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10.1 Introduction

The dryland in China is defined as the areas where the annual precipitation is less than 200 mm and the humidity index is smaller than 0.20. Therefore, the arid areas in China are located in the central part of Eurasian continent, including all of Xinjiang, Hexi Corridor in Gansu, and the west of the Helan Mountain of Inner Mongolia. Its geographical location is between longitude 73–125° E and latitude 35–50° N. This region occupies approximately 2.02 million km², accounting for more than 21% of China's total terrestrial area (Ci et al. 1994).

The Kunlun-Altun-Qilian Mountains are the southern boundary of the area which combined with the Qinghai-Tibet Plateau blocks the water vapor from the Indian Ocean. Altai Mountain is the northern boundary, blocking the water vapor from the Arctic Ocean (Fig. 10.1).

Tian Shan Mountains lie in the middle of the region and form the landscapes of alpine, inland basins, Gobi Desert, and widespread sandy desert. The average annual temperature is 6.1 °C (1971–2000), and the average annual precipitation is only 120 mm (1971–2000), both with uneven spatial and temporal distributions. The extreme minimum temperature –51.5 °C occurred in the Altai Mountain, and the extreme maximum temperature 48.9 °C occurred in the Turpan Basin.

This inland region is controlled by continental climate, with little rainfall throughout the year and strong evaporative potential. The average annual precipitation is only 130 mm, with uneven spatial and temporal distributions. The highest rainfall occurs at the eastern end of the Tian Shan Mountains in the Ili River Valley,

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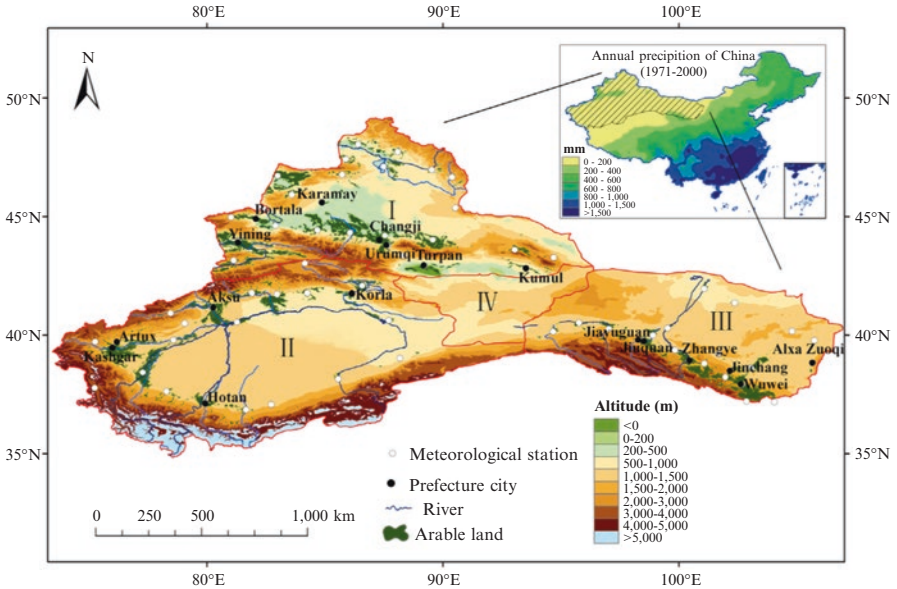


Fig. 10.1 Distribution of arid and semiarid regions of China (Shen et al. 2013) (The embedded figure shows the distribution of annual precipitation, precipitation in the arid area is generally less than 200 mm/year)

which could amount up to 800 mm/year or above; annual precipitation is generally less than 50 mm in the artificial oasis areas, where most agricultural activities exist. However, the potential evaporation in this arid region can be as high as 3,200 mm/year, eight to ten times the annual rainfall. The hyper-arid region is thus one of the most arid regions in the world (Shen and Chen 2010).

