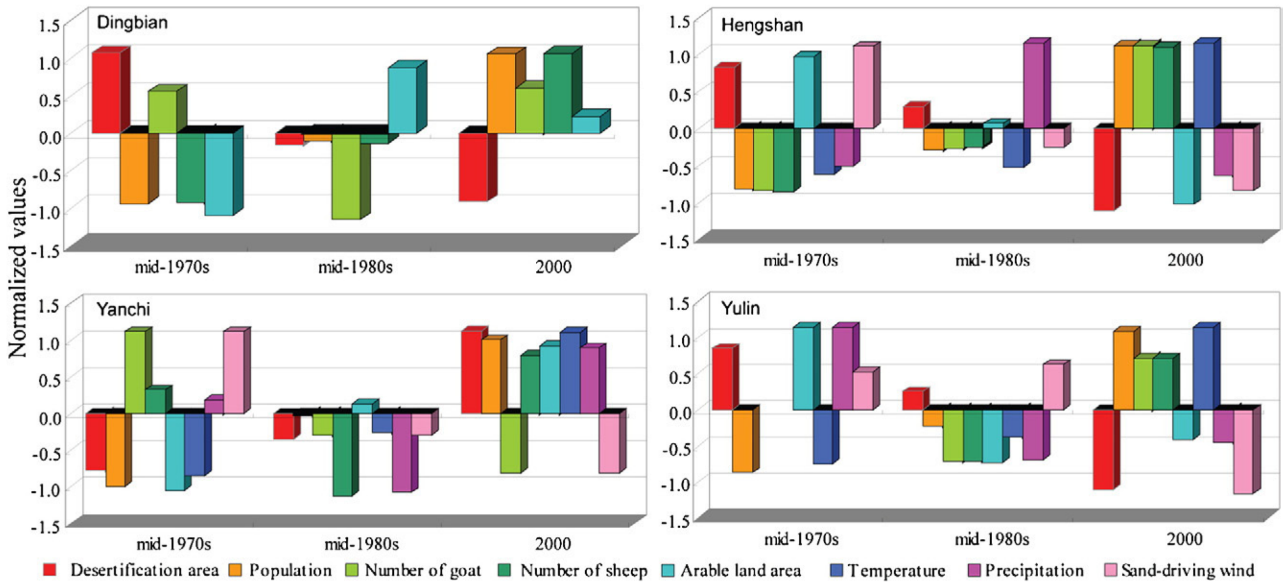


Fig. 5. Comparisons of the area of desertification in the mid-1970s, mid-1980s, and in 2000 in Dingbian, Hengshan, Yanchi, and Yulin with the proxies for human activity (population, area of arable land, and numbers of livestock) and climate indices (temperature, precipitation, and sand-driving winds). The locations are identified in Fig. 3. Data are from X. Wang et al. (2005a).

explained as the result of human activities leading to overuse of the water supply. However, during the past 2000 years, the area of the Minqin Oasis has not decreased; on the contrary, it has continuously increased due to the recession of lakes that developed since the mid-Holocene (Feng, 1963). In this region, high precipitation during the mid-Holocene (F. Chen et al., 2003) resulted in the development of extensive areas of lakes, but these lakes have shrunk significantly and continuously for at least the past 5000 to 6000 years (Fig. 7). As the areas of the lakes have decreased and ground water has retreated below the surface, the areas of oasis have increased, reaching their maximum extent at present. However, the desertification that has occurred during the past five decades in this region was due to significant decreases in groundwater levels (E, 2005) as a result of the overuse of water upstream of this area. In addition, over-reclamation has occurred in the Minqin Oasis over the past five decades. Although these changes suggest a strong human influence on desertification in the area, previous studies ignored one important fact: the lands are currently being cultured during a period in which desertification is not expanding, whereas desertification is occurring in lands being deserted due to an inadequate water supply. These findings suggest that desertification in this region represents a long-term process that has been occurring for the past 5000 to 6000 years, even if modern human activities are contributing to the problem.

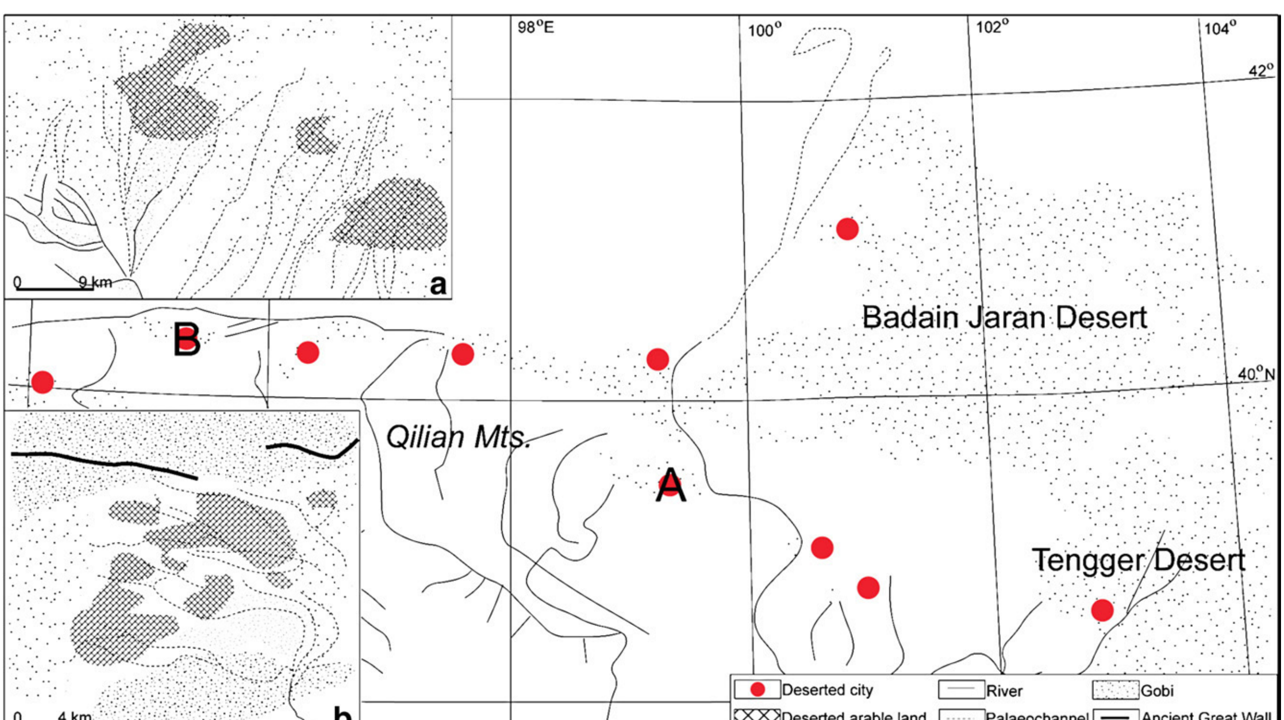


Fig. 6. Desertification during the Han and Tang dynasties (206 B.C. to 907 A.D.) of ancient China in the Hexi Corridor region. Data from B. Li (1998, 1999, 2001).

