

# Spatial and temporal changes in desertification in the southern region of the Tengger Desert from 1973 to 2009

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**Abstract** The sandy land in the southern region of the Tengger Desert is adjacent to cities and towns, and land desertification poses a threat to the livelihood and production of local residents. To determine dynamic changes in local desertification, five periods (1973, 1987, 1992, 2001, and 2009) of remote sensing data are studied by remote sensing (RS) and geographic information system (GIS). The desert contraction area is primarily centered around three units (Wuwei, Gulang, and Jingtai) and nearby regions of Zhongwei City. The primary desert expansion areas include the west side of Helan Mountain (WSHM), the Central Mountainous Area (CMA), and the eastern and western Zhongwei units far from towns. From 1973 to 2009, the degree of change in the contracting part of the primary desert expansion unit showed an increasing trend; in brief, most of the desert (especially after 2001) has been developing in a direction in which desertification has been gradually controlled. The primary desert expansion areas are less affected by human activity, but they are primarily controlled by natural factors (especially wind and terrain). The desert contraction areas occur around the towns and nearby regions with frequent human activity; desertification is primarily controlled by human factors. With rapid economic development (especially after 2000), the scale of the cultivated area, town, and ecological protection engineering has gradually expanded, and the latter two are primarily built on a previous desert, which is the root cause of the reduction in the

desert areas around the towns and the shrinkage toward north of border. Therefore, reasonable and effective human activity in the southern region of the Tengger Desert is playing a crucial role in preventing desertification.

## 1 Introduction

Desertification has always been a globally crucial resource phenomenon and an environmental problem that has attracted a lot of attention (Al-Dousari et al. 2000). It often occurs in some arid, semi-arid, and semi-humid regions (UNEP 1992), among which Asia is one of the most seriously affected areas, and the affected regions extend from the west of Central Asia to the east of northwest China (Zhu and Chen 1994). There are  $1.3 \times 10^6$  km<sup>2</sup> of desert in northern China (Yang et al. 2004), and the ecological environment of the desert and the adjacent areas have become extremely fragile because of strong wind erosion (Dong et al. 2000) and dust storms (Wang et al. 2004a). Under the influence of desertification, the Gobi Desert in China, the internal desert area, and the area with agriculture and animal husbandry experience the degradation of soil productivity and serious environmental problems (Rodriguez et al. 1993), which primarily involve soil degradation from wind erosion, as affected by human and natural factors (Zhu 1998). “Desertification” takes on the status of the contraction or expansion of desert and sandy land in China (Sun et al. 2006). In the past 50 years, the desertified area in China has been continuously expanding and reached its peak by the early 1980s. In the late 1980s, it began to shrink, and it is still continuing to shrink today (Wang et al. 2008).

Desertification is commonly affected by the natural and social economies (Thomas 1997). It is hardly possible to separate climate-induced short-term environmental changes from land degradation induced by human activities (Mainguet and

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Silva 1998). Climatic fluctuation and human activity jointly influence the desertification situation of the arid areas in northern China (Wang et al. 2008, 2009), but their influence must be evaluated before being confirmed (Runnström 2003). According to research on the Mu Us Sandland, Otindag Sandland, and nearby regions, Wang et al. (2004b, 2006) suggested that climate factors are the primary causes for regional desertification development, and later, Wang et al. (2008, 2009) suggested that although China's desertification development is affected by human activity, climate change and geomorphological processes are still the dominating factors. Some scholars also hold the view that desertification occurs because of rising temperatures (Xue et al. 2009) and erosion by the strong northwest wind along the earth's surface during winter and spring (Wang et al. 2004a; Sun et al. 2005); human activities are only accelerating desertification to a certain degree (Liu et al. 2003). However, in previous research, most scholars did not believe that climate factors make an important contribution to desertification in northern China, but primarily because of excessive logging, overgrazing, and overcultivation and a series of adverse environmental activities (Zha and Gao 1997; Saba 2001; Wu and Ci 2002; Zhang et al. 2003; Zhao et al. 2005; Zheng et al. 2006; Yang et al. 2007). There is no doubt that in some areas, humans are also playing an outstanding positive role in the prevention and control of desertification (Portnov 2004; Sun et al. 2006). In fact, natural factors, human factors, and their combined effects all have an important impact on the expansion or contraction of a desert (Thomas 1997; Zha and Gao 1997; Chen and Tang 2005; Xue et al. 2005; Wang et al. 2006), but their weights vary at different spatial and temporal scales.

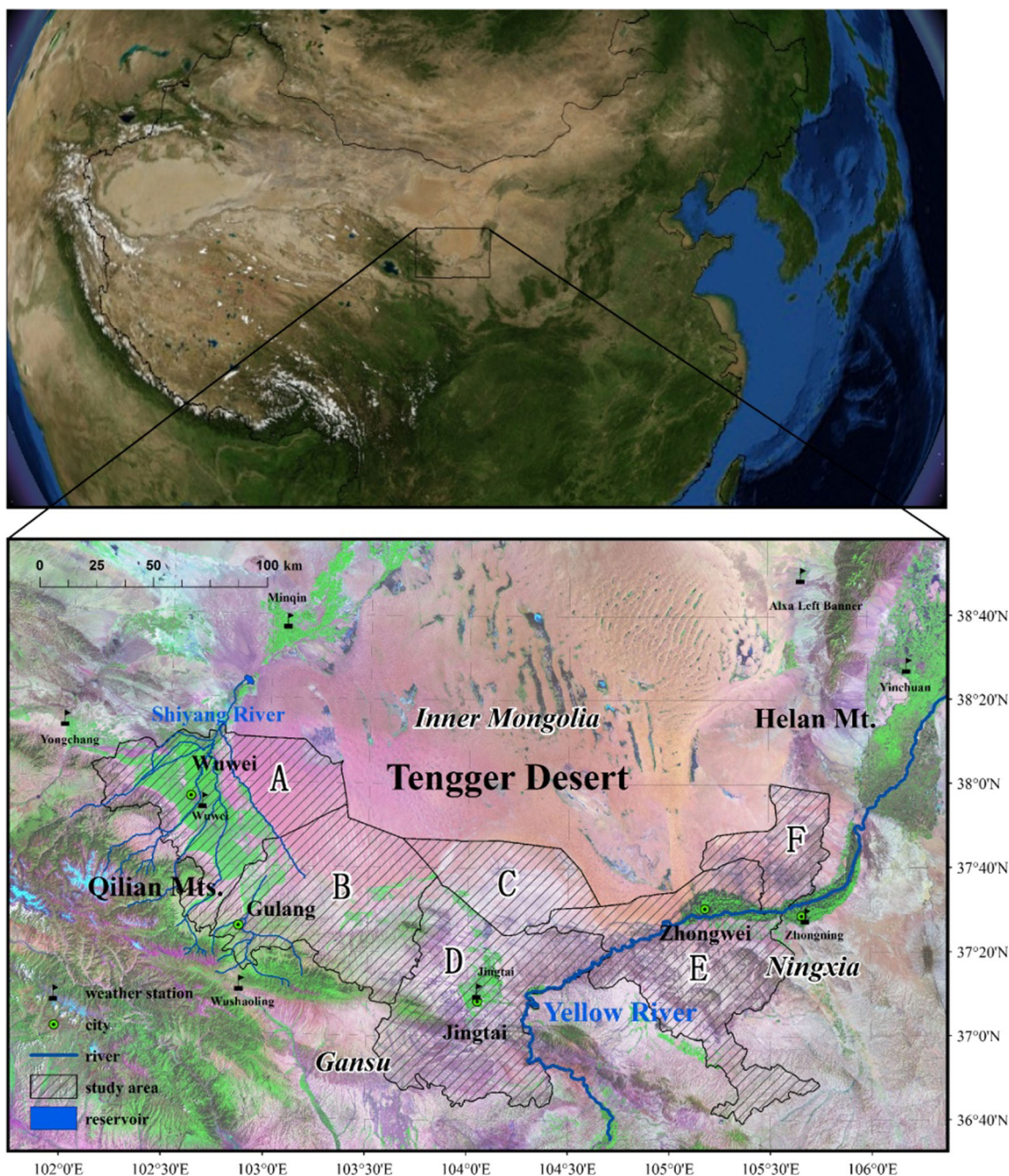
The Tengger Desert belongs to the transitional zone of the arid and semi-arid regions of China, and its southern region is adjacent to towns such as Wuwei, Gulang, Jingtai, and Zhongwei. A series of phenomena caused by the desert such as desert cover, land degradation, and sandstorms are threatening local people's production and livelihoods (Fig. 1). Although the central and local government of China has adopted a series of initiatives to reduce the losses caused by desertification (Zhao et al. 2008), the studies that could explain the local desertification dynamics and its causes in these areas are few. Therefore, there is an urgent need to perform this type of work in this area. Because land uses and changes in arid and semi-arid regions have been acknowledged as an important environmental issue, remote sensing (RS) and geographic information system (GIS) combination technology has become an important tool for monitoring land use, the use of which can effectively reveal spatial and temporal change characteristics of land use including desert expansion and extraction (Ellis et al. 2002). These technologies play more and more important roles in discussions of environmental change issues, especially land

desertification issues (Seixas 2000). We use RS and GIS to collect desert distribution data for five periods from the southern region of the Tengger Desert (1973, 1982, 1992, 2001, and 2009), and we perform a comparative analysis of the human activity index (the population at year-end, rural population, urban population, gross domestic product (GDP), cultivated area and sheep restock, normalized difference vegetation index (NDVI), and town area) and natural factor data (temperature, precipitation, maximum wind speed, and terrain), and we attempt to explore the primary influencing factors in the desert dynamic changes of the study area.