10.2 Physical Nature of Arid Lands

10.2.1 Climate

The annual average temperature in the arid areas of China varies from region to region. It is higher in the southern parts of the region and in the basins. For example, it is with 8–10 °C in Junggar Basin, with 10–13 °C in Tarim Basin, and with 7–9 °C in Alashan Plateau (Table 10.1).

Arid land of China lies in the middle latitude of the Northern Hemisphere, where it is affected by westerly wind. Due to complex influences of various factors including location (in the hinterland of Eurasia), rapidly uplift of the Qinghai-Tibet Plateau, effects of middle-scale landform, and feedback of earth surface on climate, precipitation in the region is rare and unevenly distributed (Chen 2010).

Generally, precipitation in the western part of the arid land is more than that in the eastern part, for example, precipitation in Ili River Valley is about five to six

Table 10.1 Annual average temperature of different decades in the different regions of the arid areas in China (in °C)

	Junggar Basin	Tarim Basin	Tian Shan Mountain	Hexi Corridor	Alashan Plateau	Arid areas of North China
1960s	6.0	11.0	0.6	7.2	7.1	6.4
1970s	6.0	11.1	0.8	7.3	7.4	6.5
1980s	6.5	11.4	0.7	7.4	7.8	6.8
1990s	6.9	11.6	1.2	8.0	8.4	7.2
1961–2000	6.4	11.3	0.8	7.5	7.7	6.7
2001–2007	7.4	12.0	2.0	8.6	8.7	7.8

Table 10.2 Annual average precipitation of different decades in the different regions of the arid areas in China (in mm)

	Junggar Basin	Tarim Basin	Tian Shan Mountain	Hexi Corridor	Alashan Plateau	Arid areas of North China
1960s	176.6	39.8	316.5	102.4	93.9	145.8
1970s	173.0	43.7	315.2	112.7	102.8	149.5
1980s	202.4	51.2	319.8	109.3	83.1	153.2
1990s	213.8	55.1	356.2	111.3	101.2	167.5
1961–2000	191.5	47.5	326.9	108.9	95.2	154.0
2001–2007	226.8	57.5	366.2	121.5	99.7	174.3

times of that in Alashan Plateau. A higher rainfall belt consisted of many isolated centers with mean annual precipitation of 500–1,000 mm lies between arid land of central Asia and arid land of China (Table 10.2).

This higher rainfall belt is the result of enforced uplift of the westerly airstream on the windward slopes of the Tian Shan Mountains and the Pamirs. In basin and plain, annual precipitation is usually less than 50 mm, and even less than several millimeters, for example, at Tuokesun station in the Turpan Basin, the recorded mean annual precipitation is only 7.6 mm. However, there are plentiful solar and heat energy resources in the basin and plain. In the area including basins and plains in Xinjiang Uygur Autonomous Region, the Hexi Corridor in Gansu, and the Alashan Plateau in Inner Mongolia Autonomous Region, the global solar radiation ranges from 170 to 210 W/m², taking second rank only to the Qinghai-Tibet Plateau. The photosynthetically active radiation (PAR) is about 80–100 W/m², and the mean annual total duration of sunshine reaches to 2,550–3,500 h, taking the first place in China.

Arid land of China has also plentiful wind energy resources. Spatially, the amount of wind energy resources in the northern part, the plain, and the Gobi and the fringe of basins in arid land of China are generally larger. The narrow mountain passages and mountain passes where the air current passes through are the places with the most plentiful and larger exploitable wind energy resources. It should be pointed out, however, that various disastrous weather and climatic events, such as drought, cold wave, gale, sandstorm/salt storm, blizzard, freeze injury, hail, frost, rainstorm and mud-rock flow, dry-heat wind, etc. occur frequently, which result in

a lot of losses of properties in arid land of China. In recent 30 years, arid land of China experiences significant increase in temperature and a slightly increase in precipitation under the background of global warming. Since 2000, increasing trends in temperature and precipitation have kept or even have strengthened to a certain extent. However, the intrinsic nature of arid climate in drylands of China is still sustained.