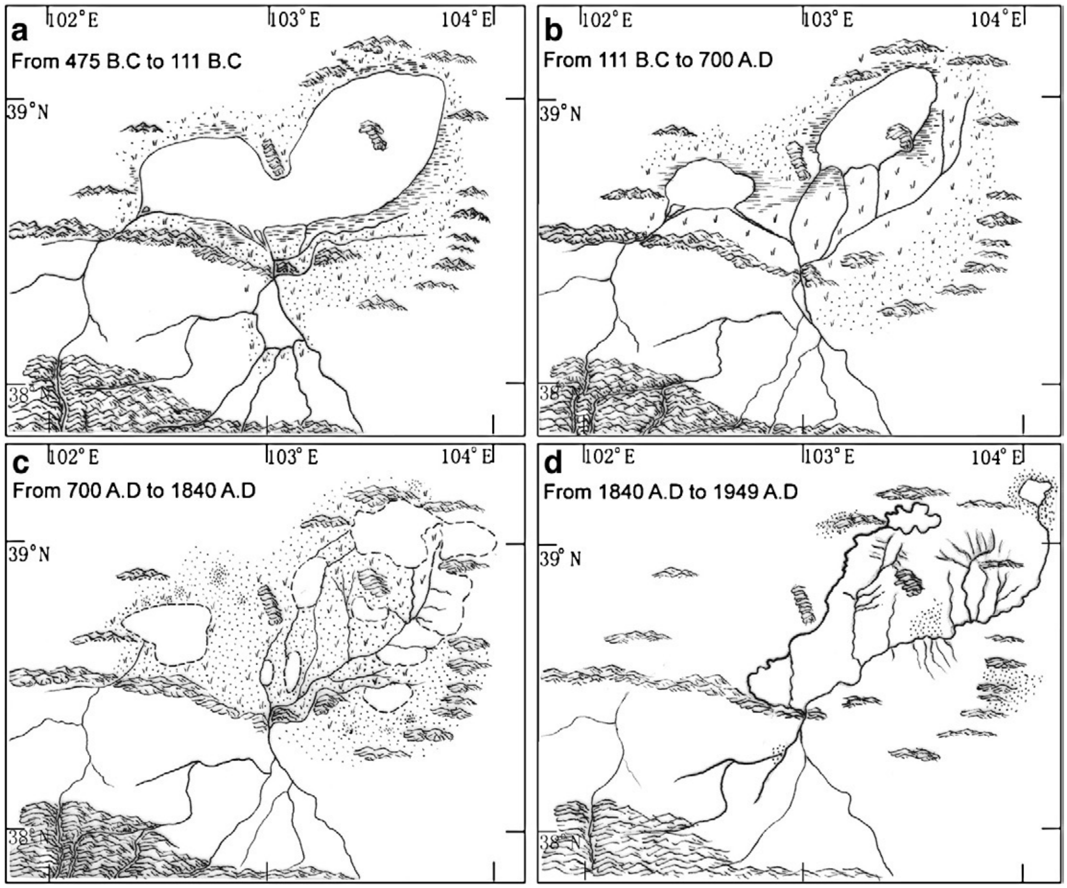


Fig. 7. Evolution of the main bodies of water in the Minqin Oasis of the Hexi Corridor from 475 B.C. to 1911 A.D., showing the increased area of oases resulting from shrinkage of the bodies of water in the region. Based on Feng (1963).

4.5. Desertification in the Taklimakan Desert

Although the Taklimakan Desert represents China's largest desert and the one with the highest risk of desertification, few researchers have studied modern desertification trends in this desert and its adjacent regions. In this region, mobile dunes are the dominant geomorphological type, and anchored and semi-anchored dunes are found only at the margins of the desert, which are the regions in which

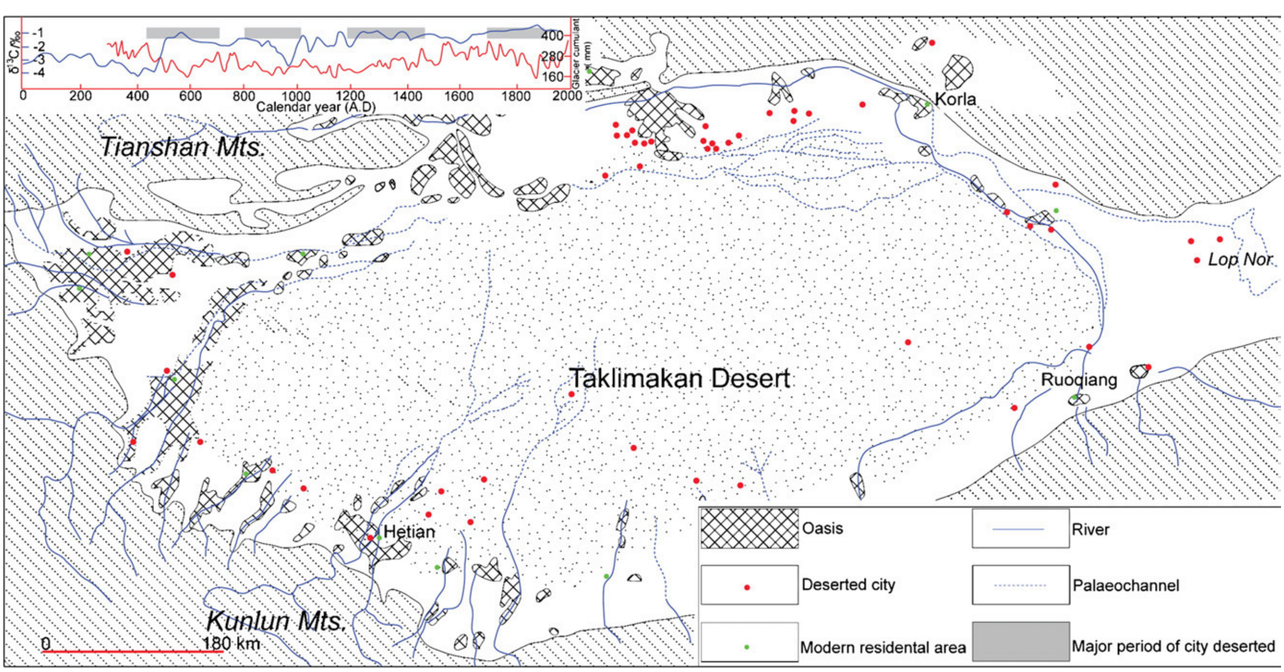


Fig. 8. Desertification during the Han and Tang dynasties (206 B.C. to 907 A.D.) of ancient China in the Taklimakan Desert region. Data from Fan (1979), Zhou (1989), and W. Zhong et al. (2004).

