Chapter 4
Driving Factors of Aeolian Desertification

Tao Wang, Xian Xue, Bing Liu, and Heqiang Du

Abstract This chapter reviews the natural features and driving factors of aeolian desertification in northern China. Drought, strong winds, and loose sandy surfaces are the main environmental factors that cause aeolian desertification in northern China, and these factors cause arid, semiarid, and dry subhumid lands to be sensitive to climate change and human activities. Climate change in the past 2000 years, 50 years, and the next decades is also introduced to explain the climatic driving forces of aeolian desertification. Human activities such as overgrazing, overfarming, overlogging, and inappropriate water management are analyzed as the driving forces of aeolian desertification. In northern China, there are three aeolian desertification regions. The agropastoral ecotone is located in semiarid and subhumid areas, where overfarming is the leading cause of aeolian desertification. Overgrazing and overcutting result in aeolian desertification in the pure pastoral regions located to the north of the agropastoral ecotone. In the irrigation oases of arid northwestern China, unsustainable water management and use are the fundamental causes of aeolian desertification. Different measures to address aeolian desertification should be developed based on regional characteristics.

T. Wang · X. Xue (✉) · H. Du
Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, Gansu, China

Key Laboratory of Desert and Desertification, Chinese Academy of Sciences, Lanzhou, Gansu, China

Drylands Salinization Research Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, Gansu, China
e-mail: xianxue@lzb.ac.cn

B. Liu
Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, Gansu, China

Key Laboratory of Desert and Desertification, Chinese Academy of Sciences, Lanzhou, Gansu, China

T. Wang et al. (eds.), *Combating Aeolian Desertification in Northeast Asia*,
Ecological Research Monographs, https://doi.org/10.1007/978-981-16-9028-0_4

Keywords Aeolian desertification · Climate variability · Driving factors · Human activities

Desertification is the process of land degradation caused by climate variability and human activities. Aeolian desertification is one of the main desertification types and is characterized by wind and sand activities. The driving forces of aeolian desertification include climate variability and human activities. In recent years, climate abnormalities such as droughts caused by global warming, increasingly heavy precipitation events, and reduced average wind speeds have greatly affected the development and reversal of aeolian desertification. Increasing populations increase food demand. Improvements in land productivity and technological advancements also positively and negatively affect the desertification process. This chapter mainly takes the northern region of China as an example to analyze the driving forces of desertification development and reversal in terms of climate variability and human activities. Before analyzing the driving forces, we introduce the natural features and ecological vulnerability of northern China and explain the sensitivity of arid and semiarid regions to climate variability and human activities.

4.1 Natural Features of Aeolian Desertification

Desertification is a process of land degradation that occurs in arid, semiarid, and dry subhumid areas. The most significant feature of the arid area is infrequent and highly variable precipitation, intense evaporation, and windy conditions. Together, drought and strong winds cause sparse vegetation and poor soil quality. In particular, most arid areas consist of paleolacustrine sediments, and sandy sediments dominate the soil. These constitute the natural features of aeolian desertification in northern China.

4.1.1 Climate Characteristics

The geographical location, atmospheric circulation, and geomorphic environment of northern China determine that the region's climate characteristics are dominated by drought and strong winds. Controlled by the subtropical high-pressure airflow, the arid areas in the world are mainly concentrated at 30°S–30°N. The climate is humid in other areas north of 30°N. However, the uplift on the Qinghai-Tibetan Plateau blocks the warm and humid airflow from the Indian Ocean and cuts off the westerly circulation but exacerbates the East Asian monsoon circulation; thus, the area north of 35°N in northern China is controlled by the influence of the Mongolian high. In addition, the eastern, southern, and western sides of the arid zone in northern China are surrounded by mountain ranges of varying heights, blocking the penetration of the warm and humid summer monsoon from the Pacific Ocean. The north is the open and flat Gobi Desert and desert grassland of the People's Republic of Mongolia, and this area is conducive to the northern dry and cold air moving southward. Together, these factors drive the climate of northern China that is characterized by drought and wind (Zhao 1990; PGSC 2000).

Meteorological data show that the precipitation in northern China gradually decreases from 500 mm in the east to approximately 20 mm in the west, which is much lower than that at the same latitude level in the Northern Hemisphere. Because precipitation occurs at the end of the summer monsoon, precipitation is greatly affected by the strength of the monsoon. In some years, the summer monsoon occurs in the arid area. However, the monsoon does not occur in the arid area some years, which results in unstable interannual precipitation. The average annual change rate of precipitation in most areas is 25–40%, and in some areas, it exceeds 50%. The seasonal distribution of precipitation is also extremely uneven. Precipitation in winter accounts for less than 10% of annual precipitation, while in summer, almost 70% of annual precipitation occurs. Although the total rainfall amount in summer is large, it is often concentrated within a few days, making it difficult for plants to utilize the precipitation.

Westerly winds are blocked by the Qinghai-Tibetan Plateau, bypassing the Altai Mountains to the north and moving south at the Sino-Mongolian border, forming a northern branch of airflow. This airflow merges with the airflow generated by Mongolian high pressure, often causing windy conditions (Geng 1986). Therefore, strong winds are another major climatic feature in the arid regions of northern China. According to meteorological records, the number of wind-blown-sand days in northern China is generally 20 to 100 days, with sand and dust storms occurring on as many as 35 to 60 days and floating dust occurring on over 100 days. Wind characteristics vary in different regions. Although there are many strong winds in the western region, they mainly occur in the spring. In the eastern area, there are strong winds in winter, spring, and autumn, and the wind is weak in summer. Sand-dust storm activity is directly related to the magnitude of wind force and is also restricted by the nature of the ground. The dry, loose ground sand material in the western region is susceptible to wind blowing and forms aeolian sandy land. The total wind force in the eastern part is greater than that in the western part during the whole year, but the plant coverage is better than that in the western part. Therefore, the sand-dust storm activity is much less than that in the west.

Therefore, the climate is arid, precipitation is extremely unstable, and windy weather is the primary feature of the climate in the arid area of northern China. These are the main climatic features and dynamic conditions underlying the occurrence of aeolian desertification.

4.1.2 Hydrological Characteristics

Most of the runoff replenishment in northern China is from rainfall, so its distribution is consistent with the annual precipitation and has longitudinal and vertical zonal characteristics. However, due to the influence of natural geographical factors, runoff replenishment also has regional characteristics. According to the depth of runoff, the sand area in northern China can be divided into four subareas. They are extremely arid areas without runoff, arid areas with annual runoff depths of less than 10 mm, semiarid areas with annual runoff depths of 10–50 mm, and dry semihumid areas with runoff depths of 50–200 mm (these areas are defined based on runoff amounts that differ from the definition system based on the aridity index).