## 2 Study area

The study area is located at the border of Gansu, Ningxia, and Inner Mongolia (102° 63' E~105° 48' E, 36° 39' N~38° 13' N; Fig. 1). It includes Wuwei City, Gulang and Jingtai Counties of Gansu Province, Zhongwei City of Ningxia Hui Autonomous Region, and the Alashan League in the Inner Mongolia Autonomous Region, with a total area of 24,692 km<sup>2</sup> and a population of approximately 1.98 million. The study area belongs to the arid and semi-arid regions of northern China, which ranges from the area northeast of Qilian Mountain to west of Helan Mountain and down to the southern Tengger Desert. The topography of the eastern study area is low, and it is high in the west (with an average altitude of 1730 m for the western Wuwei region and 1623 m for the eastern Zhongwei region). The area is influenced by a temperate continental climate and prevailing NW, WNW, and NWN winds (Yang et al. 2014) with average annual wind speeds from 2.4 to 3.3 m/s (Walker 1982). The maximum annual wind speed (MWS) is 9.8–14.4 m/s; the mean annual temperature (MAT) of the study area is 7.1–8.4 °C with cold winters and warm summers (absolute maximum/minimum temperatures of 39/–29.6 °C); the mean annual precipitation (MAP) is 195–223 mm, with more precipitation in the summer (50.8–61.8 % of the MAP); and the Yellow River and the Shiyang River flow through the area. The southern desert border is near a town, and the local government uses the Yellow River and snow-melt water from the Qilian Mountain to plant trees in these areas and develop agriculture and animal husbandry to reduce the social, economic, and ecological damages caused by desertification. Economic activities inside the study area mainly cover industry (including chemical building material, metallurgy, mining, electricity, equipment manufacturing, and wind-solar hybrid power generation), agriculture (planting crops such as spring wheat, corn, beet, potato, flax, and rape), and stockbreeding.



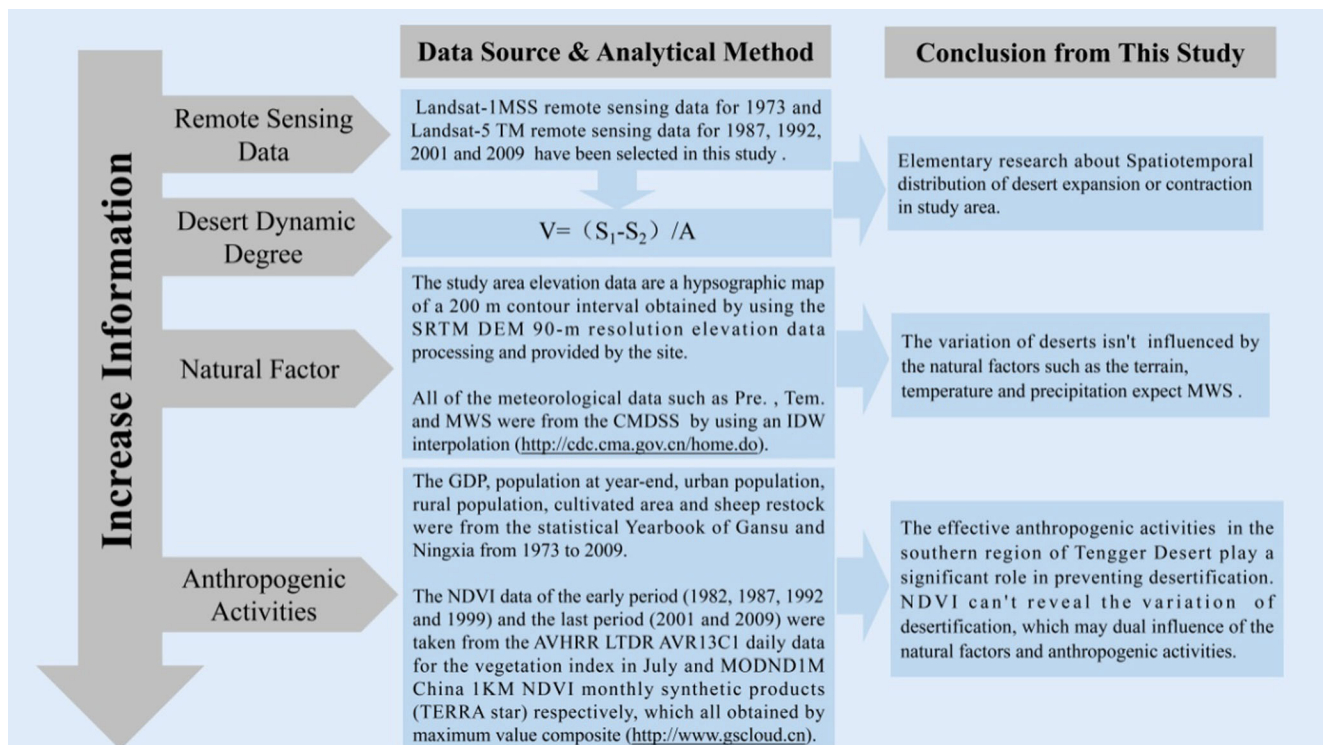


**Fig. 1** The location of the study area. The study area is divided into the following six parts: **A** Weiwei, **B** Gulang, **C** Central Mountainous Area (CMA), **D** Jingtai, **E** Zhongwei, and **F** the west side of Helan Mountain (WSHM), which all refer to the same parts in Figs. 3, 4, 5, 6, 7, 9, and 10

### 3 Data sources and analytical methods

To ensure the integrity of the administrative units and that the southern edge of the Tengger Desert would be fully addressed within the scope of this study, the study areas were divided into six units, namely, Wuwei, Gulang, Jingtai, the Central Mountainous Area (CMA), Zhongwei, and the west side of Helan Mountain (WSHM), for analysis (Fig. 1). This study selected remote sensing data from 1973 to 2009 (Fig. 2). The data of spatiotemporal distribution data for desert expansion

and contraction (Fig. 3) and desert cover and towns' area (Fig. 9) were classified by the derivative system of the technical specification for investigation of land use status established by ARP (Chinese Society of Agricultural Resources and Regional Planning). The study also employed statistical and overlay analysis methods to obtain changing data for desert-covered areas (Table 1), spatial and temporal distribution data for desert expansion and contraction (Table 2), and changing degree data for the desert expansion and contraction area (Table 3) within the study area. In addition, to reflect the degree of change for the



**Fig. 2** Evaluation methodologies and conclusions of each level obtained by this study. The acronyms in this picture SRTM, LTDR, and DEM mean shuttle radar topography mission, land long-term data record, and digital elevation model, respectively. The complete site about DEM was obtained from International Scientific and Technical Date Mirror Site,

Computer Network Information Center, and Chinese Academy of Sciences. The CMDSS was the site of China Meteorological Data Sharing Service. The acronyms of IDW and MVC mean inverse distance weighted and maximum value composite, respectively

desert, we introduce the concept of the desert dynamic degree (Fig. 2) as follows:

$$V = (S_1 - S_2) / A \quad (\text{Formula1})$$

where  $V$  is the dynamic degree of desertification,  $S_1$  is the area for the year,  $S_2$  is the desert area for the previous year, and  $A$  is the time interval between  $S_1$  and  $S_2$ . We then calculated desert dynamic change information for the five periods in the study area from 1973 to 2009 by using the above equation (Table 2).

In order to have a comprehensive analysis about the mechanism of how human activities and natural factors influence the desertification in the study area, we did following researches. First, we try to compare and analyze the relationship between hypsographic map and desert change to explore the influence of terrain characteristics on the desertification (Figs. 2 and 4). Second, we use the map of spatiotemporal distribution for meteorological elements based on data sets which are from eight meteorological stations from 1971 to 2011 surrounding the Tengger Desert to find out how meteorological elements influence on the desertification (Figs. 1, 2, 5, 6, and 7). Then, we try to find out how human factors affect desertification in area by comparing and analyzing the relationship between human activities and desert change in study area from 1973 to 2009 (Figs. 2, 8, and 9). Finally, we

comprehensively discuss the effects of natural factors and anthropogenic activities on the desertification by analyzing the relationship between the desert change and NDVI (the NDVI data sets have been corrected to minimize the effects of volcanic eruptions, solar angle, and sensor errors and shifts and thus can be used to evaluate the long-term trends in vegetation activity (Slayback et al. 2003; Piao et al. 2006)) (Figs. 2 and 10).