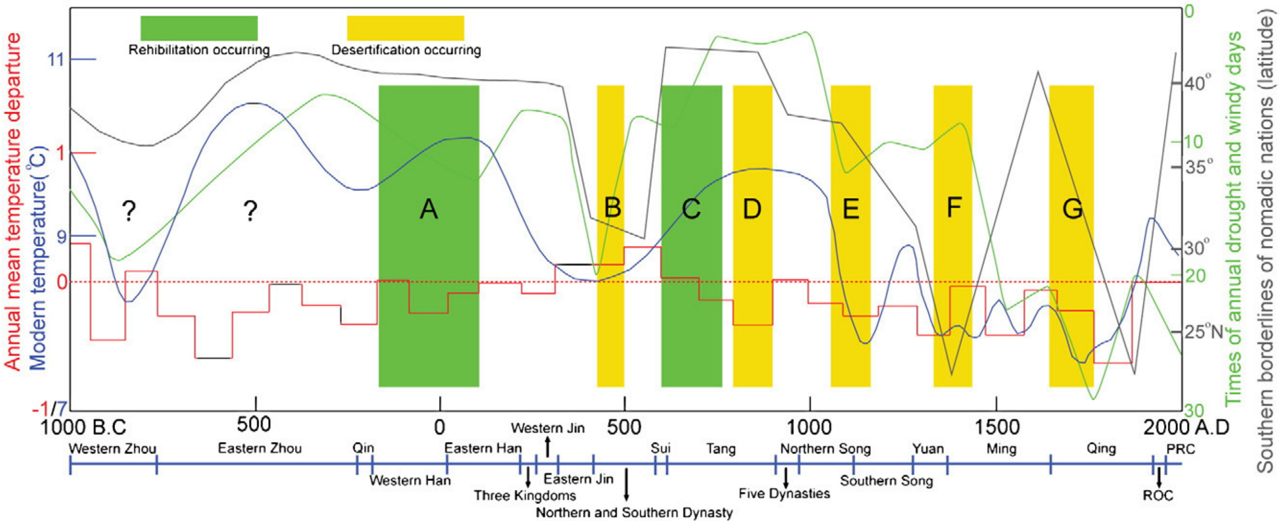


Fig. 9. Desertification, rehabilitation, and their relationships with temperature, drought, and wind regime during historical periods in ancient and modern China. Changes in temperature, drought, and wind regime, as well as in the southern border reached by nomadic nations, were obtained from Guo et al. (2006), K. Zhu (1973), and H. Wang (2006). The occurrence of desertification and rehabilitation was obtained from B. Li (1998, 2001), N. Wang et al. (2003), Yan (2004), Niu and Zhao (2000), S. Wang (2000), Zhou (1989), Bao and Zhang (1984), and Han (2003). Regions in which desertification or rehabilitation occurring: A, Hexi Corridor, Alaxa Plateau, and Mu Us deserts and adjacent regions; B, Hexi Corridor, Mu Us, and Taklimakan Deserts; C, Hexi Corridor and Mu Us Deserts and adjacent regions; D, Hexi Corridor; E, Horqin Desert; F, Hexi Corridor, Tarim Basin, and Mu Us Desert; G, Hexi Corridor, Tarim Basin, Mu Us Desert, and adjacent regions.

desertification or rehabilitation are occurring. From the mid-1950s to the mid-1990s, desertification was expressed primarily by the evolution of anchored or semi-anchored dunes into mobile dunes in the western part of the desert, but the areas in which rehabilitation has occurred were far higher than the areas that underwent desertification (Fig. 3). The variations in dune activity from the 1960s to the early 2000s have been closely related to the desertification trends, and showed that rapid desertification occurred in the 1970s and 1980s; however, the dune activity trends since the 1990s show that rehabilitation has occurred during this period (X. Wang et al., 2004). In addition, desertification monitoring results since the 1990s have shown that desertified areas decreased by 50%, and rehabilitation is continuing (H. Wang and Zhang, 2005).

During historical periods, alternating periods of desertification and rehabilitation have accompanied evolution of the Tarim Basin's water systems, development of oases, and climate changes. These processes are recorded by ancient abandoned cities and desertified oases in the region (Fig. 8). For instance, many ancient cities developed and flourished during the Western Han (206 B.C. to 24 A.D.) and Tang (618 to 907 A.D.) dynasties due to the warm and moist climate during this period, whereas extensive desertification occurred during the drier and colder climate of the Eastern Han Dynasty (25 to 220 A.D.), as witnessed by the abandonment of many cities and residential areas in this region during this period (Fan, 1979, Zhou, 1989) due to decreased precipitation and temperatures (W. Zhong et al., 2004). In addition, although the population increase may be a significant signal for the causes of regional desertification (Y. Dong and Liu, 1993), there appears to be no correlation between desertification and population increase before 1900 in the Tarim Basin region because the population never exceeded 20,000,00. In contrast, regions that experienced rapid desertification from the late 1940s to the early 1980s were