In the northwestern arid area, the rivers are called inland rivers. The inland rivers usually originate from the mountains and disappear in the desert hinterland. Along the river, some natural or artificial oases are irrigated by inland rivers. Due to the replenishment of glaciers and snowmelt water and mountain precipitation, the main characteristics of the runoff are mainly spring floods and summer floods. The flood seasons mostly occur from April to June every year. Various reservoirs have been built in the upper and middle reaches of these inland rivers, and the runoff has been mainly controlled manually (Xiao 2000).

In the semiarid grassland areas, many rivers are seasonal. Seasonal rivers are shorter in length, generally less than 400 km; the catchment area is also small; and there is no fixed channel. During flooding, seasonal rivers overflow both banks, forming many inland lakes and wetlands. Because the river is wide and shallow, it is not recharged by groundwater.

The dry subhumid area has a climatic transition, so it has many different river hydrological characteristics. Due to the instability of climate and hydrological systems, river hydrology is very sensitive to environmental changes. The overall performance is as follows: (1) the annual runoff variability is large, the flood peak variation coefficient is large, and there are many drought and flood disasters. (2) Runoff is concentrated in summer, and there is less runoff in spring. (3) The river has a large amount of sediment transport and high sediment content, and the regional differences are obvious. (4) There is a special connection between river water and groundwater.

In addition to surface water, northern China also has abundant groundwater resources. Groundwater is mainly stored in the Meso-Cenozoic tectonic basin in the form of loose sediment pore water. Groundwater characteristics also differ significantly from west to east. In the west, large thick gravel layers are deposited in the piedmont zone on the edge of the basin, an important place for storing groundwater. The Quaternary sediments in the eastern grassland area are extremely thick and rich in groundwater. Since the 1970s, due to the increase in cultivated land area and the popularization of machine well technology, the development and utilization of groundwater in northern China have been very high. Therefore, in terms of groundwater resources, consumption is greater than recharge, and the groundwater level is declining. In addition, the reuse of groundwater in arid areas has also led to increased salinity levels and decreased water quality (Xue et al. 2015).

4.1.3 Soil Characteristics

The soil types in northern China are diverse but mainly consist of Sandic Entisols distributed continuously from east to west. Relatively new sandy facies are a kind of soil with lithological characteristics of sandy sediments in new facies, also known as aeolian sandy soils. The soil is mainly distributed in inland basins and plateaus between 35°–50°N and 75°–125°E (Chen and Li 1999).

Sandic Entisol is a common product of an arid climate and aeolian sand. Aeolian sand has a wide range of material sources, including alluvial river deposits (dry deltas or alluvial fans), alluvial lake deposits, alluvial deposits, and weathered bedrock residues. Due to the arid climate and sparse vegetation, biological effects have a slow impact on the formation of sandy soil. Therefore, the formation process of sandy soil is long, and it is closely related to the process of natural vegetation growth and succession on sandy land. The evolution of aeolian sand into sandy soil can generally involve three stages: fine soil accumulation, crust formation, and organic matter accumulation. With the completion of these three stages, mobile sand or dunes gradually evolved into semifixed sand, fixed sand, and sandy grasslands (Chen et al. 1998).

Because the process of soil formation is slow, the content of organic matter is low, the water holding capacity is poor, and the soil easily blows away. Therefore, sandy soil provides the sand source for the development of aeolian desertification in northern China.

4.1.4 Vegetation Characteristics

Due to the arid climate and barren soil, vegetation in northern China is sparse. Forest cover is low, and its coverage rate is less than 5%. Forests are mainly distributed in the Daxinganling, Xiaoxinganling, and Changbai Mountains in eastern China, the Taihang Mountains in central China, and the Qilian Mountains in western China.

In most areas outside the mountains, grassland is the dominant ecosystem in northern China. Grassland type is consistent with the distribution of precipitation. At the same time, grasslands are also affected by temperature and show characteristics based on longitude and latitude. Meadow steppe, typical steppe, desert steppe, and steppe desert are distributed from east to west. From south to north, the warm temperate zone transitions to the moderate temperate zone. The Son-Nen Sandy Land is located in the moderate temperature, forest-steppe zone in the temperate steppe area. Hulun Buir, Horqin, Hunshandake, and other sandy areas and their surrounding areas are in the moderate temperature typical steppe zone.

Ulanqab-Wulate is a moderate-temperature desert steppe. The eastern half of the Hobq Sand Belt and the Mu Us Sandy Land are in the typical warm temperate steppe. The western half of the Hobq sand belt and the Hedong Sandy Land in Ning Xia are in the warm temperate desert steppe (Liao and Jia 1996).

In those places west of the Helan Mountains, Wushaoling, and East Qilian Mountains, the annual precipitation is less than 200 mm. The vegetation type is temperate desert. The Ulan Buh Desert, Tengger Desert, Badain Jaran Desert, Western Hexi Corridor, Qaidam Basin Desert, Gurbantunggut Desert, and surrounding areas are in the moderate-temperature desert zone. Eastern Xinjiang, southern Xinjiang, the Kumtag and Taklimakan Deserts, and their surrounding areas are in warm-temperature deserts. Vegetation types gradually change from xerophytes to severe xerophytes and ultra-xerophytes from east to west in the region.

Vegetation is an essential factor in protecting surfaces from wind erosion, and the influence of vegetation is especially obvious in grasslands dominated by annual species. Temperature and precipitation greatly determine the greening season of grasslands in northern China. In the years when there is less precipitation in spring, the vegetation turns green later, and the large sandy surface is directly exposed and partly exposed. At the same time, spring is also the season of frequent strong winds in northern China. Wind force acts directly on the surface of the sand, resulting in aeolian desertification (Wang 2011).

According to the above brief introduction to the climate, soil, hydrology, and vegetation, we can see that the aeolian desertified areas in northern China are characterized by drought, strong winds, loose surface materials, and sparse vegetation. These characteristics make the ecosystem extraordinarily fragile and sensitive, and its ability to resist climate fluctuations and the impact of human activities is low. When influenced by external factors, aeolian desertification occurs extremely easily.

4.2 Climatic Driving Force of Aeolian Desertification

Under vulnerable natural conditions, it is difficult for the ecosystem to withstand the impact of climate change and human activities, so aeolian desertification occurs to varying degrees. Since the Western Han Dynasty, aeolian desertification occurred in northern China, and it has aggravated or been reversed based on cyclical climate changes (Zhu and Chen 1994). Understanding the driving mechanism of climate change helps forecast aeolian desertification development in the future and develop prevention strategies in advance. This section mainly reviews climate change in northern China during the historical period and the past 50 years.