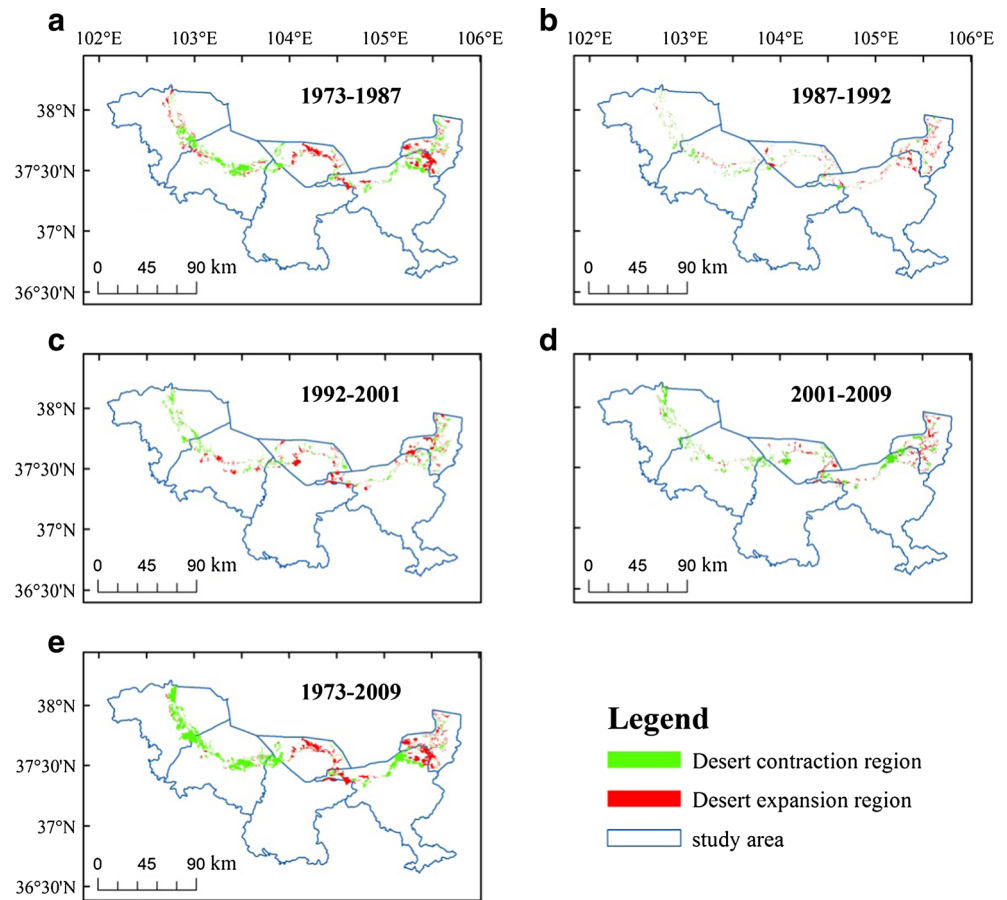
## 4 Results and discussion

### 4.1 The spatial distribution characteristics of the study area

From 1973 to 2009, the desert in this study area showed a decreasing trend as a whole, especially from 2001 to 2009, decreasing by 330 km<sup>2</sup> (Table 1) with a desert dynamic degree of -41.2 km<sup>2</sup>/year (Table 3). The situation is somewhat different if specific to each unit. With Wuwei and Gulang located in the west and central Jingtai (especially Wuwei), the change in the desert area situation was consistent with the circumstances of the study area; that is, the desert area basically decreases in the same way as the desert degree decreases, which was greater from 2001 to 2009 (Tables 1 and 3). The



**Fig. 3** Desert contraction and expansion in terms of spatial and temporal distributions within the study area



difference is that the desert area of the CMA and WSHM (especially the latter) gradually increases at each studied time node, but over time, the trend slowed (Tables 1 and 3). The Zhongwei unit behaved in a relatively unique fashion, except in 1992 and 2001 when the desert area increased slightly, and the desert area remained at the same level in the other three nodes (Table 1).

Although the contraction and expansion of deserts occur at the same time in each research unit, their degree of change

varies over five time periods, and the variation is consistent with the area changes (Fig. 3 and Tables 1 and 2). For the entire study area, except 1987 to 1992 (the expansion degree was greater than the contraction degree), the other four time periods (especially 2001 to 2009) are all dominated by the contraction degree (Table 2). In the internal Wuwei unit, the contraction degree of the five analyzed time periods are basically greater than the expansion degree, and from 1973 to 2009, the contraction degree gradually increased, and the expansion degree substantially decreased (Table 2). In terms of the Gulang and Jingtai units, except the time period from 1992 to 2001, the contraction degrees of the other four time periods are similarly greater than the expansion degree (Table 2). In a dramatically different fashion from the above three units, the desert expansion degrees of WSHM and CMA (especially the former) were dominated in comparison with the contraction degree, but from 1973 to 2009, its contraction degree showed an increasing trend similar to that of the Wuwei unit (Table 2). The situation of the Zhongwei unit is special, although the contraction and expansion degrees are almost the same on the whole (sometimes the contraction degree is greater than the expansion degree, and sometimes the contraction degree is greater than contraction degree). These two degrees were almost the same from 1973 to 2009 (Table 2), when the

**Table 1** The desert area of the southern Tengger Desert from 1973 to 2009 (km<sup>2</sup>)

Study area	1973	1987	1992	2001	2009
Wuwei	1857	1842	1793	1675	1565
Gulang	1866	1664	1629	1638	1545
Jingtai	92	74	53	61	45
CMA	961	1031	1051	1082	1049
WSHM	510	552	595	615	631
Zhongwei	898	881	941	976	882
Total	6184	6025	6062	6047	5717

**Table 2** The changing degree of desert expansion and the contraction area in the southern region of the Tengger Desert from 1973 to 2009 (km<sup>2</sup>/year)

Study unit	Contraction/expansion	1973–1987	1987–1992	1992–2001	2001–2009	1973–2009
Wuwei	Contraction	7.01	7.9	14.02	14.61	8.39
	Expansion	4.68	1.78	0.84	0.9	0.3
Gulang	Contraction	17.76	12.34	7.92	13.56	9.49
	Expansion	3.36	5.35	8.84	1.95	0.57
Jingtai	Contraction	2.35	4.62	1.39	2.88	1.85
	Expansion	1.01	0.54	2.3	0.78	0.53
CMA	Contraction	4.61	4.4	6.67	11.19	1.64
	Expansion	9.56	8.45	10.13	7.11	4.08
WSHM	Contraction	6.33	7.17	9.16	9.9	1.43
	Expansion	9.32	15.71	11.38	11.9	4.77
Zhongwei	Contraction	11.61	3.66	7.76	19.73	5.92
	Expansion	10.37	15.7	11.69	8.01	5.49
Total	Contraction	49.67	40.09	46.91	71.87	28.72
	Expansion	38.3	47.52	45.17	30.65	15.73

contraction areas were primarily distributed near Zhongwei City with the expansion area primarily in the east and west sides far from town (near the units of WSHM and CMA).

In conclusion, the primary concentrations of desert contraction area are the Wuwei, Gulang, Jingtai, and areas near Zhongwei City, and the primary desert expansion areas are the WSHM, CMA, and the east and west sides far from the town of Zhongwei unit (Tables 1, 2, and 3 and Fig. 3). Although the WSHM and CMA are the primary expansion areas, their degree of contraction from 1973 to 2009 showed an increasing trend (Table 2). Therefore, we suggest that most deserts in the southern region of the Tengger Desert are developing toward the direction in which desertification is under control. The desertification situation of agro-pastoral mixed regions in northern China primarily appeared as a developing trend before the 1980s, but the trend reversed during the 20 years that followed (Xue et al. 2005). The degree of desertification in northern China decreased from 59 % in 1980s to 43 % in the early twenty-first century, among which the desertification degree in the northwest appeared to have its most significant decrease, reaching 37 % (Wang et al. 2010). From the mid-1950s to 2000, the recovery degree (445 km<sup>2</sup>/year) of China's desertification was greater than the expansion degree

(310 km<sup>2</sup>/year), and during this period, 0.13 % of the desertification was improved per year, and rehabilitation generally exceeded desertification in the Hexi Corridor Desert (Zhong and Qu 2003; Wang et al. 2008). The above studies also indirectly support our findings.