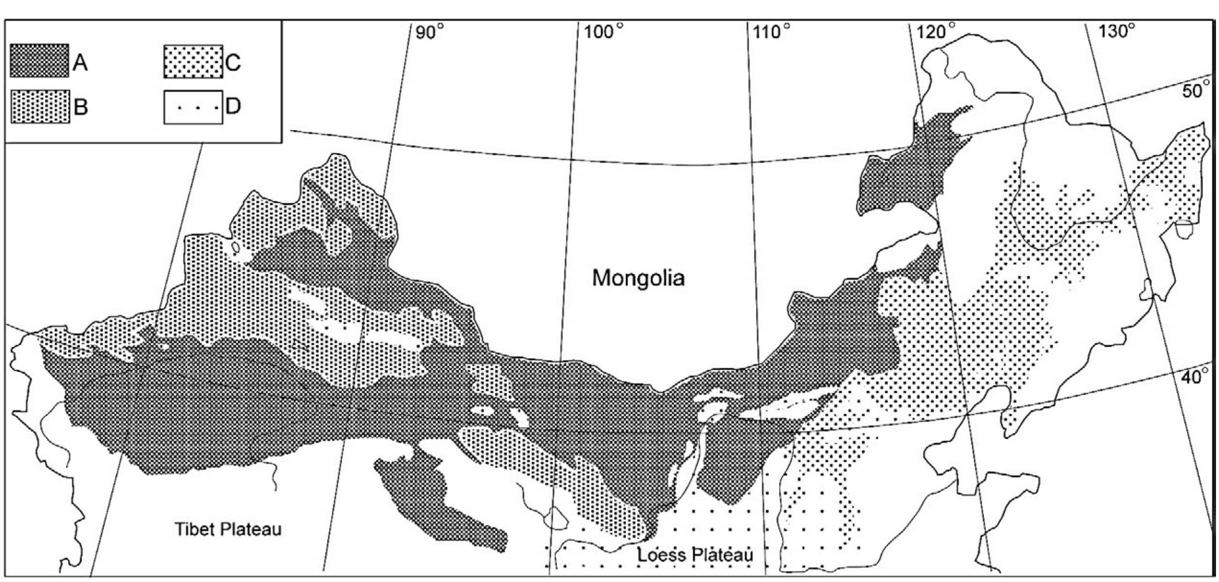


Fig. 10. The distribution of surface materials subject to wind erosion in arid and semiarid northern China. (A) Areas with severe wind erosion. (B) Areas with moderate wind erosion. (C) Areas with a low level of wind erosion. (D) Areas with very low levels of wind erosion. This map is based on the data compiled by Sinomaps Press (1998).

those with a low population increase, whereas regions that experienced rehabilitation exhibited a rapid population increase (Y. Chen, 1984).

4.6. Desertification in the Gurbantunggut Desert and adjacent regions

Few studies have examined desertification in the Gurbantunggut Desert and adjacent regions even though this desert first developed around 1.2 million years ago (Z. Shi et al., 2006). However, several phases of desertification have been detected that resulted from significant climatic fluctuations between the Medieval Warm Period and the present (Y. Zhang et al., 2004). However, although most desert areas in the region are currently covered by anchored and semi-anchored dunes, rapid desertification in the 1970s was signaled by the activation of most dunes (Z. Zhu et al., 1980; X. Wang et al., 2005b). However, after the 1980s, most activated dunes became anchored, and significant and extensive rehabilitation occurred at the margins of the desert and in adjacent regions (Fig. 3). This appears to have resulted from stabilization of the sand surface during this period as a result of a significant decrease in wind activity (X.Q. Wang et al., 2004).

5. Causes of modern desertification in China

Over the past several thousand years, arid and semiarid China has experienced several phases of desertification and rehabilitation that have been confirmed by historical records and archaeological evidence. Periods in which desertification has occurred have consistently been associated with specific trends in temperature, drought, and wind regime: desertification has always occurred during periods with low temperature, frequent strong winds, and drought (Fig. 9). In addition, desertification in ancient China was always accompanied by changes in the extent of grazing; the southern border of areas grazed by nomadic nations historically moved southward under the control of a relatively warm and moist climate, agricultural cultivation developed, and the population increased (i.e., when rehabilitation occurred); in contrast, under the control of a relatively cold and dry climate, grazing expanded, cultivation decreased, and population decreased (i.e., desertification occurred).

Modern forms and causes of desertification differ somewhat from those observed during historical periods, but the human impacts on modern desertification require more careful evaluation. Based on remote-sensing data for China as a whole, Z. Zhu and Chen (1994) concluded that the rate of modern desertification from the late 1950s to the mid-1970s averaged 1560 km^2/yr, versus 2100 km^2/yr from the mid-1970s to the late 1980s, and these findings were subsequently and extensively used in policy development by Chinese governments as firm evidence to support the hypothesis that desertification resulted from human activities. Despite the regional desertification trends reviewed in the previous section of this paper, trends in the desertification in different regions of arid and semiarid China are similar, even though their causes continue to be disputed. For instance, although Z. Zhu et al. (1980, 1981), Z. Zhu and Liu (1982), Z. Zhu (1994), T. Wang et al. (2003, 2004b, 2006) and other researchers (e.g., S. Liu, 1988; Yang et al., 1994) believe that the desertification has been triggered by human activities such as over-reclamation, over-grazing, over-cutting of trees, and (in some regions) unsustainable use of water resources, these papers present little strong evidence to support this hypothesis. In contrast, X. Wang et al. (2004, 2005a, 2006a, 2007) proposed that desertification in arid and semiarid China has mainly resulted from climatic changes, and especially increases in potential sand transport, decreases in spring precipitation. The rehabilitation that has occurred since the 1990s has instead resulted from decreased potential sand transport, increased temperature, and increased spring precipitation.

5.1. Variations in wind activity

Wind activity is a key factor that controls aeolian geomorphological processes, dust transportation and deposition, and desertification in arid and semiarid China. In comparison with other arid and semiarid regions such as Southern Africa and some parts of North America, most of arid and semiarid China is controlled by a low-energy wind regime (X. Wang et al., 2005b, 2007). Despite this, many regions have surface materials that make them highly vulnerable to desertification and that have resulted in severe wind erosion (Fig. 10). Therefore, significant variations in wind activity have played major roles in the cycles of desertification and rehabilitation in the region. The trends for potential sand transport are highly consistent with the trends for desertification and rehabilitation during the study period (Fig. 11): from the 1960s to the 1970s, when desertification was most rapid and severe, potential sand transport was two to three times the values recorded between the 1980s and the present, when rehabilitation was occurring. This indicates that the magnitude of the wind erosion (determined by the wind erosivity) from the 1980s to the present was only 20 to 50% of that before the 1980s; in addition, from the 1990s to the early 2000s, the erosivity was particularly lower than that during the 1970s (Fig. 11). Consequently, if wind activity did not play a major role in determining the trends in desertification and rehabilitation, it is very difficult to explain the similarity of the trends in wind activity and desertification in this region. Previous research has shown strong control of the development of extensive aeolian geomorphological types in the study area throughout the Quaternary under the influence of wind activity (Yang, 1985; G. Dong et al., 1988; H. Liu et al., 2002).