4.2.1 Historic Climate Change and Its Impact on Aeolian Desertification

Climate change over the past 2000 years in northern China has mainly occurred as changes in temperature and precipitation. By analyzing historical documents, tree rings, ice cores, lake sediments, and stalagmites, Ge et al. (2013, 2015) proposed four warm periods and four cold periods in northern China (Fig. 4.1). The four warm

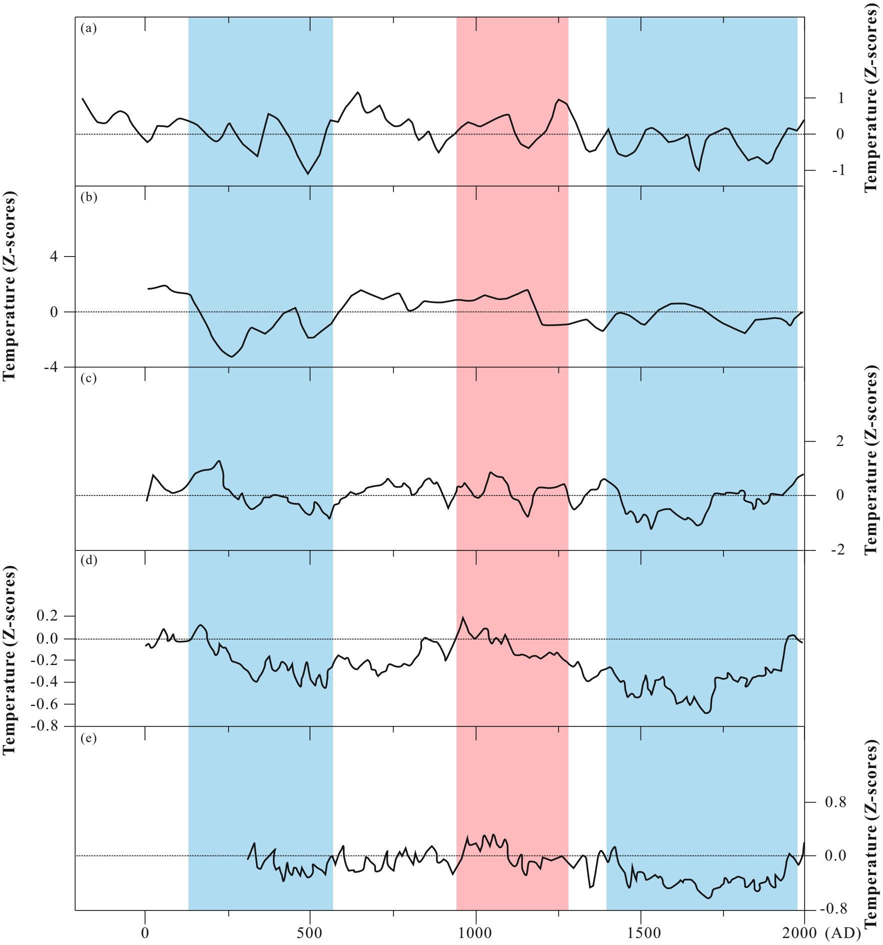

Fig. 4.1 Temperature changes in different regions in the past 2000 years (Ge et al. 2013). (**a**) Winter half-year temperature changes in the central and eastern regions of northern China; (**b**) temperature changes indicated by the sediments of Sugan Lake in Qinghai; (**c**) national temperature changes reconstructed based on multiple pieces of evidence; (**d**) Northern Hemisphere subtropical temperature changes reconstructed based on multiple pieces of evidence; and (**e**) reconstruction based on evidence of temperature changes in the Northern Hemisphere

periods were in 1–200, 550–760, 950–1300 AD, and the twentieth century. The cold periods were in 210–350, 420–530, 780–940, and 1320–1900 AD. The historic precipitation change was different between the eastern and western areas (Fig. 4.2). The boundary line of dry and wet conditions in northern China was approximately 105°E. The west to the line was dry, and the east was wet.

The sandy lands in the semiarid regions of northern China are very sensitive to climate change (Lu et al. 2005, 2013; Mason et al. 2009; Yang et al. 2013, 2015). The sandy lands in the eastern part of northern China have experienced several large fixations and activations in the past 2000 years. For example, the Hulun Buir and Horqin sandy lands have experienced three reversals (0~210, 770~1050, and 1170~1440 AD) and three expansions (210~770, 1050~1170, and 1440 AD). The expansion of the sandy lands in these periods was aeolian desertification (Zhu and Chen 1994). The reversal period of aeolian desertification was closely related to the warm and humid climate, and the expansion of aeolian desertification was related to the cold and dry climate (Li et al. 2018). Wu and Lu (2005) and Zhang et al. (2012) found that sandy soils, peat, and river-lake sediments developed in the Hunshandake Sandy Land during the Medieval Warm Period (700–1300 AD), which implicates the reversal of aeolian desertification. Sand-dust storm activity has occurred frequently again since the Little Ice Age. In the Mu Us sandy land, aeolian sand-paleosol deposition experienced three stages of aeolian desertification with high-frequency dust storm events in 440–570, 840–960, and 1525–1890 AD (Bai and Cui 2019). The climate in all three periods was cold and dry. During the previous two periods, climate was the dominant driver because of minimal human activities. In the third period, the human population and activity intensity gradually increased. The dominant driving force of aeolian desertification transitioned from climate to unsustainable human activities.

In the arid western part of northern China, the climate has experienced changes over the past 2000 years. Multi-index analysis of the core of Lake Ungertu in the southeastern Tengger Desert showed that since 988 AD, the regional climate has exhibited the characteristics of alternating changes in cold and wet and warm and dry (Cao et al. 2018). The overall climate from 988 to 1383 AD was relatively cold and wet. During 1383 to 1560 AD, the climate became warm and arid. In the period of 1560 to 1700 AD, the climate was at its coldest with increased precipitation. Then, a warmer climate appeared again from 1700 to 1900 AD. On the northeastern margin of the Tibetan Plateau, Stauch (2016) found that there have been six periods of enhanced sandstorm activity at a 100-year scale in the past 2000 years, namely, 1630–1725, 1450–1530, 1250–1350, 750–950, 390–540, and 50–225 AD. These periods belong to the Little Ice Age, when the sandstorm activity was strong.

The desert and its neighboring areas in the monsoon marginal zone of northern China have experienced two warm and humid climate periods (0–200 and 900–1300 AD) and two cold and dry climate periods (700–1000 and 1400 AD), which is consistent with the two cold and two warm climate change conditions shown by temperature integration in the Northern Hemisphere. During the warm and wet periods, aeolian desertification reversed. When the climate became colder and dry, wind and sand activities occurred, and aeolian desertification developed.