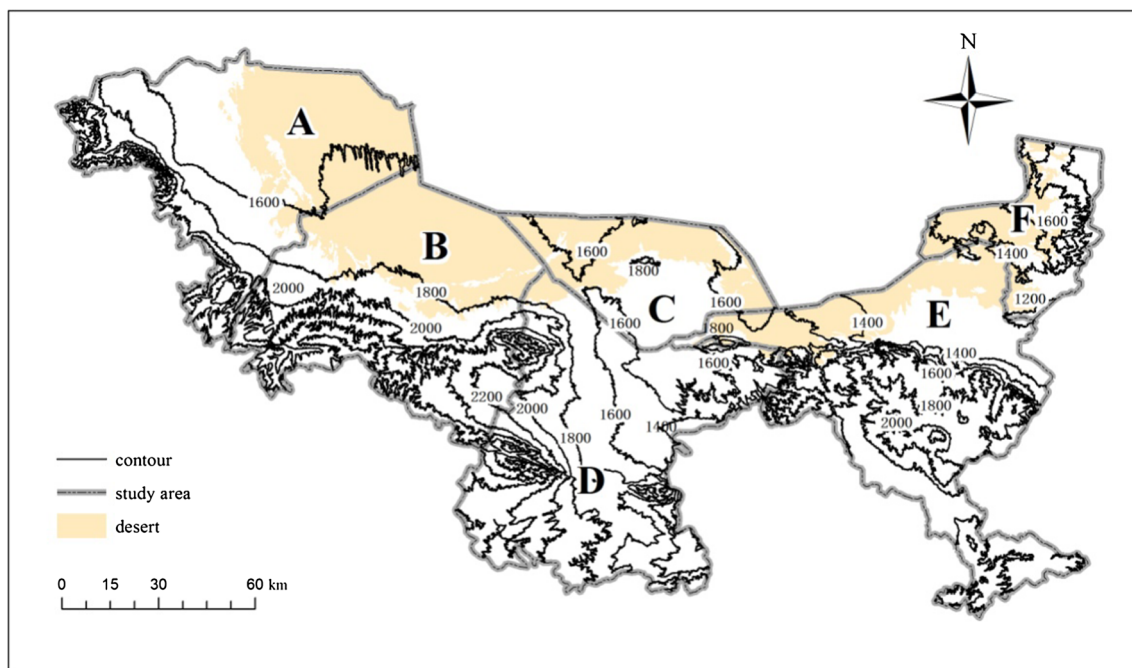
#### 4.2 The relationship between desertification and natural factor

Because the terrain (Wang et al. 2008), precipitation (Houérou 1996; Herrmann et al. 2005; Zheng et al. 2006; Yang et al. 2007; Wang et al. 2008), temperature (Houérou 1996; Yang et al. 2007), and wind (Ayoub 1998; Wang et al. 2004a, 2008) are the primary natural factors, so we primarily analyze the above factors for the same period in the study area (Figs. 4, 5, 6, and 7).

The overall terrain of the study area shows low-lying west to the east, and except for WSHM in the east, the whole terrain exhibits features with a northern low and southern high. The dunes are primarily distributed in the region below an altitude of 2000 m (Fig. 4). The terrain of the WSHM unit is conducive to the advancing of sand dunes to the south. By contrast, the terrain in the other units is helpful for preventing sand

**Table 3** The desert dynamic degree of the southern Tengger Desert from 1973 to 2009 (km<sup>2</sup>/year)

Study area	1973–1987	1987–1992	1992–2001	2001–2009	1973–2009
Wuwei	-2.3	-6.1	-13.2	-13.7	-8.1
Gulang	-14.4	-7	0.9	-11.6	-8.9
Jingtai	-1.3	-4.1	0.9	-2.1	-1.3
CMA	5	4	3.5	-4.1	2.4
WSHM	3	8.5	2.2	2	3.3
Zhongwei	-1.2	12	3.9	-11.7	-0.4
Total	-11.4	7.4	-1.7	-41.2	-13



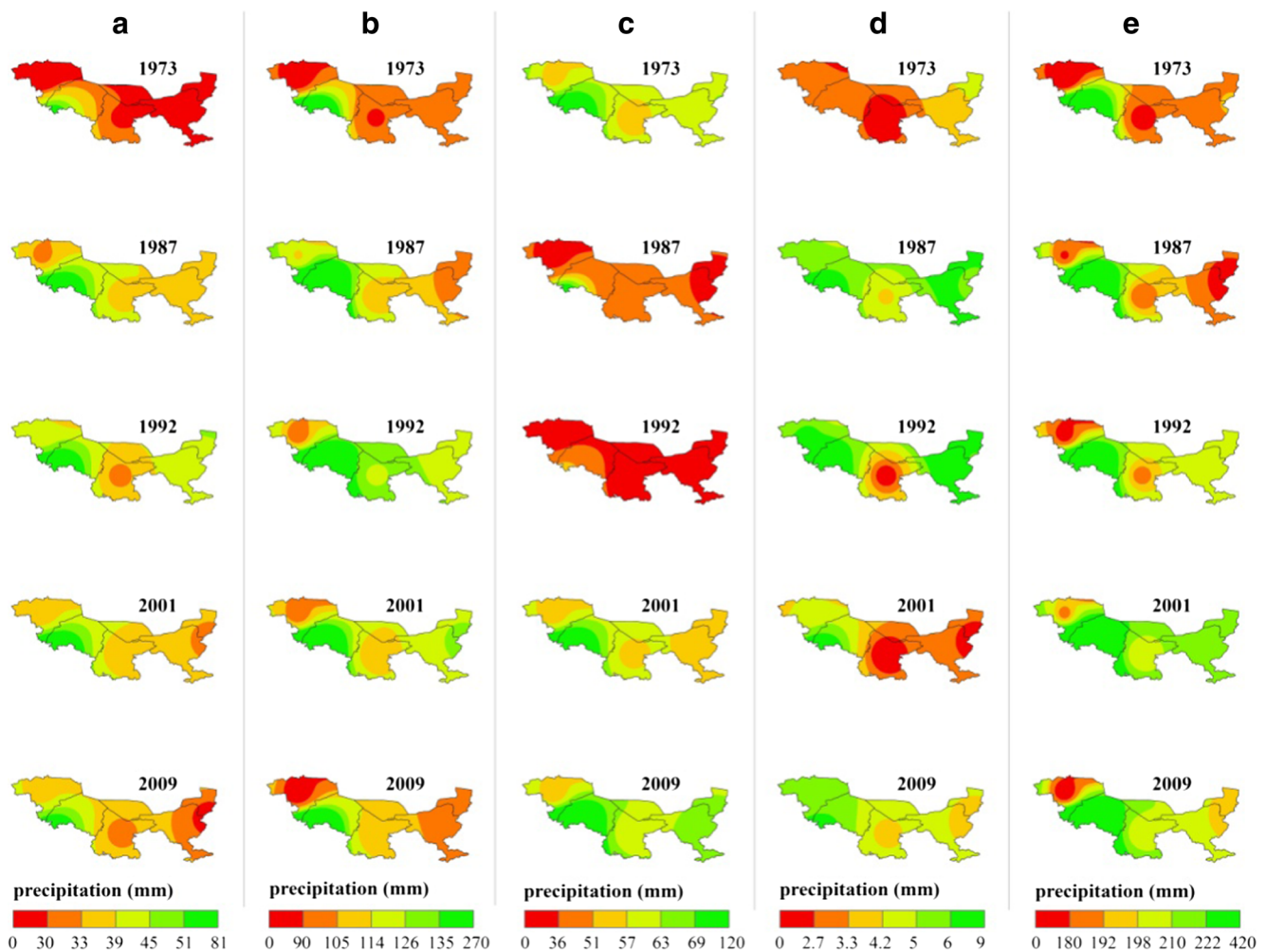
**Fig. 4** Elevation data for the study area

dunes to the south. Because the sand dunes continually move southward in the WSHM during the five periods between 1973 and 2009, and the sand dunes of the three units (Wuwei, Gulang, and Jingtai) exhibit an obvious shrinking trend (Table 1), the influence of the terrain over changes in the southern desert could therefore not be neglected, and it is still an important and dominant factor in the WSHM. Although the CMA desert gradually expanded southward at the beginning of the four periods (Table 1), the change in the degree of its desert area, that is, the desert dynamic degree, gradually decreased (Table 3). Thus, the influence of terrain factors could not be excluded. Because terrain factors cannot provide a reasonable explanation for the desert change of the Zhongwei unit individually, we suggest that the terrain is not the dominant factor in this unit.