5.2. Variations in spring precipitation

Although total annual precipitation has not varied significantly in arid and semiarid China over the past five decades (Ding et al., 2006), as has been suggested by many previous studies (e.g., Ha Si, 1994; G. Qiu et al., 2001), this may not be an important observation. Spring precipitation is a more important parameter because high precipitation during this period is most beneficial for vegetation growth, and thus improves the vegetation cover; as a result, it decreases sand transport, which contributes significantly to rehabilitation. The level of spring precipitation has increased significantly in Northwest China since the 1990s (Y. Shi et al., 2003) and in other regions of arid and semiarid China, for which precipitation generally increased by 20 to 50% compared with the levels recorded before the 1980s, greatly benefiting the rehabilitation of land in the region (Fig. 12). In addition, the observed rehabilitation in Northwest China may be partially due to the increased water supply resulting from thawing of the region's glaciers due to increasing temperatures; this effect is not significant in Northeast China, where there are few glaciers. If the glaciers in Northwest China continue to melt, they will eventually disappear, and the resulting decrease in moisture may lead to a new phase of desertification in this region.

5.3. Dune mobilization

Dune activity is significantly inhibited by increased vegetation cover and soil moisture, but is promoted by exposure to wind activity (Thomas et al., 2005, Thomas and Leason, 2005). Significant variations in aeolian sand transport and rainfall can dramatically affect vegetation cover, leading to the evolution of dunes among their mobile, semi-anchored, and anchored forms (Z. Zhu, 1998). In arid and semiarid China, more than 80% of the area undergoing desertification exhibits strong aeolian dune activity and is thus described as undergoing sandy desertification (T. Wang et al., 2003, 2004a). The trends in dune activity (measured using the dune mobility index) from 1960 to 2003 were consistent with the desertification trends (Fig. 13). After 2000, inactive and partly inactive dunes and sand sheets were mainly located at the margins of the Taklimakan, Badain Jaran, and Tengger deserts, and in most parts of the Gurbantunggut, Mu Us, Otindag, Horqin, and Hulunbuir deserts, which are regions in which

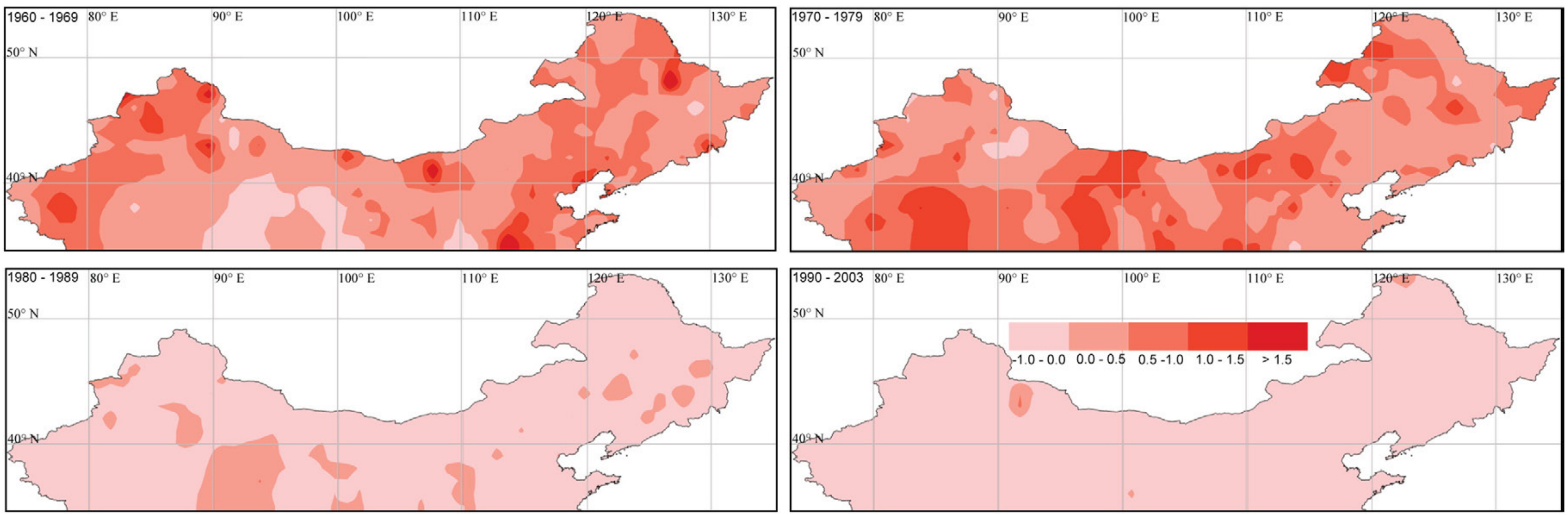


Fig. 11. Distributions of drift potentials from 1960 to 2003 in arid and semiarid China. The data in A to D represent departures from the mean values. Data compiled from X. Wang et al. (2007).

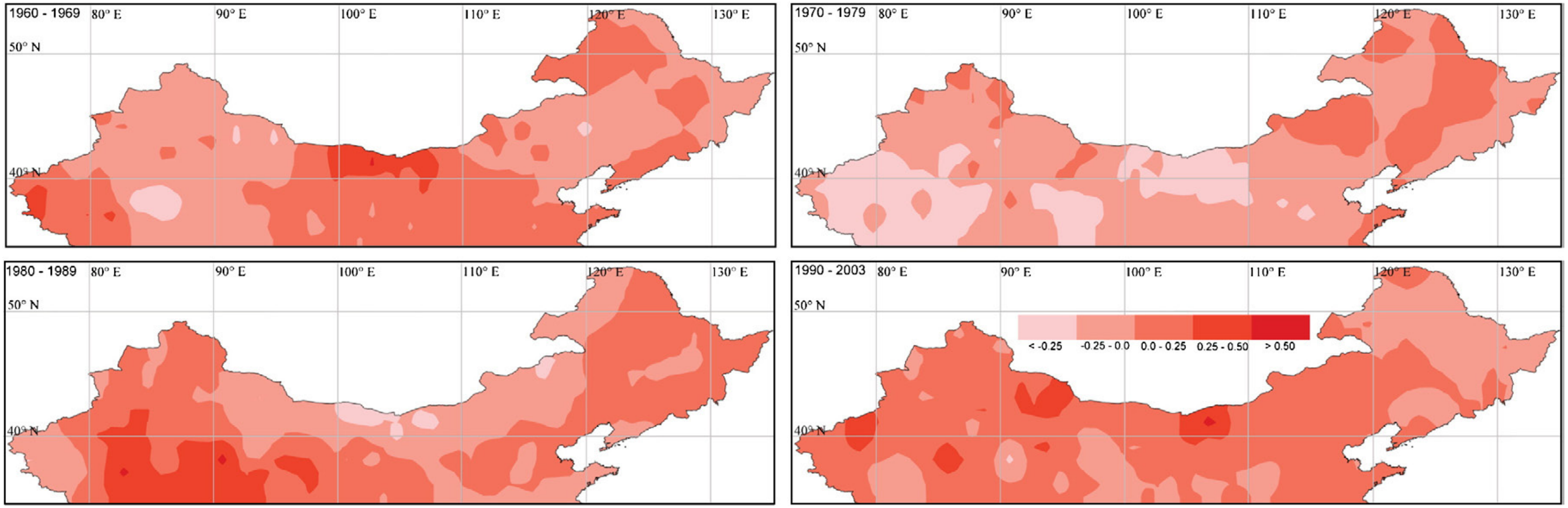


Fig. 12. Distributions of spring precipitation from 1960 to 2003 in arid and semiarid China. The data represent departures from the mean values (1960 to 2003). Data from X. Wang et al. (2008).