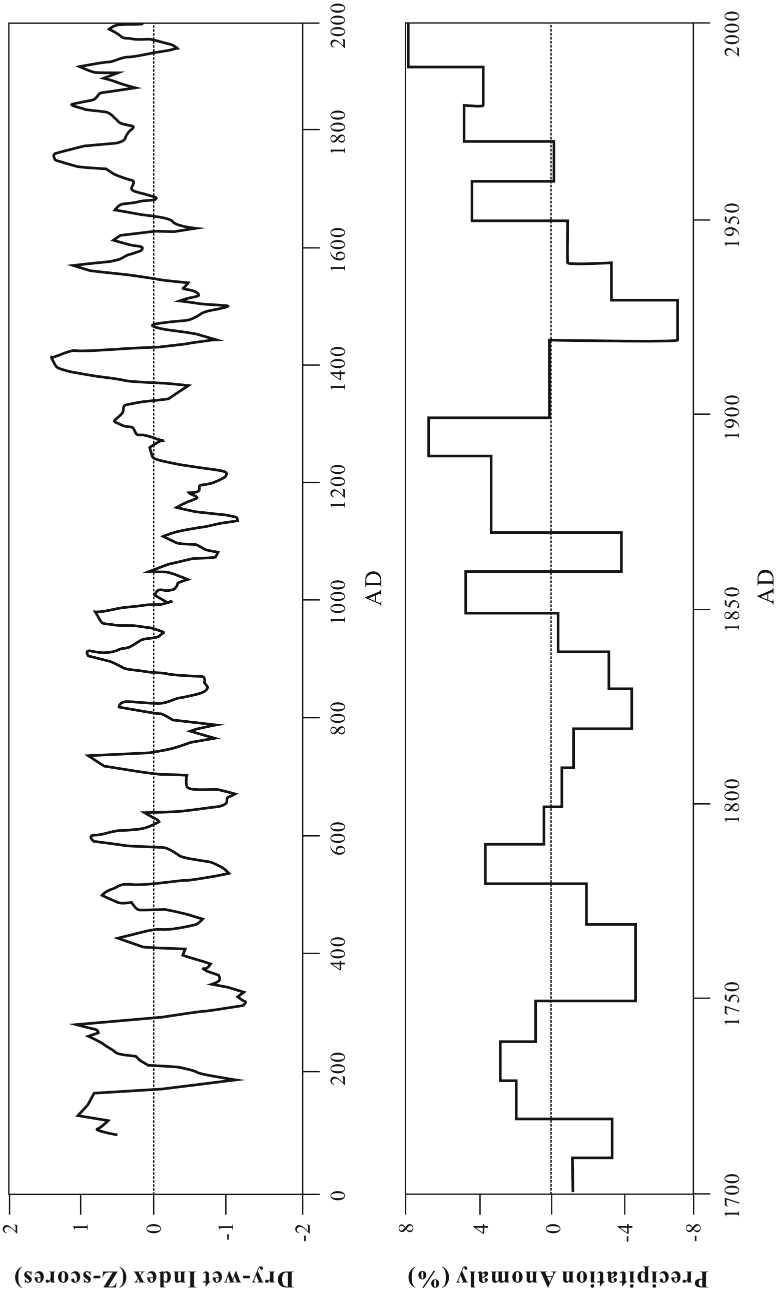

Fig. 4.2 Changes in precipitation (dry and wet) in the monsoon region of eastern China and the arid region of western China in the past 2000 years (Ge et al. 2013). (**a**) Eastern monsoon area; (**b**) western arid area

4.2.2 Recent and Future Climate Change in Northern China

Extreme weather and climate events accompanying warming in China have recently become increasingly stronger. The melting of the cryosphere is accelerating, and the level of climate risk is increasing. However, the regional difference in climate change was very obvious from 1961 to 2018. For example, the rate of temperature increase in northern China was significantly greater than that in the south, and the rate in the western region was greater than that in the eastern region. The highest rate of temperature increase on the Qinghai-Tibet Plateau was 0.37 °C/10 a. During this period, the average precipitation in China showed a slight increasing trend, the regional variation in precipitation change was also obvious, and precipitation showed a significant increasing trend on the Qinghai-Tibetan Plateau, a weak decreasing trend in the southwest area, and a substantial fluctuation with no obvious change trend in other areas (Xue et al. 2012).

Based on China's climate change over the past few decades, scientists have used climate models to simulate climate change in northern China in the coming decades. The results show that in the next few decades, near-surface temperature and precipitation in northern China will increase significantly, the frequency of extreme arid climate will increase, the scope of influence will expand significantly, and there will be significant differences between regions (Hu et al. 2015). Northern China will be the region with the most significant warming and will experience the greatest warming on mainland China from 2015 to 2025. By 2030, the winter temperature increase in northern China will increase by 2.5 °C relative to the multiyear average temperature (1961–1990). In the summer of the next 10 years, northern China will be in a clear water vapor convergence zone, and summer precipitation in northern China will increase significantly (Hu et al. 2015).

According to the simulation results (Fang et al. 2020), the climate in the agropastoral ecotone zone of northern China shows a warming and humidification trend from 2006 to 2050. The average increase rate of the temperature will be 0.2–0.5 °C/10 a, and the annual precipitation rate of change will be 1.49–15.59 mm/10 a. If greenhouse gases are not effectively controlled, then the instability in the regional climate system will increase significantly. For example, as the concentration of greenhouse gases increases, the rate of temperature increase in the agropastoral ecotone zone of northern China will increase from 0.25 °C/10 a to 0.48 °C/10 a, and the rate of change in precipitation will increase from 3.97 mm/10 a to 14.58 mm/10 a (Fang et al. 2020). The Loess Plateau in northern China will also increase significantly with obvious seasonal variation in the next 100 years. The spatial variation coefficient of the average winter temperature is the largest under the same RCP scenario, and the overall trend in the rate of temperature increase gradually from south to north will increase; under the same RCP scenario, the spatial variation coefficient of spring rainfall will be the largest, and the rate of increase in precipitation will gradually increase from north to south (Ren et al. 2019).

By 2030, the average temperature in the western part of northern China will increase by approximately 1.67 °C. The maximum increase will be 1.79 °C and will occur in the western part of Tianshan Mountain and southern Xinjiang. The minimum increase will be 1.56 °C and occur in northern Xinjiang. The eastern region (including western Inner Mongolia, most of Gansu, and central and northern Qinghai) will have a temperature increase between the previously stated values, and the temperature increasing range will be 1.65 °C. The spatial and temporal distribution of precipitation will be more complicated. Overall, precipitation in the western region will increase and relatively decrease in the northern and eastern regions. Overall, drought in northwestern China will increase significantly in the next 10 years (Feng et al. 2019).

4.3 Anthropogenic Mechanism of Aeolian Desertification

As mentioned above, aeolian desertification is mainly caused by unsustainable land use activities in the context of climate variability. Several factors mainly control unsustainable land use. First, excessive land use is often associated with an increase in population. The increase in population will inevitably lead to an increase in demand for food, water, and other necessary materials for living. When the productivity per unit area of land remains unchanged, the increased demand can only be addressed by increasing the use of land resources, such as expanding the area of cultivated land and increasing the number of animals per unit area. Land use is often directly related to state policies. The government will encourage people to change or exacerbate land use due to various needs. For example, at the end of the Qing Dynasty, to pay war compensation, the government encouraged farmers to reclaim the northern grasslands. In the 1930s, the US government promulgated various land policies to attract farmers to carry out reclamation. To build the cotton base in Central Asia, the former Soviet Union called on local people to use the Amu Darya and the Syr Darya to plant vast fields of cotton (Xue et al. 2015). Facts show that land use supported by policies is the most critical factor leading to desertification because the scale of policy is more significant than personal behavior. Changes in the original traditional production methods and improvements in levels of technology will also possibly cause aeolian desertification. When people gradually change from a nomadic civilization to a farming civilization, land reclamation occurs. The increase in drilling for water has made the use of groundwater possible, which has led to the continuous expansion of irrigated agriculture in arid areas. The unrestricted expansion of irrigated agriculture is likely to cause desertification of the land.