Precipitation directly determines the dry and wet conditions of the earth's surface and thereby affects the likelihood of windblown sand. Precipitation is the primary determinant of natural vegetation growth in the study area, and natural vegetation is particularly sensitive to precipitation. Even a small change in precipitation can significantly alter surface vegetation cover, especially during the growing season (Malo and Nicholson 1990; Hess et al. 1996; Kawabata et al. 2001). Vegetation can reduce the surface wind speed and inhibit sand shift transport, and thus, precipitation can indirectly affect sand transport by directly controlling the growth conditions of vegetation. The precipitation in the study area occurs primarily during the summer, then the autumn, and spring (on the whole, the autumn precipitation is greater than that of the spring), and winter precipitation is minimal (Fig. 5). From

1973 to 2009, the MAP in the study area showed an overall continual increase with a small amplitude (5–13 mm) during the first four periods, after which the growth momentum was interrupted. From 2001 to 2009, the MAP was reduced by nearly 10 mm, and the MAP of the two units in Jingtai and CMA also show the same change characteristics (Fig. 5e). Unlike the entire study area and the above two units, the MAP of the units for the west side (Wuwei and Gulang) and the east side (Zhongwei and WSHM) have their own trends during the five studied periods, showing a model of “increase-decrease-increase-decrease” and “decrease-increase-increase-decrease,” respectively (Fig. 5e). Except for Jingtai, the changing characteristics of MAP in the other five units do not match the desert evolution characteristics, and there is only a partial match between the two even in the Jingtai unit, and we found a weak negative correlation between precipitation and desert dynamic degree (the values of correlation coefficient range from  $-0.12$  to  $-0.38$ ), which indicates that MAP is not the dominant factor that controls the desert advance or retreat in an entire study area. Because temporal trends in total annual precipitation did not show a significant decrease or increase in arid and semiarid China, Wang et al. (2008) suggested that it is difficult to accept annual precipitation as a key factor in explaining desertification. 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 toward desertification or rehabilitation in China (Wang et al. 2008). From 1973 to 2009, the spring precipitation could be summarized on the basis of the five analyzed periods as





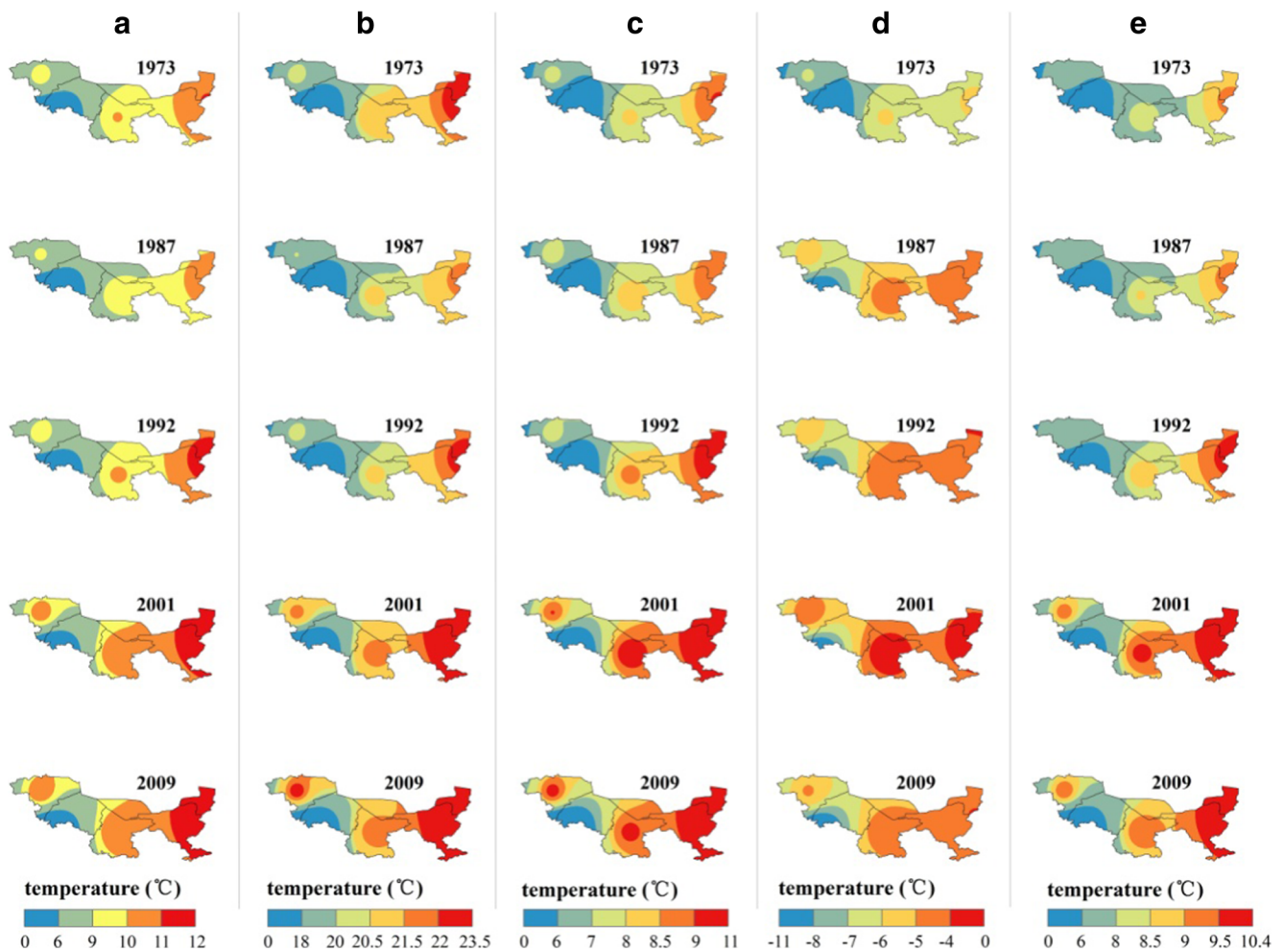
**Fig. 5** The spatial and temporal distributions of precipitation in the study area from 1973 to 2009. **a, b, c, d, e** The average data from the spring, summer, autumn, winter, and the whole year, respectively, and data for 1973, 1987, 1992, 2001, and 2009 are obtained by interpolating the

average data for 1971–1975, 1985–1989, 1990–1994, 1999–2003, and 2007–2011 by meteorological site, and they have the same meanings as those in Figs. 6 and 7

three changing trends of “increase-increase-decrease-decrease” (corresponding units of Wuwei, Zhongwei, WSHM, and the entire study area), increase-decrease-increase-decrease (corresponding units of Jingtai and CMA), and “increase-decrease-decrease-decrease” (corresponding units of Gulang). The spring precipitation in Wuwei, Gulang, Zhongwei, and WSHM match well with their desert dynamic degree during half the periods (the increase/decrease of precipitation corresponds to desert retreat/expansion), which also shows that the function of spring precipitation is better than that of the MAP during the evolution of the desert in the southern region of the Tengger Desert. However, the above relations are not obvious in Jingtai, CMA, and the whole study area, which indicates that spring precipitation plays a certain role in the evolution of a desert, but not the dominant one. This finding may be explained by too little precipitation in the spring (<50 mm) and a large amount of evaporation in the study area (average annual potential

evaporation >2000 mm; Wang et al. 2006), thus leading to a further reduction in effective surface precipitation, reducing its impact on the evolution of the desert. Despite the large amount of precipitation during the summer and autumn for each unit, its simultaneously changing directions cannot separately provide a reasonable explanation for the evolution of the desert. Minimal winter precipitation (<8 mm) and withered vegetation lead to the result in which the impact of the precipitation during winter on desert evolution is one in a million.

From 1973 to 2009, the temperature change trend of the six units in the southern region of the Tengger Desert showed a high degree of consistency (Fig. 6). The fall temperature and mean annual temperature (MAT) continued to rise (Fig. 6c, 6e), the winter temperature continued to rise from 1973 to 2001, there was a slight cooling from 2001 to 2009 (Fig. 6d), spring and summer temperatures only showed slight cooling during the initial period (1973–1987), and other periods are expressed as warming (Fig. 6a, 6b). Therefore, in the



**Fig. 6** Spatial and temporal distributions of temperatures in the study area from 1973 to 2009

context of global warming, from the temperature of the four seasons and the MAT of each unit in the study area, there emerges an increasing trend (Fig. 6). Obviously, the consistency changes in temperature cannot separately give a reasonable explanation for the retreat/expansion of the desert. In fact, the effect of the temperature on desertification is more complicated. For example, on one hand, a temperature increase could increase the amount of evaporation and lead to drier ground and thereby make the sand easier to transport (Houérou 1996). On the other hand, it could provide land vegetation and underground biomass with a much more suitable temperature under the premise of relatively low temperature that is beneficial to the dune fixture. Therefore, it is difficult to determine the temperature effect on desertification in the study area, and it must be combined with other factors to judge the effect of the temperature increase on desertification in the study area. The precipitation in the study area is not abundant, except the southern mountainous regions in Gulang with its annual precipitation of over 300 mm, and other regions basically receive less than 220 mm (Fig. 5). The temperature increase leads to a reduction in the effective precipitation of the atmosphere and drier surfaces, which

provides for desert expansion under favorable conditions and gives the primary cause for the southern direction of the two units in the CMA and WSHM in the last 36 years. However, there was a negative correlation between temperature and desert dynamic degree (the values of correlation coefficient range from  $-0.62$  to  $-0.67$ ), which indicates that temperature cannot provide a reasonable explanation for the desertification (especially in Wuwei, Gulang, Jingtai, and the Zhongwei units). In fact, although the desert moves forward to the south in the CMA and WSHM, its degree is gradually slowing down (Table 2), which cannot be explained by temperature and precipitation. All of these findings indicate that there are other factors that play a more critical role.