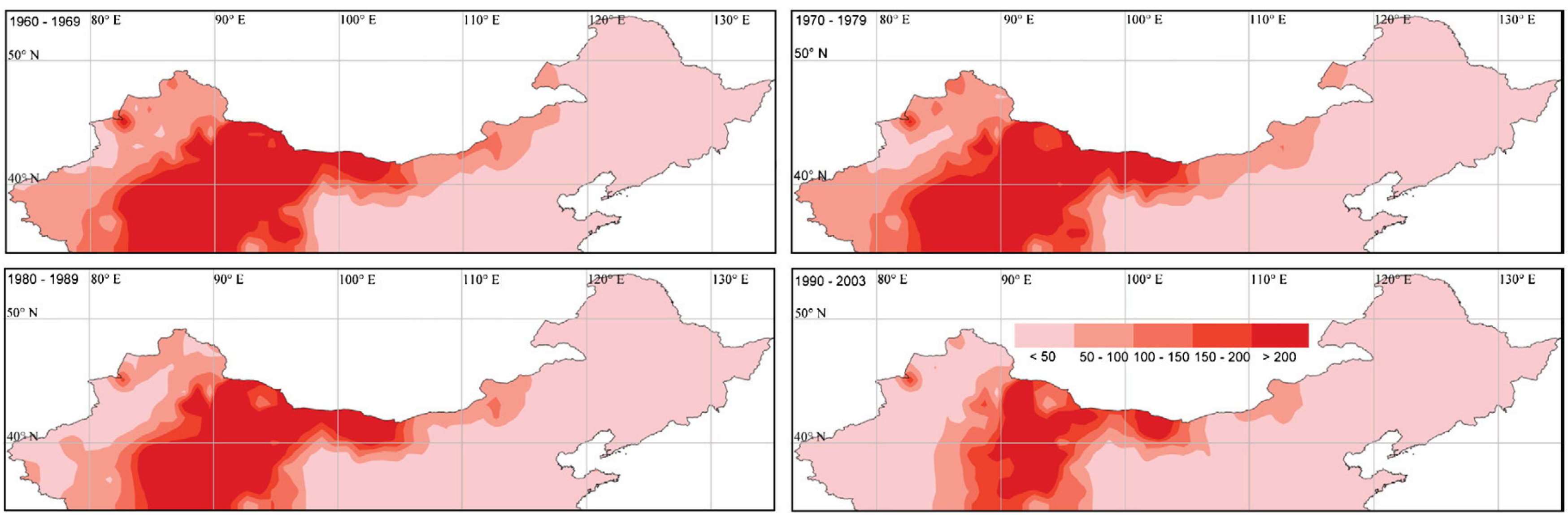


Fig. 13. Trends in the dune mobility index from 1960 to 2003 in arid and semiarid China. Data from X. Wang et al. (2007).

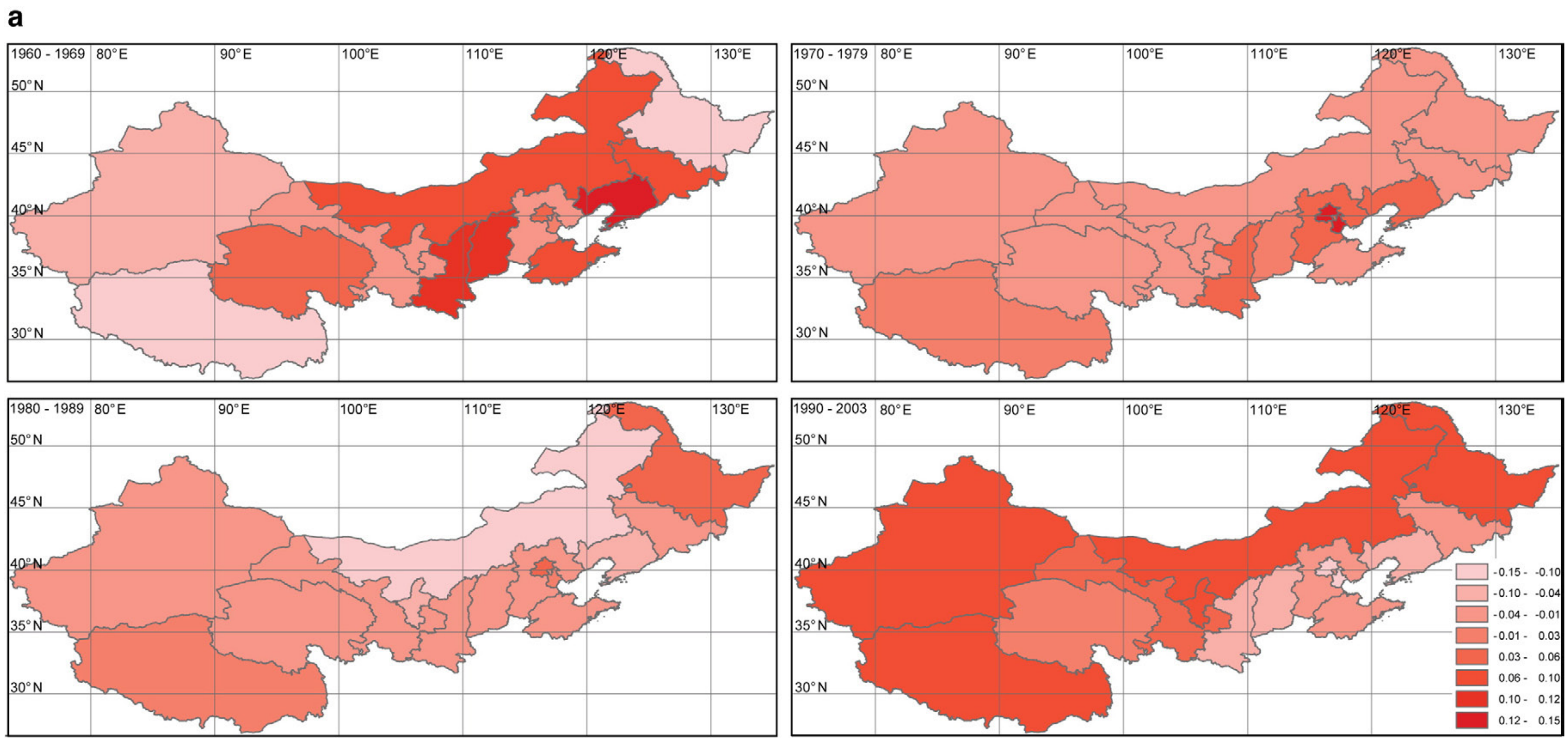


Fig. 14. Trends in three proxies of human activity in arid and semiarid China from 1960 to 2003: (a) the area devoted to agriculture, (b) the livestock population, and (c) the human population. The data represent departures from the mean values (1960 to 2003). Data from X. Wang et al. (2008).