10.2.2 Geomorphology

Arid land of China is located in the hinterland of Eurasia and the northern fringe of the Qinghai-Tibet Plateau (or the high Asia territory). Unique geographic location creates conditions for formation and evolution of the particular landforms, vegetation covers, and pedo-types. The geomorphologic and climatic distribution patterns featured by mountain alternating with basin enrich greatly natural landscape in arid land of China and provide ideal bases for living and developing of human being in arid land and hence prompt the formation, development, and evolution of the artificial oases by storing and diverting water from inland rivers.

Geological and geomorphologic patterns in arid land of China are mainly comprised of grand high mountains and large lower inland basins, featured by mountain alternating with basin. The Altai Mountains, the Junggar Basin, the Tian Shan Mountains, the Tarim Basin, and the Kunlun Mountains-Arjin Mountains distribute from the north to the south in turn (Chen 2010).

Various grand mountains are usually called as “wet islands” and are water sources in arid land. Snow-icing, periglacial, and fluvial action are common external forces sculpturing various alpine landforms. Basin is the water consumption region and is very dry. Formation of main landforms in basins is related to aridness. Sand dune, Gobi, and bad land can be seen everywhere, which form the typical desert landscape in arid land of China. However, the loneliness landscape is occasionally interrupted by oasis dotted in them. The arid geomorphologic pattern is seldom seen in other arid land of the world. The distinctive landforms in arid land of China, such as Yadan, Mud volcano, Karez, Desert Highway, etc., are praiseworthy.

The major rivers include the Tarim River, Ili River, and Heihe River. The Tarim River is the largest inland river in China and originates from the confluence of the Aksu River, Hotan River, and Yarkand River. The Ili River is located inside Tian Shan Mountain and is affected by westerlies, so more rain falls in this basin than in the other areas in Northwest China. The annual runoff is 17 billion m³ in the Ili River, which is the largest in all of the river basins in the arid areas of China.

Except the Erjis River, not any surface and ground runoff in arid land of China is connected with remote oceans and other watersheds in semiarid and humid area. The flows of mass, energy, and information in arid land of China have obvious locality. Every river basin in the region has its tail lake and its constant circling system in lower air layer. Water circulation is characterized by local circle in each of river valley. The formation area and the consumption area of the water resources are separated by vast desert or Gobi. Water flow as a tie links the mountain area and

the basin. As a result, a unique and completed local inland water circling system, or an organic and interacted mountain in forest and grassland-oasis-desert system, is formed by taking water circulation as the main and the bio-system in a tight link.

The amount, quality, and spatiotemporal distribution of water resources are obviously uneven in different geographic environment of the arid land. Water resources are comprised mainly of snowmelt water. Glacier and snow, groundwater, and lake and surface runoff as different types of water present jointly in a shorter-arid watershed. Water resources are sensitive to the influence of global warming. However, presently, water resources in arid land of China sustain a roughly constant condition owing to the unique water circling process.

Accumulated snow and glaciers play an important role in the discharge regulation of these inland rivers and reduce the variations in the inter-annual discharge at the mouths of mountain valleys. Owing to the alternately distributed terrain of high mountains and basins, all the rivers form into centripetal stream systems. Some of the rivers with small discharges soon disappear in the desert region after flowing out of the mouths of the mountain valleys, while a few larger rivers flow to depressions to form inland lakes. Such distribution characteristics of water resources decide the close interconnection of surface runoff and groundwater resources and also lay a basis for the economic development and hydrological regimes in the middle and lower reaches of the river basins. Under the influence of such water resource distribution and dry climatic conditions, the middle and lower reaches are macroscopically eco-environment fragile belts and thus seriously influenced by the hydrological regimes (Chen 2010). Since the 1940s, great changes have taken place in both the hydrological regimes and ecological environment in these areas due to population growth, socioeconomic development, and large-scale exploitation of water and land resources. Such changes seriously affect the sustainable development of human habitats.