The human driving force behind the occurrence and development of aeolian desertification in northern China is also determined by the population size, policies, and production methods. The specific human activities are overfarming, overgrazing, overlogging, overmining, and unsustainable exploiting of water resources. According to research (Wang 2011), aeolian desertified land caused by inappropriate land use accounts for approximately 95% of the total aeolian desertification area in northern China. However, in different regions, the leading factors are different. The aeolian desertified land in northern China is mainly divided into agropastoral ecotones, pure pastoral zones, and irrigation oasis zones in inland river basins. The following sections introduce the driving mechanisms of aeolian desertification in these three regions.

4.3.1 Agropastoral Ecotone

The agropastoral ecotone in northern China mainly refers to the transition zone between the agricultural zone and the pastoral zone in northern China. In this transition zone, planting and grassland animal husbandry are spatially staggered and overlap in time. Land uses shifted with time. In different historical periods, the geographical scope of the agropastoral ecotone in northern China was not the same. Before the Qing Dynasty, the area was mainly distributed on both sides of the Great Wall, but now it is more distributed north of the Great Wall. During the historical period, factors such as climate change and ethnic migration often led to the northward or southward invasion of the agropastoral ecotone. At present, the pattern of the agropastoral ecotone is more controlled by changes in policies and land use methods.

At present, the agropastoral ecotone in northern China is mainly located to the north of the Great Wall and is a semiarid temperate zone. The ecotone consists of the Horqin region, the regions in southern Inner Mongolia and northern Hebei Province (SIM and NH), and the Ordos region (Fig. 4.3). The precipitation in this ecotone is about 200–400 mm, and the evaporation is 2000–2500 mm. The natural landscape is mainly dry steppe, including part of a sparse forest steppe and desert steppe. Almost all the regions were nomadic pastures 200 years ago. From the perspective of geographical area, the ecotone is located at the junction of semiarid and subhumid areas. From the perspective of population and cultural distribution, the ecotone is located at the junction of the Han population with a farming culture and a minority population with nomadic culture. Because this ecotone is at the edge of the monsoon, the interannual and intra-annual changes in precipitation in this area are quite significant. When the monsoon is strong, it often produces abundant precipitation, and when the monsoon is weak, the opposite occurs. These characteristics are concrete examples of the vulnerability and sensitivity of the geographical environment in the agropastoral region, and this vulnerability and sensitivity serve as the main sources of the generation and development of land desertification.

The inhabitants of the agropastoral ecotone 200 years ago were pastoral minority populations, and grazing was dominant because strong winds, drought, and a loose soil surface were not conducive to cultivation. However, since the eighteenth century, agriculture has gradually replaced animal husbandry (Wang et al. 2015). According to research (Yang and Ta 2002), farmland increased from 50,200 km^2 in 1952 to 82000 km^2 in 1998 in Inner Mongolia. The same research also showed that the farmland area increased by 1150 km^2 from 1915 to 1928 and reached 13,330 km^2 in 1949 in the Ordos region. Other studies have shown that farmland increased from 700 km^2 in 1948 to 7300 km^2 in the late 1980s and natural pasture decreased from

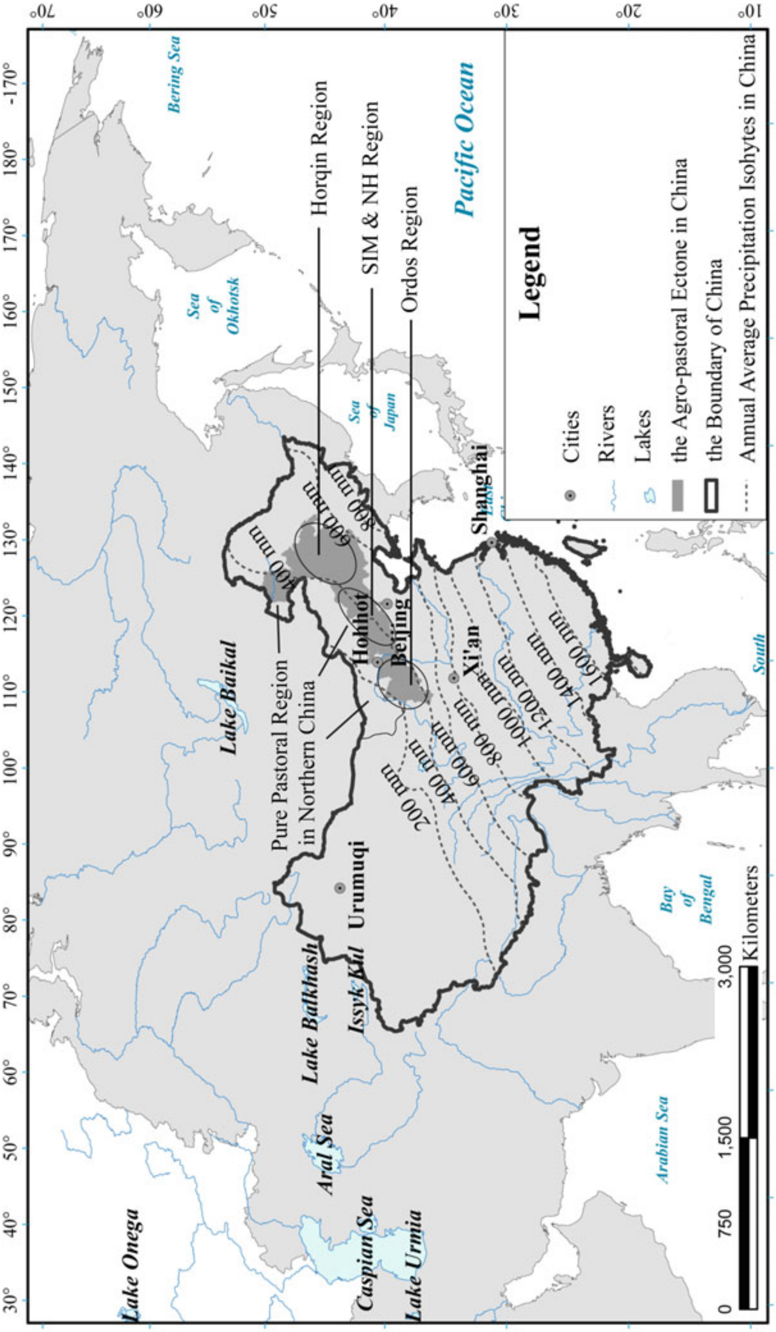

Fig. 4.3 The location of the current agropastoral ecotone and pure pastoral region in northern China (revised according to Wang et al. 2015)

8700 to 2700 km^2 in the same period in northern Hebei Province (Han and Han 2003; Sheng et al. 2003). Consequently, land use conversion extended farmlands northwestward and pushed the boundary of the historical agropastoral ecotones northward by an average of 180–220 km into the Booe typical steppe or desert steppe (Fig. 4.4) (Wang et al. 2008).