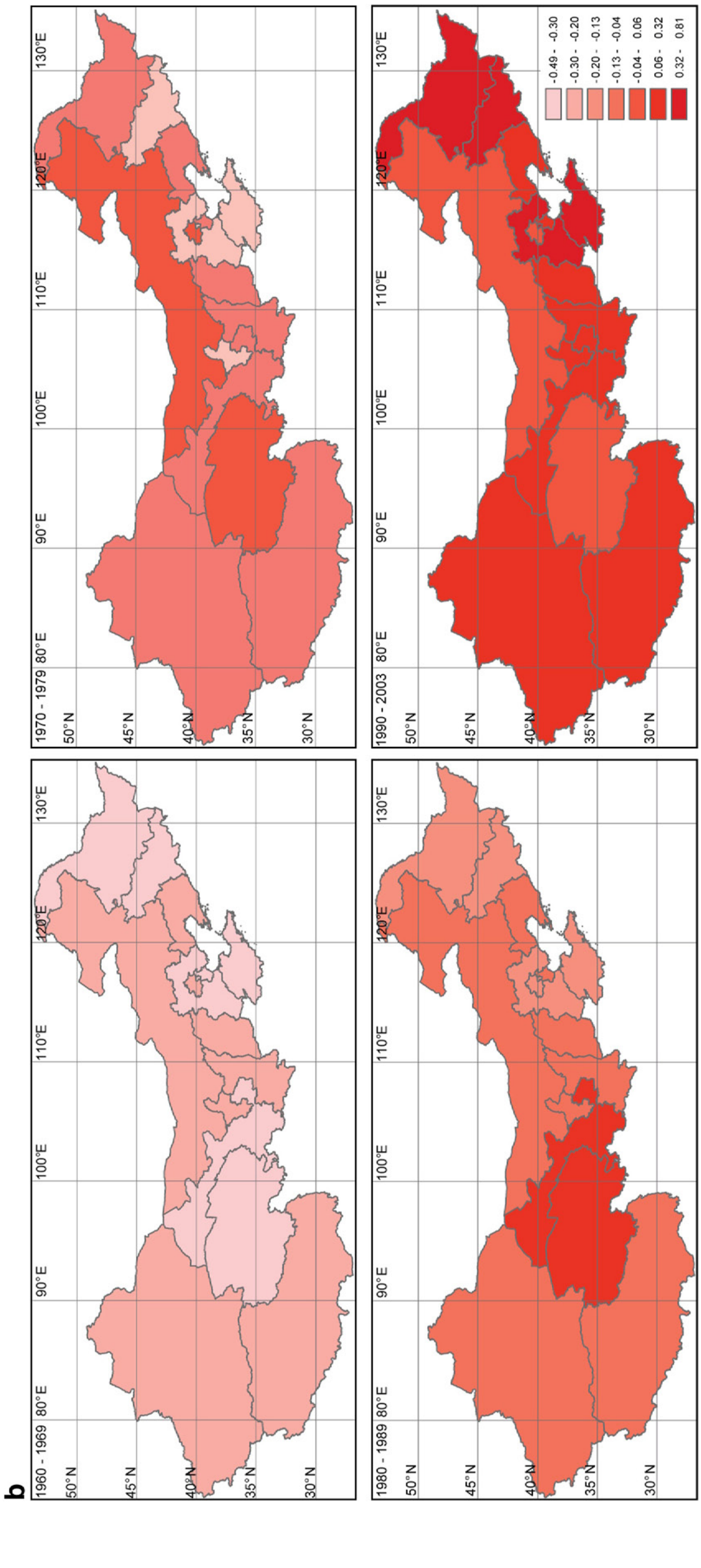


Fig. 14 *(continued)*.