10.2.3 Terrestrial Ecology or Vegetation

In recent decades, land use, global climate change, etc. have exerted enormous effects on habitat of various plant species in arid land of China, and as a result, plant diversity is seriously threatened and some ecological and geographic systems verge on collapse. To get endangered ecosystem out of dangerous condition, it is necessary to protect effectively and utilize rationally these ecosystems so as to realize sustainable development of society and economy in arid land of China (Chen 2010).

Arid land of China is located in the eastern section of the Africa-Asia desert. Varied natural geographic types and distinctive and extreme habitats are presented in the region in the special regional environment. Under this habitat condition, latitude, longitude, and altitude zonality of vegetation stamped with the brand of “desert” are clear.

During the historical period, the natural geographic environment in the region has changed repeatedly, which provided conditions for the contact, mix, and particularization of the components of florae. As a result of these, the flora of the region

presents striking xerophytic and distinctively temperate characteristics. The flora shows a great disparity and distributes unevenly. The flora with an ancient origin has fewer endemic genera, but has more endemic species, in which seed plants reach to 109 species. These seed plants occupy an important position in the vegetation component and constitute xerophytic and extra-xerophytic shrub communities.

The desert vegetation constitutes the base belt of the vertical belts of mountain vegetation. The desert base belt is structurally simple and differs obviously in different aspects. In addition, after long-term evolution, the region carries within itself the plentiful and distinguished resources of plant species. These halophytic, xerophytic, and short-lived vegetations, wild fruit trees, etc. have irreplaceable advantages in aspects of resisting adverse circumstance, raising efficiencies of photosynthesis and water use, and breeding of fruit trees, and hence provide plentiful gene resources for human being.

Vegetation growth in most areas of arid and semiarid regions in Western China experienced an overall increase over the past two decades, which supported the conclusion that part of Northern China has undergone reversal of desertification since the 1980s (Zhang et al. 2003). According to the national monitoring data on desertification in Western China, the annual desertification rate decreased from 1.2% in the 1950s to 0.2% in 2003 (Piao et al. 2005).

The increases of temperature and pan evaporation may bring some adverse ecological effects. Recent research results show that the vegetation coverage and NDVI in the arid region of Northwest China exhibit an increased trend before 2000. However, the trends reversed to decrease since 2000 (Fig. 10.2) (Zhao et al. 2011; Li and Chen 2014).

Average rainy season NDVI in arid and semiarid regions both increased significantly during the period 1982–1999, while that in the Taklimakan (Takla Makan) Desert did not show statistically significant trend over time ($R^2 = 0.05$; $P = 0.366$), suggesting the stability of the NDVI time series used in this study to identify interannual variations in green vegetation in arid and semiarid regions (Fig. 10.2). Over the past 18 years, average rainy season NDVI in arid regions increased by 0.0006 per year, with an annual increase rate of 0.5% ($R^2 = 0.31$; $P = 0.017$). The relative annual increase rate of 0.8% in rainy season NDVI ($R^2 = 0.58$; $P < 0.001$) in semiarid regions exceeded that of arid regions (Piao et al. 2005).

10.2.4 Soil

In the formation process of natural soil, two material circulations, the grand geological circulation as the base and the small biological circulation as the condition. These must coexist and interact before the soil with a certain profile and fertility level forms. The soil formation process in arid land has obvious vertical zonality. During geological historical period, especially since early Pleistocene, a glacial epoch alternated with an interglacial stage. On alpine glacial deposits at different times, organisms and generated soil evolved simultaneously, and accumulated an organic horizon with different properties. On the old and new moraine