Reclamation activities have created favorable conditions for surface sandy particles to be blown, transported and accumulated under the force of the winder, which caused a significant change in the original landscape of the sandy grassland. Therefore, reclamation is the main cause of aeolian desertification in grassland ecosystems. As mentioned above, land use patterns mainly occur based on two situations: one is the change in the natural environment, and the other is the change in national policies. Changes in the natural environment often cause farmers to spontaneously change land use patterns. When the climate is dry and cold, agricultural plantations will be replaced by animal husbandry due to limited conditions. When the climate changes toward warm and humid conditions, people usually reclaim grasslands for crop plantations.

Studies have shown that there is often a period of increased crop planting area after a wet year (Xue et al. 2005a). However, when farmers reclaim grasslands spontaneously, they often overlook the geographical characteristics of the land they inhabit differently from those of other areas. These overlooked characteristics are large precipitation variability, loose surface material, and frequent strong winds. People forget that abundant rainfall is only temporary. The year after abundant precipitation is often a dry year. With a reduction in precipitation, there is not enough water to continue to support the growth of crops. Cultivated land must be abandoned (Zhu and Liu 1981). For example, in Yijinhuoluo County in the Ordos region, the total area converted from pasture to farmland was 700 km^2, but only 300 km^2 of the farmland remained after 20 years (Jia et al. 2003). When cultivated land is abandoned and grass has not yet grown, the loose surface is exposed directly to the wind. Fine particles and nutrients are thus eroded in these regions, and the sediment moves to the downwind regions. Aeolian desertification occurs in these downwind regions. The large precipitation variability in the semiarid area provides a good natural background for aeolian desertification. In the other areas, there are also long-term or short-term precipitation changes, but such precipitation changes will not have a substantial impact on land use. For example, in the region with an annual average precipitation greater than 800 mm, the change in precipitation of 100–200 mm will not change the local agriculture. Similarly, in the desert hinterland with an average annual rainfall of approximately 50 mm, a certain year or years with rainfall of 100 mm will not turn desert into farmland. However, in the agropastoral ecotone with rainfall of approximately 400 mm, small precipitation changes may lead to landscape changes and a shift in land use (Xue et al. 2005a).

Being aware of the vulnerability and sensitivity of the geographical environment and formulating long-term and sustainable land uses that adapt to environmental changes are not determined by the ability of some individuals but must rely on national policies. Large-scale army reclamation during the Qin and Han Dynasties, subsidy reclamation in the late Qing and the Republic of China, migration

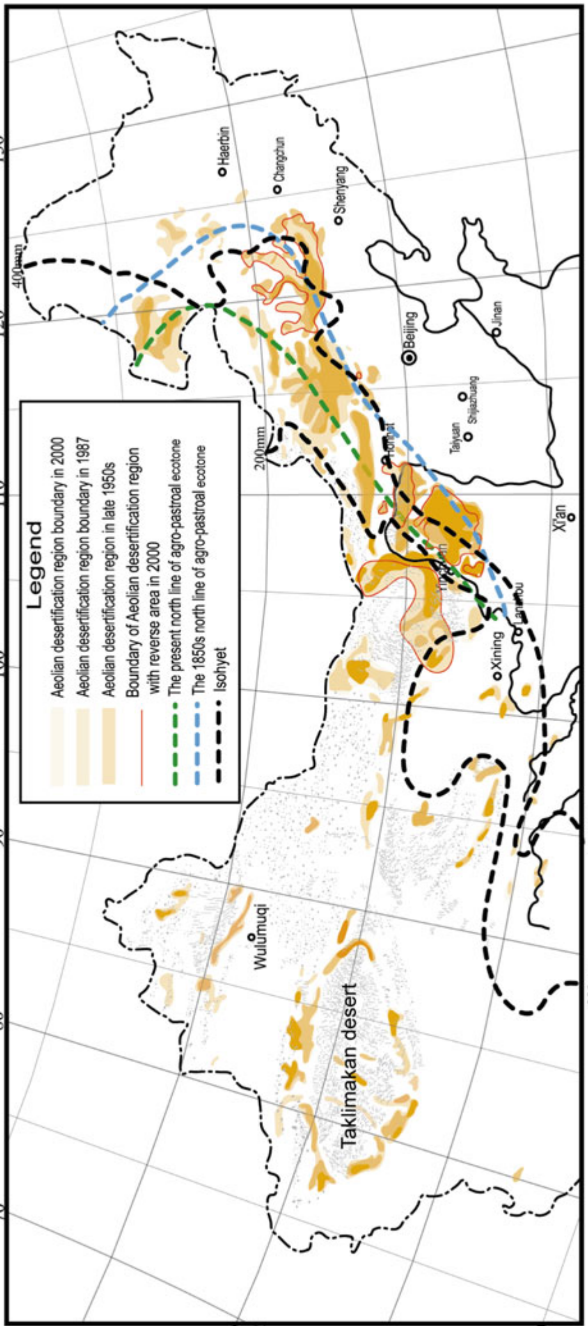

Fig. 4.4 The change in the agropastoral ecotone of northern China in the last 200 years (revised according to Wang et al. 2008)

reclamation in the 1950s and 1960s, and the conversion of farmland to forests and grasslands after the 1980s are all nationally dominated land uses. When land use changes are coordinated with the evolution of the natural environment, the human-land system is at an equilibrium, and it has a strong resistance to external interference. The reversal of aeolian desertified land in some areas of northern China in the past 20 years mainly comes from the implementation of the policy of returning farmland to forest and grassland. In contrast, when policy development only considers short-term economic benefits and ignores long-term ecological and social benefits, it leads to an unbalanced relationship between people and land. When the external conditions change slightly, various ecological problems, economic problems, and even social problems will appear in the system, such as aeolian desertification in the agropastoral ecotone before the 1980s.

4.3.2 Pure Pastoral Region

Pure pastoral areas refer to areas where grazing is the only or dominant land use activity. China's pure pastoral areas are mainly distributed in the temperate grasslands in the north and the alpine grasslands on the Qinghai-Tibetan Plateau. Aeolian desertification of the alpine grasslands on the Tibetan Plateau is largely affected by climate change (Xue et al. 2009). The pure pastoral area discussed here refers to the temperate grassland north of the agropastoral ecotone in northern China (Fig. 4.3). The precipitation in this area ranges mostly from 100 to 300 mm. Landscape types include typical steppe, dry steppe, desert steppe, and steppe desert. Overgrazing is the main cause of aeolian desertification in pure pastoral areas. In recent years, with the popularization of solar energy and wind energy, overlogging has been effectively resolved. However, before the end of the last century, of the aeolian desertification caused by the range of human activities, that caused by excessive woodcutting was the largest.