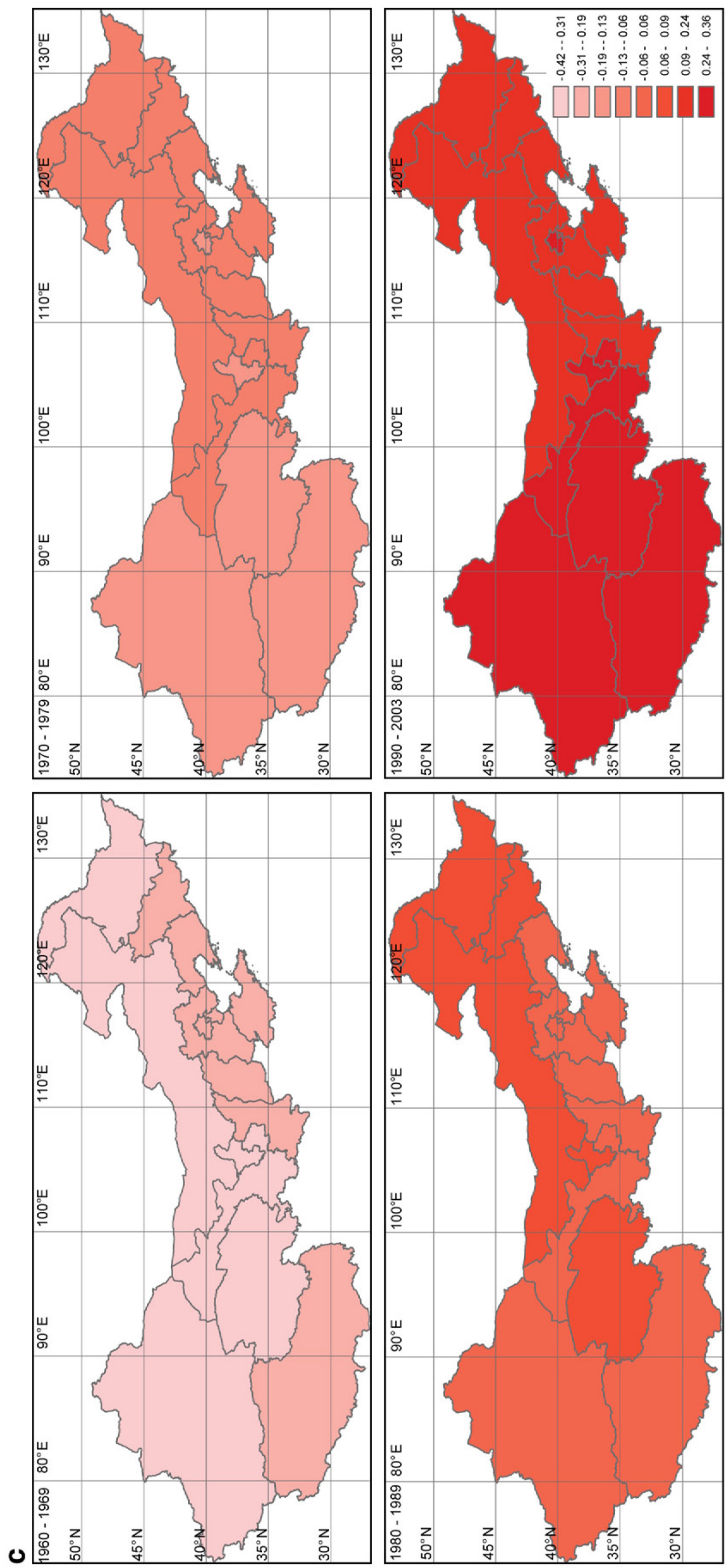


Fig. 14 *(continued)*.

rehabilitation occurred. The regions with high levels of dune activity migrated towards the most arid regions after the 1980s (i.e., primarily Northwest China), with fully active dunes located primarily in the eastern and central parts of the Taklimakan desert, the southern part of the Badain Jaran Desert, all of the Tengger Desert, parts of the Ulan Buh and Hobq deserts, and some parts of the Tibet Plateau (SFAC, 2005).

The values of the dune mobility index and the results of field investigations indicate that from the 1960s to 2003, dune activity varied greatly (Fig. 13), but was highly consistent with the desertification trends. In highly dynamic deserts, mobile dunes were replaced by semi-anchored or anchored dunes after the 1980s, and semi-anchored dunes were replaced by anchored ones. Only a few areas of semi-anchored or anchored dunes were replaced by mobile dunes during the same period, and these mobile dunes may represent residuals that resulted from high sand transport during previous periods. In addition, the vegetation cover has changed dramatically even on the surfaces of semi-anchored dunes. In the Gurbantunggut Desert during the 1970s, most of the crests of linear dunes were active and the vegetation cover ranged from 15 to 25% (Z. Zhu et al., 1980); in contrast, field investigations during the early 2000s revealed that only a few of these dune crests were still active, and the vegetation cover had reached 40 to 50% (J. Fang et al., 2003). The Otindag and Hobq deserts also had highly variable dune activity. During the 1960s and 1970s, some nebkha dunes developed in the Otindag Desert, where the vegetation mainly comprised trees and shrubs, but by the early 2000s, herbaceous vegetation had also become established on the dune surfaces, which further limited dune activity.

5.4. Human impacts on desertification

Although many of the research studies cited previously in the present paper suggested that human activities were the major contributors to desertification in arid and semiarid China, the trends in several key proxies of human impacts were not consistent with the desertification trends in this region (Fig. 14). In most previous studies related to human impacts and their significance, researchers have provided only descriptive evidence to support the claim that human impacts were the primary factors responsible for desertification. However, these explanations cannot explain why all three proxies for human impacts (human and livestock populations and the area devoted to agriculture) have increased continuously since the 1950s, yet rehabilitation has occurred since the 1990s. In addition, although some land rehabilitation techniques have been used since the 2000s to combat desertification (e.g., afforestation, engineering to control sand movement, and returning farmland to forestry uses), and may have assisted ecological recovery in some regions of arid and semiarid China, this change cannot explain why rehabilitation has occurred in many parts of arid and semiarid China since the late 1980s, before these measures were implemented. If human activity was the primary factor responsible for desertification in arid and semiarid China, desertification should have increased continuously in parallel to the increased human impacts. Because it did not, human activities are unlikely to be the key factors responsible for desertification or rehabilitation.

6. Conclusions

Desert formation and the modern occurrence of desertification in arid and semiarid China have passed through multiple phases throughout the Quaternary, and these phases cannot be associated primarily with human impacts. Desertification increased since the 1950s, but the most rapid desertification occurred from the 1970s to the early 1980s, and rehabilitation mainly occurred from the mid-1980s to the present. The review of recent studies in the present paper suggests that human activities are unlikely to be the primary factors responsible for the period of rapid desertification because anthropogenic pressures have increased continuously from the 1950s to the present, even during the recent period of recovery. Assuming that over-reclamation and over-grazing are most important would make it difficult to explain the observed rehabilitation that occurred after the mid-1980s in this region. Although numerous field observations have led researchers to propose that human activity drove the rapid desertification in China, political and economic agendas may have influenced the interpretation of ambiguous results or casual observations (Ellis et al., 2002).

Because temporal trends in total annual precipitation did not show a significant decrease or increase in arid and semiarid China, it is difficult to accept annual rainfall as a key factor in explaining desertification. However, significant variations in spring precipitation have been observed since the 1960s, and these variations were closely associated with the observed trends in desertification. Thus, spring precipitation may play a major role in desertification because it strongly affects the vegetation cover that develops, which in turn controls the severity of wind erosion, further affecting the trend towards desertification or rehabilitation China. In addition, the region's wind regime has a strong effect on the trend towards desertification or rehabilitation because of its effects on potential wind erosion, which strongly affects desertification in this region because of the nature of the region's soils, which are highly vulnerable to wind. As a result, the trends in potential sand transport were closely related to desertification or rehabilitation throughout the Quaternary.

Human activities such as over-grazing, over-reclamation of land, and over-cutting of natural vegetation such as forests in arid and semiarid China are not the primary causes of desertification or rehabilitation, though they have undoubtedly exacerbated trends resulting from longer-term changes in climate. Despite the fact that it is impossible to fully separate climate-induced, short-term environmental changes from land degradation triggered by human activity (Mainguet and Silva, 1998; Mainguet, 1999), the evidence gathered in the present paper shows that the modern trends in desertification or rehabilitation thus appear to reflect fundamental aspects of climate change and the resulting geomorphological processes. Because these changes and processes are not yet adequately understood, and because firm evidence is not yet available that human activities cause (rather than merely exacerbating) desertification, additional research will be required to help governments determine the most appropriate solutions to the problem of desertification.

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