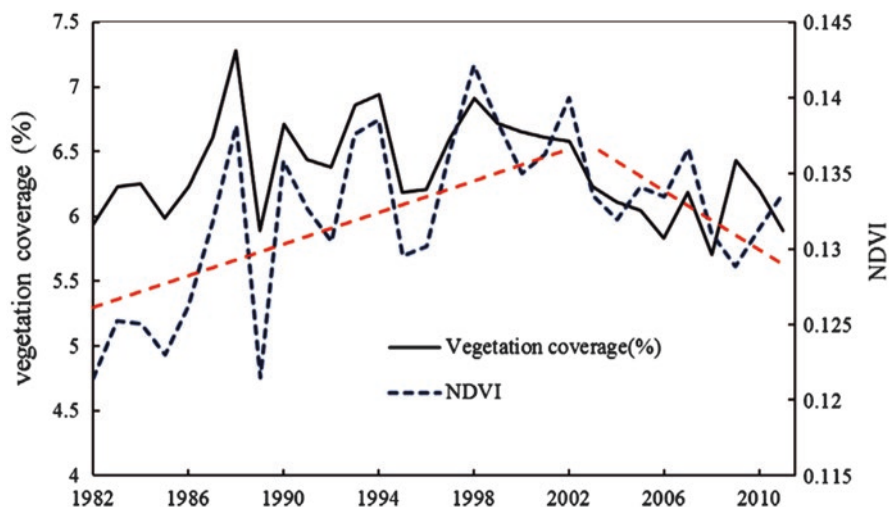


Fig. 10.2 Dynamic changes of vegetation area and NDVI in the Northwest China (Chen et al. 2015)

parent materials, primitive soil and climax soil developed separately. During interglacial stage, large area of melted water from alpine snow and glacier conveyed not only lots of solid runoff materials but also solvable salts and animal remains to the plain. In soils on shoals of ancient lakes, old river terraces, and fringes of alluvial fans, single gypsum layer or multiple gypsum horizons formed, and xerosol, halogenic soil, and anthropogenic soil developed separately. It is worth noting that in the deep soil profile, many soil genetic horizons developed and were preserved. These are the formative layer for determining ancient environment under global change (Chen 2010; Zhang et al. 2014).

The soil classification in the arid areas of China is shown in Table 10.3. Based on the pedogenesis, the soils in the arid areas of China are classified to 8 soil orders and 13 soil great groups (Chen 2010).

10.3 Anthropogenic Nature of Arid Lands

10.3.1 Land Use

Land use and cover change (LUCC) is increasingly recognized as a sensitive indicator of earth systems (Zhou et al. 2008). In the arid zone of Western China, rapid and frequent LUCC has been observed around the oasis where the majority of the regional population is concentrated. The observed changes largely reflect the impact of human activities on the fragile natural environment. Changes became most noticeable from the early 1990s when local governments launched and supported an agricultural development plan (Hu and Li 2010). It is a commonly held belief that

Table 10.3 Soil classification in the arid areas of China (Chen 2010)

No.	Soil order	Soil great group
1	Primosols	Gelic-orthic primosols
		Aridi-sandic primosols
2	Cambisols	Matti-gelic cambisols
3	Alfisols	Calci-ustic alfisols
4	Isohumisols	Calci-ustic isohumisols
5	Aridisols	Calci-cryic aridisols
		Calci-orthic aridisols
6	Halosols	Aridi-orthic halosols
		Takyri-alkalic halosols
7	Gleysols	Histi-stagnic gleysols
		Histi-orthic gleysols
8	Anthrosols	Gleyi-stagnic anthrosols
		Siltigi-orthic anthrosols

Table 10.4 Status of land desertification in several main regions in northwest China (unit: 1,000 ha)

Region	Desertified land area	Total land area (%)	Oasis area (%)	Severe desertified land (%)	Potential desertification area	Total land area (%)
Xinjiang	304.71	1.82	43.14	24.99	154.96	0.92
Hexi Corridor	252.22	9.15	19.6	31.82	168.94	6.13
Alxa plateau	118.0	6.1	–	61.28	60.22	3.1

the rapid expansion of farmland (irrigated land, primarily cotton fields) and its subsequent abandonment or neglect would lead to increasing soil salinity and ultimately to desertification (Zhang et al. 2003; Ma et al. 2011).