There are two reasons for overgrazing in pure pastoral areas. On the one hand, because the original grassland was reclaimed to farmland, the grassland area was greatly reduced. Even when the number of livestock remained unchanged, the livestock load per unit of grassland increased significantly. This scenario is often referred to as relative overgrazing. On the other hand, the total number of livestock has also increased significantly, which is called absolute overgrazing. Inner Mongolia is the main distribution area of pure pastoral husbandry in northern China. Research (Wang 2011) shows that the livestock amount in Inner Mongolia increased from 2447.3×10^4 sheep units in the 1950s to 6460.14×10^4 sheep units at the end of the last century. In the 1990s, the theoretical livestock carrying capacity in Inner Mongolia was 4837×10^4 sheep units, and the overload rate reached 33.56%. Overloading was even more severe in other regions. For example, overload rates in the same period were 135.70% and 138.93% in Gansu Province and Ningxia Province, respectively. In addition to the increase in livestock amount, a decrease in grassland productivity also resulted in overloading in the pure pastoral regions.

According to our investigation in Xiuzhumqin Qi (county) of Inner Mongolia, 0.54 ha of grasslands could support one sheep in 1955, but the data showed that 1.09 ha of grasslands could support one sheep in 1982 and 2.45 ha of grasslands in 2000 (unpublished data).

Overgrazing mainly occurs because an increase in the number of people and improvements in living standards increase the demand for products such as meat, milk, wool, and cashmere. In addition, improvements in herdsmen's own living standards and an increasing emphasis on education have prompted them to expand their livestock scales as much as possible to obtain increased economic benefits. These are the main reasons for the current overgrazing issue. Notably, herdsmen's instincts for pasture protection and the grazing experience will not cause severe damage to pastures due to overgrazing. However, frequent climate fluctuations in recent years have often resulted in unpredictable consequences. The abundant precipitation in the spring increased grassland biomass, and the number of livestock increased rapidly. However, when the next year's drought arrived or the rainy season was postponed, the productivity of the vegetation decreased, and the grassland was overeaten by the increased livestock, making it difficult to recover it in the short term. For example, in 2000–2001, the drought of Sunite Zhuo Qi (a county of Inner Mongolia) decreased the livestock carrying capacity of a grassland by approximately half, which made the region become one of the most severely aeolian desertified regions in northern China.

For both absolute overgrazing and relative overgrazing, the number of livestock exceeds the carrying capacity of a pasture. An excessive load on a pasture will not only decrease the vegetation coverage but also induce wind erosion. More importantly, over browsing by livestock destroys the root system, reduces the number of seeds and germination capacity, and inhibits vegetation restoration, which reduces the stability of the ecosystem. In addition, under heavy trampling of livestock, the surface crusts are broken, sands are exposed, and wind erosion increases. Remote sensor monitoring shows that the aeolian desertification occurred in 25–35% of the pure pastoral region in 2010.

The aeolian desertification process caused by overgrazing is more obvious around wells. Field investigations show that within a radius of 500 m around a water well or livestock habitat, native vegetation is destroyed and presents a sandy or gravel textured surface. Within a radius of 500–1000 m, only uneatable or even poisonous weeds grow. Forage grass gradually appears 1000 m away from wells. Therefore, the emergence of this kind of landscape with different types of grasslands centered around water wells usually represents the emergence of aeolian desertification. In addition to wells and livestock habitat sites, this aeolian desert landscape caused by overgrazing is also distributed around some small lakes.

In a grassland area, after excessive browsing and trampling damage the surface vegetation and crusts, wind erosion begins to occur. As the degree of wind erosion increases, wind erosion dens first appear on the surface. The sizes of wind erosion dens continue to increase, and sometimes large wind erosion pits are formed. Fixed dunes or semifixed dunes with higher vegetation coverage, affected by overgrazing and overlogging, will be gradually activated and eventually form mobile dunes.

Therefore, fixed sand dune activation and sandy grassland wind erosion are the two main types of land desertification that occur in pure pastoral areas. The particles eroded by wind can be transported and accumulate several meters to hundreds of meters downwind. Fine silt and clay particles easily become airborne and form dust storms in downwind areas (Liu et al. 2008). Sandy grasslands might be one of the principal dust sources for Beijing and its surrounding area. Furthermore, sand particles move downwind along the land surface and form sand patches or active dunes when they encounter barriers. After long periods of wind erosion, the land becomes coarse and loses productivity.

In the process of aeolian desertification of grasslands, overfarming and overgrazing affect each other, and they are closely related.

4.3.3 Irrigation Oasis Zone in Inland River Basins

Because irrigation oases provide habitats for animals and humans in drylands (Mainguet 1991), they are vitally essential for people living in drylands (Reynolds et al. 2007; UNCCD 2008). Irrigation oases only occupy 4–5% of arid northwestern China (Fig. 4.5) but support 90% of the local population and produce 95% of social wealth (Li et al. 2007). Water is the most fundamental resource for the sustainability of oases because it sustains the lives of local people, livestock, and agriculture, as well as environmental health and ecosystem services. However, unsustainable water use is widespread at almost all these oases are also the leading cause of aeolian desertification in these areas. Mainguet (1991) said, *where is the wrong management method, where there is wind erosion*.

Irrigation oases in northwestern China are distributed in a beaded pattern along the inland rivers from the middle reaches to the lower reaches (Fig. 4.5). The rivers originate in the mountainous areas in the upper reaches and flow through oases and deserts, which make up the inland river catchment or watershed. Environmental factors such as hydrology, climate, soil, and vegetation in the same catchment, as a subsystem, are interconnected and interdependent. By changing one or several subsystems, an entire river basin system can be changed. In addition, various natural geographic processes are consistent, and various human activities occur in a watershed system. This also means that land use in the upstream region of a basin system is closely related to environmental change in the midstream and downstream regions. A reduction in upstream water intake is sometimes controlled by natural factors, but often, a reduction is due to an excessive use of water resources from the unrestricted expansion of farmland. This conflict of water resource use in basins has occurred consistently for more than 2000 years and reached its peak in the 1980s (Xue et al. 2005b, 2015).