Although desertification is controlled by many factors at the same time, many studies suggest that desertification in China is caused by a strong wind (Dong et al. 2000; Sun 2006; Wang et al. 2008; Zhang et al. 2008b). Soil erosion by wind was up to  $1400\text{--}3200\text{ t/km}^2$  each year in northern China (Dong 2000). Strong wind erosion could make fixed dunes active again and deepen the risk of land being converted to desert (Wu and Ci 2002; Zhang et al. 2003; Wang et al. 2005). Especially in the winter and spring, the cold and dry climate

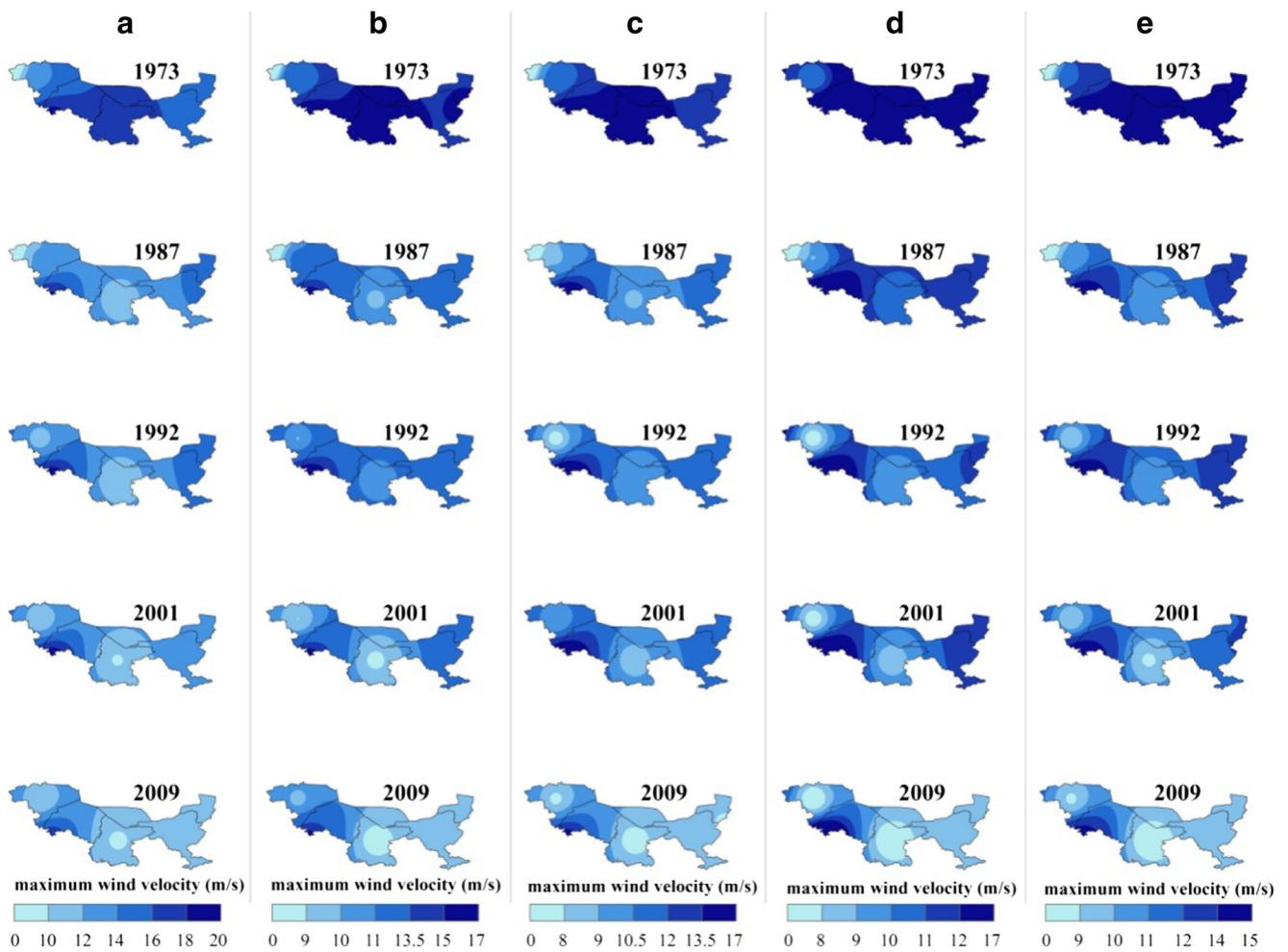


Fig. 7 The spatial and temporal distributions of MWS in the study area from 1973 to 2009

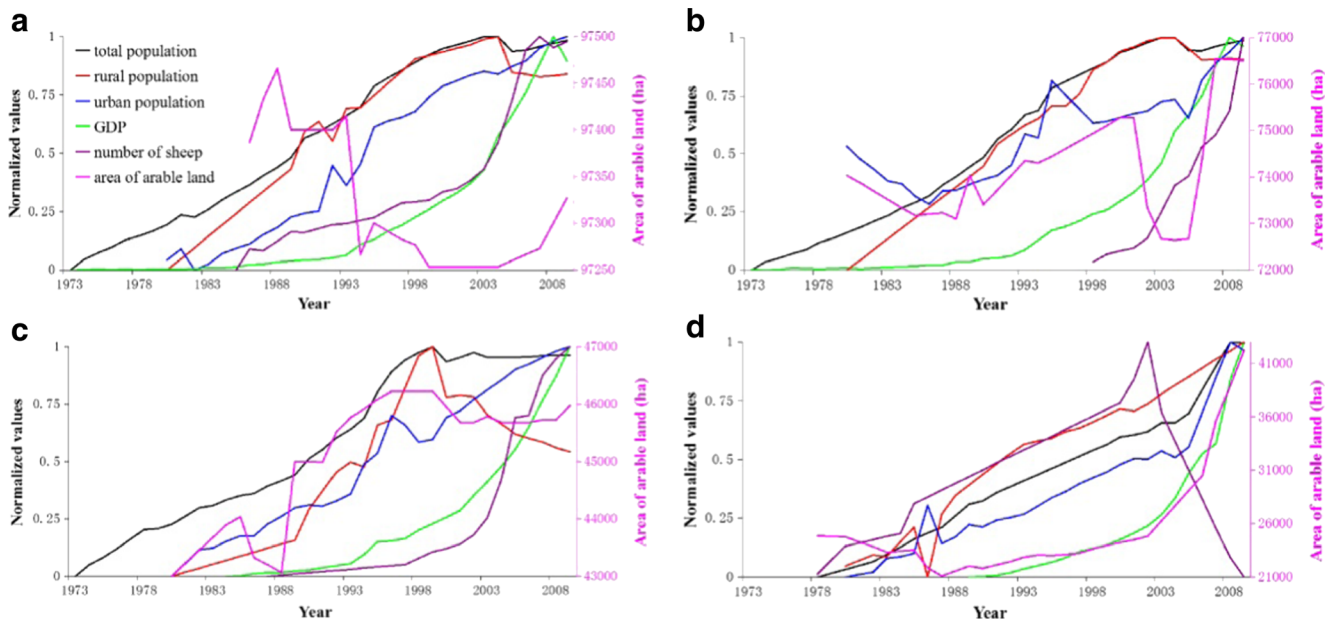
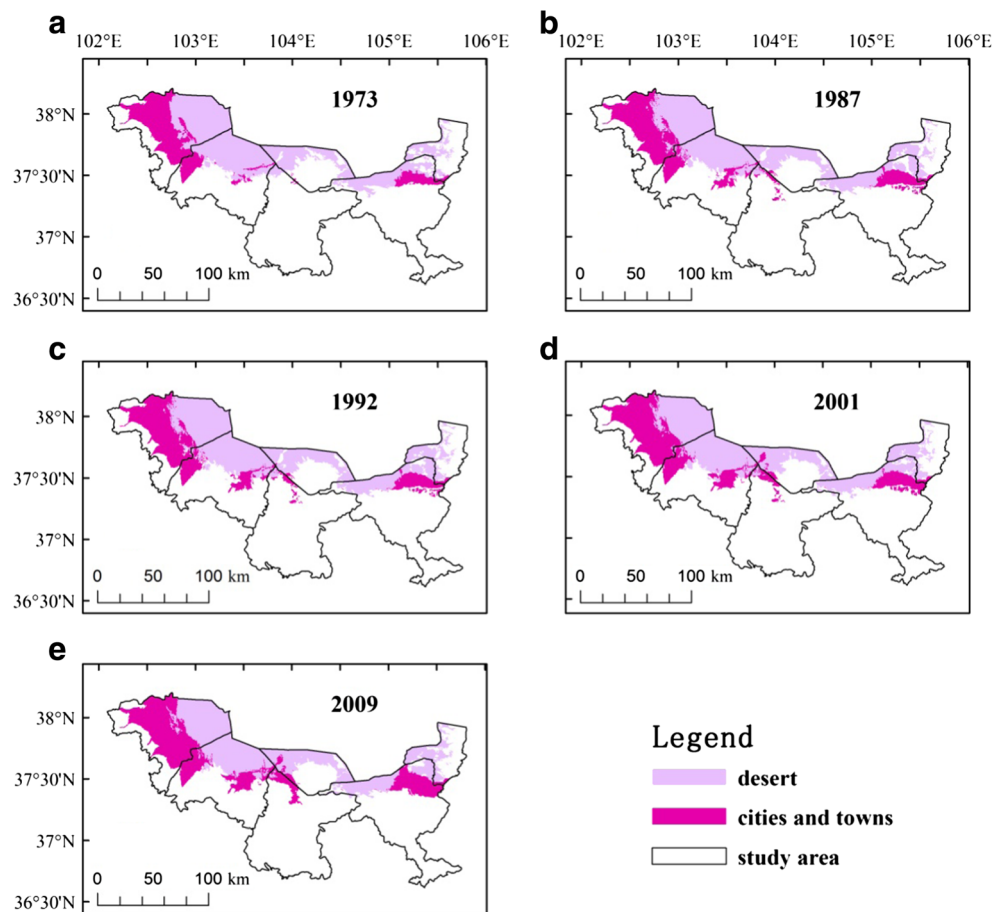


Fig. 8 The human activity index in the study area from 1973 to 2009. a, b, c, d The human activity indexes of the Wuwei, Gulang, Jingtai, and Zhongwei units, respectively



**Fig. 9** The spatial and temporal distributions of urban and desert regions in the study area from 1973 to 2009. **a, b, c, d, e** The urban and desert distribution areas during 1973, 1987, 1992, 2001, and 2009, respectively



lead to dry vegetation, loose surface material, and a large bare area, and at this time (especially in spring), there are frequent strong winds, which promote surface wind erosion and lead to desert expansion (Chen and Tang 2005). The MWS in the spring for the southern region of the Tengger Desert is the biggest, and the other three seasons are roughly equal; in 1992, only the MWS during the winter continued to maintain the previous decreasing trend. The MWS of the other three seasons and the average annual value presented a small increasing trend. Overall, the MWS in the six units of the study area present a clear decreasing trend from 1973 to 2009 (Fig. 7). The above features for the MWS could offer a more reasonable explanation for the changing trend in the total desert areas over the whole study area (Table 1) at the same time, which could provide favorable external conditions for desert area contraction in the three units (Wuwei, Gulang, and Jingtai) of the west side. In the CMA, the WSHM and the east and west sides of the Zhongwei unit where there are few human activities and a distance from town, because of the gradual reduction in MWS, the speed of desert expansion gradually decreases but does not reverse the trend of the southern forward (Table 2). Of particular note is that the desert contracts northward in the relatively more human activity areas; the MWS shows a strong negative correlation with

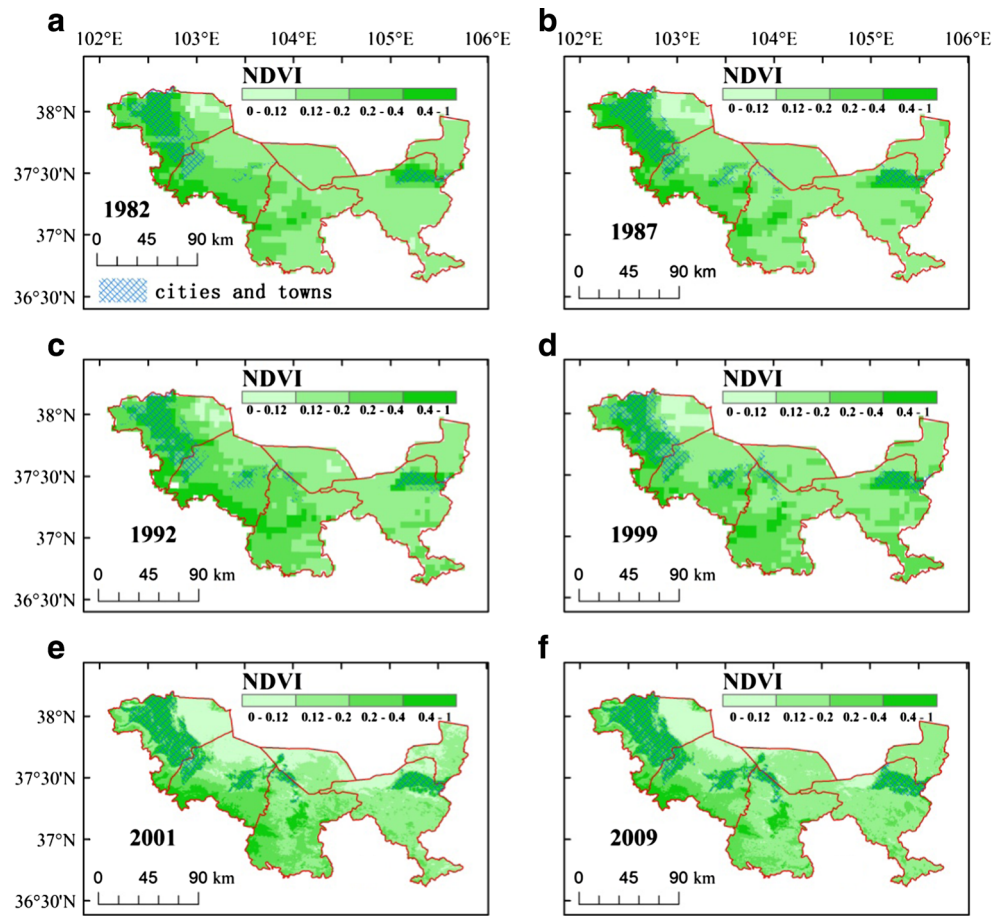
desert dynamic degree (the values of correlation coefficient range from 0.08 to  $-0.90$ ). The MWS clearly could not give a reasonable explanation for this phenomenon, which indicates that the role of human beings could not be underestimated.

#### 4.3 The relationship between desertification and anthropogenic activities

The population (Ayoub 1998; Girma 2001; Liu et al. 2003; Sun et al. 2005), arable land (Ayoub 1998; McClure 1998; Wu and Ci 2002; Sun et al. 2005; Zhang et al. 2008a, b; Barbero-Sierra et al. 2013), sheep restock (Sun et al. 2005), urbanization (McClure 1998), and GDP (Ayoub 1998; Sun et al. 2005) are common factors in anthropogenic activities; vegetation (Wu and Ci 2002; Liu et al. 2003; Runnström 2003; Herrmann et al. 2005; Zheng et al. 2006; Zhang et al. 2008b) is a comprehensive factor. So, we primarily analyze the above factors for the same period in the study area (Figs. 8, 9, and 10).

In some studies about the impact of human activities on desertification, population pressure becomes the dominant factor in local desertification (Ayoub 1998; Darkoh 1998; McClure 1998; Girma 2001). For example, McClure (1998) noted that desertification in the USA was caused by a variety

**Fig. 10** The spatial and temporal distributions of NDVI in the study area. **a, b, c, d, e, f** NDVI figures for 1982, 1987, 1992, 1999, 2001, and 2009, respectively



of factors including improper agricultural practices, livestock overgrazing, mining, fire management schemes, recreational practices, deforestation, urbanization, and the introduction of exotic species. Girma (2001) holds the same view and suggested that the major causes of land degradation in Ethiopia were related to rapid population increases, severe soil loss, deforestation, low vegetative cover, and unbalanced crop and livestock production. However, human activities and population growth not only destroy the environment but also they intentionally or unintentionally have a favorable impact on desertification prevention and treatment. For some examples in Africa, the population and population increase density reduce the extent of desertification (Darkoh 1994). Some rational human activities such as the rational use of water resources and afforestation could have positive effects on the prevention of desertification (Su et al. 2007; Yang et al. 2007; Zhang et al. 2008a). The three units (Wuwei, Gulang, and Jingtai) and nearby Zhongwei in the southern region of the Tengger Desert were subject to strong human activities from 1973 to 2009, and the total population, urban population, and rural population all presented increasing trends (Fig. 8). The demand for living space, energy, and the pursuit of material life increased as result of population growth. The increased demand for living space and energy leads acceleration of

industrialization and urbanization and the expansion of the cultivated land to satisfy the requirement for food (Figs. 8 and 9). At the meantime, with remarkable modernization of agriculture, the area of soil fertility declining resulted abandoned farmland is decreasing, which could effectively restrain the desertification (Portnov and Safriel 2004). The fast expansion of the city and vigorous development of secondary and tertiary industries have led to quick development of GDP (Figs. 8 and 9).