During the 1970s–1980s, the central and local governments called for the construction of irrigated oases in the northwest that transformed the area into a base of commercial grain and cotton. Encouraged by the policy, reservoirs were built in the upper and middle reaches to block floods and expand cultivated land. This caused

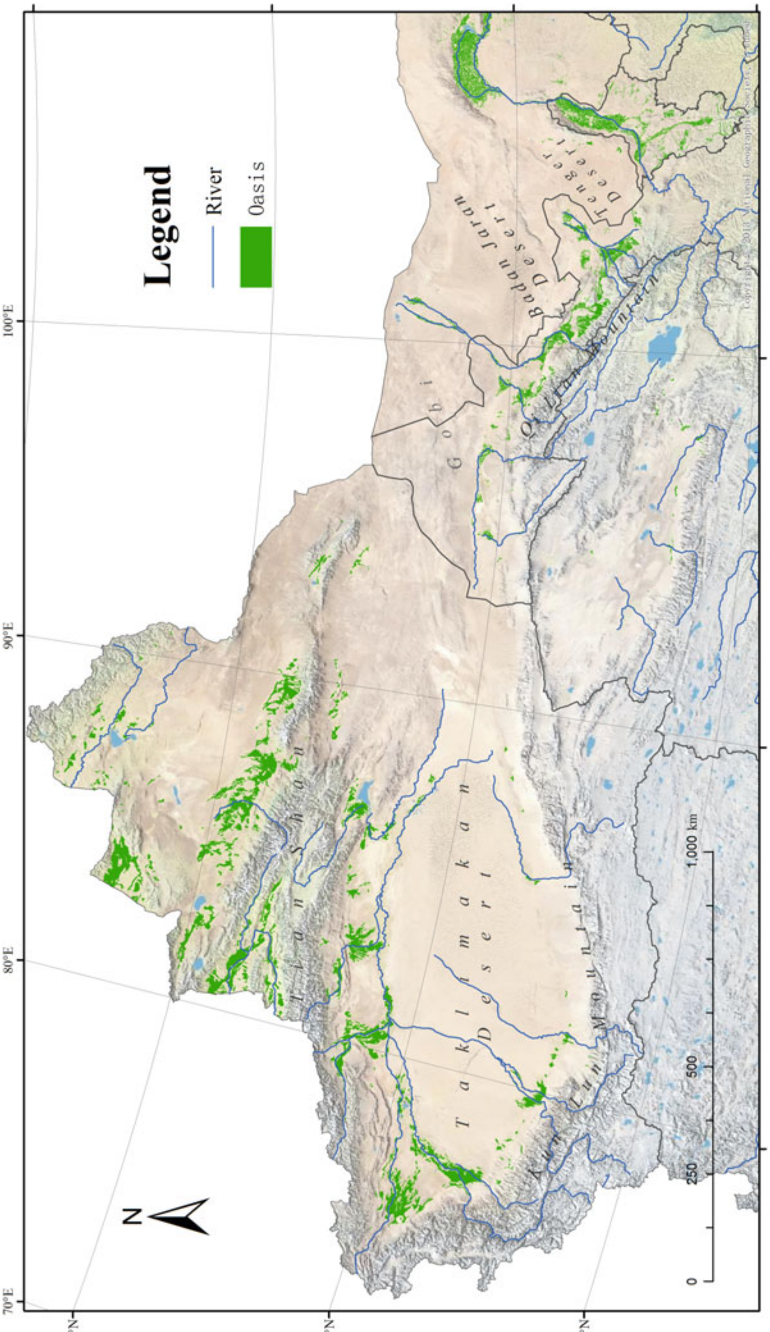

Fig. 4.5 The distribution of irrigation oases in northwestern China

the water volume in the lower reaches of the basin to continually decrease. Considering the Shiyang River Basin (Fig. 4.5), which is located on the easternmost side of the Hexi Corridor, as an example, from 1971 to 2000, overfarming in the middle reaches led to an accumulated reduction of 30×10^8 m^3 in the water flowing into the downstream oasis, with an average reduction rate of 0.83×10^8 m^3 year^{-1}. In 2000, the per capita water consumption was 1552 m^3 in the middle reach oases but only 537 m^3 in the downstream oasis. The shortage of fresh river water and the increase in farmland irrigation forced local farmers to dig wells and extract groundwater to irrigate their crops in the downstream oasis (Xue et al. 2015). Groundwater has been used to flood irrigated cropland over many years. Frequent flood irrigation has led to a decrease in the groundwater table and an increase in the salinity of the groundwater because of intense evaporation and high salt concentrations. Field surveys and literature analysis show that the average value of total dissolved salt content (TDS) in the downstream oasis groundwater increased from 0.7 g l^{-1} in the 1950s to 2.5 g l^{-1} in 2005. In the northern oasis region, TDS reached 6–10 g l^{-1} and even as high as 16 g l^{-}1 in the northern end area of the oasis (Li et al. 2006; Zhu et al. 2007). Similar patterns in water quantity and quality degradation from the overuse of water resources also exist in other arid areas (Wada et al. 2010), such as the Heihe Basin, the Sule River Basin, and the Tarim River Basin in northwestern China and the Aral region in Central Asia.

Therefore, unsustainable water use and management first led to a decline in groundwater levels and deterioration of water quality. After the groundwater table lowered, natural and artificial vegetation dried, and shelter forest systems protecting oases became degraded because the tree roots could not absorb water from the shallow soil layer. Without the protection of the shelter forest, dunes moved toward the oases and buried farmlands and settlements (Xue et al. 2015). Since the 1950s, desert areas located in the north of the Shiyang River Basin have encroached southward into the oasis by 50–70 m and destroyed 400 ha of farmland. Desert areas located in the west have moved east by 30–60 m and have destroyed 467 ha of farmland (Zhang et al. 2004; Sun et al. 2005; Dong et al. 2010). Irrigation with saline or high-sodium water resulted in the formation of alkaline soil, damaging the soil structure. The farmland areas were abandoned because of their high salinity levels and low productivity. Saline wasteland and abandoned farmland areas increased the danger of wind erosion and aeolian desertification. According to research conducted in the downstream oasis of the Shiyang River Basin, 70% of local farmland has been affected by aeolian desertification, and 85% has been affected by different degrees of salinization (Sun et al. 2007). Based on satellite remote sensing, aeolian desertification rapidly developed from the 1970s to the 1990s in the lower part of the Shiyang River Basin. Aeolian desertified land has increased by 1.13×10^4 ha at the margins of the downstream oasis (Zhang et al. 2004). Severe aeolian desertification has resulted in the lower reaches of the Shiyang River Basin becoming one of the primary sources of sand-dust storms in China (Wang et al. 2004).

4.4 Conclusion

Although climate variability and human activities are the leading causes of aeolian desertification, the natural environment of areas with aeolian desertification also plays an important role. The vulnerability and low carrying capacity of ecosystems are the main characteristics of the natural environments in arid areas. Generally, the vulnerability of ecosystems in arid areas makes these areas more prone to degradation than humid areas when short-term climate variability occurs. The lower carrying capacities of arid ecosystems result in human activities having a larger impact there than in other areas. This scenario indicates that land use and management in arid areas need more attention than those in other regions. Given global warming, extreme events can cause the arid ecosystem to become degraded rapidly. Developing sustainable land management policies to cope with future climate change is essential and urgent.

In addition, when carrying out aeolian desertification prevention and control, appropriate policies and measures should be developed according to regional characteristics. For example, in dry subhumid areas, reducing excessive farming may be the main means to control aeolian desertification, but in semiarid areas, a reasonable animal number based on the local carrying capacity and future climate change needs to be determined. Sustainable water use and management are the fundamental solution for aeolian desertification in the irrigated oases of arid areas.

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