The development of towns often causes excessive pollution and wasted resources, and therefore, urbanization is considered by some scholars to be the dominant factor in land desertification (Chen and Tang 2005; Marcotullio et al. 2008). However, in the arid and semi-arid areas, urban areas are not as often related to land degradation from the effects of the population density, energy use, heat trapping, and water demand (Barbero-Sierra et al. 2013). For example, in Negev, Israel, since agriculture and livestock grazing are the major contributors to desertification, replacing them with urban development may lessen the risk of desertification in the future (Portnov and Safriel 2004). Urban development, if properly planned and regulated, may reduce the spatial extent of the area affected by agricultural development and thus minimizes the anthropogenic impact on the desert environment (Portnov

and Safriel 2004). GDP and per capita GDP reflect economic aggregate in the economic system. Since early 1990s, the primary industry proportion of total GDP had decreased more than the secondary industry in study area, suggesting that economic gravity shifts from agricultural activities to non-agricultural activities such as construction and industry. From 1995 to 2009, for example, the primary industry proportion of total GDP was decreasing in Wuwei, Gulang, Jingtai, and Zhongwei, while the secondary industry proportion was increasing (<http://tongji.cnki.net/kns55/index.aspx>). The decreased contribution of agriculture-dominated primary industry to GDP has reduced the long-term stress on farmland and pasture. With the quick developing of secondary industry, industrial land in study area was increasing. In China, arable land has been strictly protected especially in the northwest arid area, and the original Gobi and desert areas could only be solidified to build new residential areas and factories, which led to the creation of towns in the three units (Wuwei, Gulang, and Jingtai). Zhongwei City was pushed gradually into the northern desert regions and has caused desert area decreases since 1973 (Fig. 9). To protect their homes and maintain sustained economic development, local residents take advantage of integrating straw checkerboards, sand-fixing plant belts, and farmland shelterbelts to build an oasis-protection system and block off the desert southern forward in the surrounding towns, especially in the north and northwest. The NDVI of the town and nearby area is clearly higher than that of other regions (Fig. 10), which indicates that these measures indeed played a positive role and controlled the desertification surrounding the town (Wu and Ci 2002; Su et al. 2007; Peng and Wang 2008; Zhao et al. 2008).

Land degradation starts with wind and water erosion that may occur naturally and/or may be triggered by human activity (UNEP 1992). This degradation refers to deterioration in the physical, chemical, and biological characteristics of soil and the long-term loss of natural vegetation (UNEP 1992). Because the NDVI is a crucial index for representing the situation of land vegetation (Herrmann et al. 2005), it can be used to reflect the degree of soil degradation and desertification. In the three units (Wuwei, Gulang, and Jingtai) and nearby Zhongwei City, not only the NDVI increased to a certain degree but the high vegetation coverage area also gradually and internally expanded into desert (Fig. 10). These areas are primarily farmlands surrounding towns and oasis-protection systems that consisted of integrating straw checkerboards, a sand-fixing plant belt, and farmland shelterbelt. Since 1979, based on the oasis-protection system, Chinese government began to build the Three-North (northeastern, northwestern, and northern China) Shelter Forest Program (the research area is the key area in northwest of the project). On the basis of protecting original vegetation, adopt artificial forestation and close hillsides to facilitate afforestation to prevent desertification. The third stage of the project has been launched in 1996 with total investment of 7.857 billion, which is twice more

than the total investment in the first two periods. According to some research, the oasis-protection system can reduce wind speed by 70 % and the sand transportation rate by 96 % when wind reached the farmland after passing through the oasis-protection system (Zhao et al. 2008). Although the precipitation of the study area has increased since 1973, the precipitation increment is limited, and the MAP in most of the region does not exceed 300 mm (Fig. 5). At the same time, the temperature of the entire study area increases, resulting in increasing evaporation and further reducing the effective precipitation (Fig. 6). Therefore, the local meteoric water cannot provide sufficient moisture for vegetation (Wu and Ci 2002), and the rise in the NDVI surrounding the town is not primarily caused by local precipitation. Human exploration will change due to the limited water resource redistribution. If there is no outside water diversion, human generally move to upstream for abundant water and the lower reaches are gradually abandoned with the water shortage. In fact, industry and agriculture water, people's domestic water, and ecologically engineering-protected water in the study area are primarily provided by water transfer from other regions. The snowmelt water on Qilian Mountain is the primary water source in the study area (Xie et al. 2004), and from there, the Shiyang River meets the water usage needs of towns in Wuwei and the western region of Gulang. The Yellow River, which flows through the southeastern part of the study area, provides a necessary water source for Zhongwei, Jingtai, Gulang, and Wuwei, irrigating large areas of farmland in the southern Tengger Desert. The local government uses water-saving techniques such as low-pressure pipe irrigation, sprinkling irrigation, drip irrigation, and narrow border irrigation to utilize water resource reasonably and effectively. In addition, the outside water carries some fine sediments that could be deposited in farmland and effectively improve the farmland soil, which was dominated by sandy loam and is also favorable for the growth of crops (Qin et al. 2007). The water from other regions meets the needs for the development of local agriculture to a large extent. Judged by cultivated areas only, the Wuwei unit uses the most water (Wuwei is known as the granary of Hexi Corridor), with Gulang second most, Jingtai next, and Zhongwei the least (Fig. 8). Although the cultivated areas of the latter three units are smaller than that of Wuwei, ever since 1973, they have shown significant growth trends (Fig. 8). The continuous and effective operation of cultivated areas and a peripheral ecological protection system played a significant role in blocking sand to a certain extent and in the stabilization of sand dunes.

The sheep restock of Wuwei, Gulang, and Jingtai exhibits an increasing trend (especially after 2000). The sheep restock of the Zhongwei unit was continually rising before 2000, after which there was a drastic decline (Fig. 8). Before the 1980s, the primary approach to animal husbandry in the study area was nomadic, and in arid zones, this activity and especially overgrazing lead to the occurrence and development of



desertification (Zha and Gao 1997; Saba 2001; Wu and Ci 2002; Zhao et al. 2005). To reduce the threat of desertification and protect the environment, the Chinese government began to implement large-scale ecological protection measures in the 1980s including changes in animal husbandry methods, namely, transferring the original “nomadic” to “captive” status. After entering the twenty-first century, the implementation of policies increased, for instance, a program of returning grazing pasture to native grassland experiments in 2001–2002 that was launched in 2003 (Dong et al. 2010), which may also be the direct cause of the sharp decline in the sheep restock after 2000 in the Zhongwei unit. Given the developed agriculture of Wuwei, Gulang, and Jingtai, large amounts of crop foliage could provide food for sheep, which, to a large extent, adapt to the continual increase in the number of sheep. Although there was an increase in the number of sheep, captive is the primary method, and the extent of its damage to the environment was greatly reduced. Therefore, we suggest that animal husbandry did not lead to the development of desertification in the southern region of the Tengger Desert from 1973 to 2009. With the developing of social and economic reforms, especially with the implementation of the Western China Development project (Dong et al. 2010), which transfers the remaining economic development capacity from eastern coastal areas of China to western areas to improve the level of its economic and social development. As an important part of the Western China Development project, since 2000, Chinese government has started a series of ecosystem construction, such as returning farmland to forest, protecting natural forests, and returning grazing land to grassland. From 2000 to 2007, the projects of returning farmland to forest and returning grazing land to grassland have finished construction tasks of 63.4 and  $85.5 \times 10^6$  ac, respectively (<http://www.gansu.gov.cn>). The projects have achieved obviously ecological, social, and economic benefits in study area, which leads the change for local GDP growth mode from linear to exponential growth (Fig. 8), and it is also the most direct reason for the dramatic decrease in the desert area in the above four units from 2001 to 2009 (Table 1).

## 5 Conclusions

- (1) From 1973 to 2009, the desert contraction area was primarily concentrated in Wuwei, Gulang, Jingtai, and Zhongwei Cities, and the primary desert expansion areas occurred in the WSHM, CMA, and the east and west sides of the Zhongwei City, which presented increasingly trends of their contraction degree. Most of the desertification in the study area has been being controlled especially after 2001.
- (2) The influence of the terrain factor on the other southern region changes within the five units, except the Zhongwei

unit could not be excluded, and it is still a dominant factor in the WSHM. The precipitation is not the dominant factor for controlling desert contraction or expansion in the study area. The temperature during the four seasons of each unit and the MAT has emerged with an increasing trend, and this consistency cannot separately provide a reasonable explanation for the difference in desert expansion or contraction. The precipitation in the study area is relatively small, and the surface becomes much drier after warming, which provides favorable conditions for desert expansion, which is the primary reason for the southern forward of the primary desert expansion areas over the last 36 years. However, the southern forward degree of the desert is gradually decreasing, and the temperature and precipitation could not explain why this phenomenon occurs. Similarly, the temperature and precipitation cannot explain the desertification behaviors of the three units of Wuwei, Gulang, and Jingtai and the nearby Zhongwei City. The MWS in the study area present a decreasing trend from 1973 to 2009, which gives a more reasonable explanation for the desertification behaviors.

- (3) From 1973 to 2009, the populations of Wuwei, Gulang, and Jingtai and nearby Zhongwei grew under the efficient support of the Shiyang River and outside water from the Yellow River. The cultivated area was increasing and the scope of the town and ecological protection project was gradually expanding (especially since 2000). New towns and ecological protection engineering are primarily constructed on the original desert, which is the root cause of the reduced desert area near the town and the northward retreat of the border. Since 2000, the WCD implemented by the Chinese government has begun to promote the rapid development of economy and ecological protection projects in the above areas, which is the most direct cause of the dramatic reduction in the desert area of these regions from 2001 to 2009. Since the 1980s, the Chinese government has begun to implement large-scale ecological protection measures. Therefore, the land in the southern region of the desert did not obviously promote desertification because of the development of animal husbandry. In conclusion, the effective human activities in the southern region of Tengger Desert play a significant role in preventing desertification.

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