In the arid zone of Western China, a widely accepted belief is that rapid farmland expansion and the subsequent abandonment of the farms, or their mismanagement, would lead to soil salinization and desertification (Sun and Zhou 2016).

Land desertification is developing rapidly due to the erodible surface of sandy deposits, frequent wind erosion, and over-exploitation of water and land resources. As shown in Table 10.4, the desertified land accounts for about 19–43% of the total. The severely desertified land has now reached 25–61.3% of the total desertified area. Besides the desertified land in Northwest China, there are about 3.8 Mha of potential desertification area (Wang and Cheng 2000).

There are three factors mainly responsible for the rapid development of modern desertification in arid Northwest China, namely, wind erosion due to the lack of protection, destruction of vegetation due to misuse of water resources and soil salinization, and sand dune encroachment of the oasis. Of particular importance are the latter two factors. For example, 83% of the total desertified land area in the Tarim Basin has been attributed to the latter two factors. From variations of the desertified land area during the period of 1949–1993 in the middle and lower reaches of Tarim and Heihe River basins, it can be seen that the development rates of land desertification are different for different periods.

The most rapid development period of desertification for the midstream regions of the inland river basins occurred in the 1970–1980s, with the quickest expansion rate of desertification occurring in the most recent half century (0.76% in the middle reach of Tarim River basin and 2.6% in the middle reach of Heihe River basin). Since 1990 the rate of desertification in the Tarim and Heihe River basins was reduced by 0.27% and 0.5%, respectively, and in local places, desertification has been arrested or even reversed. However, desertification in the lower reaches of inland river basins still tends to increase, and, in the lower reach of the Tarim River basin, the area of moving sand dunes has increased from 44.34% in 1958 to 64.47% in 1993 with the severe and very severe desertified sand area increasing by 3.12% and 3.56%, respectively. Since the 1960s the desertification development rate in the lower reach of the Heihe River basin has increased from 5.0% to 6.8% (Wang and Cheng 2000).

In addition, the oasis in the arid Northwest China is facing severe problems of soil salinization. In the Xinjiang Uygur Autonomous Region, there are 1.2 Mha of salinized cultivated land, occupying 31.1% of its total area. In the Hexi Corridor region, there are now 0.926 Mha of salinized cultivated land, occupying 14.7% of the total area (Wang and Cheng 2000).

10.3.2 Irrigation

Water is one of the essential resources in arid and semiarid regions especially for agriculture. The arid region in Northwestern China is one of the mostly water-stressed regions in the world (Shen and Chen 2010). This region is also an important food and cotton-producing region in China, but the imbalance between water supply and demand is also very prominent in the region.

Agricultural water consumption accounted for more than 95% of the total water use in the region, becoming the main factor affecting water resource allocation into the socioeconomic sectors and ecosystems in the region. The shortage of water resources has become a major limiting factor for the socioeconomic development in the areas. Even in places with relatively abundant water resources, it is not sufficient to meet the water demand of crop growth all the year round. With increasing acreage of crop growing, unreasonable crop planting structure, high irrigation quota, and low water use efficiency, the shortage of water resources is becoming increasingly serious.

Crop and irrigation water requirements for five main crops, including wheat, corn, cotton, oilseed, and sugar beet, from 1989 to 2010 were calculated, and the spatiotemporal variations were analyzed (Shen et al. 2013). The results suggested that the demand of irrigation water in the arid areas of China showed increasing trend during the past two decades, which mainly resulted from fast increase in cotton cultivation areas, because irrigation water requirement for cotton was much larger than other crops. The changes in cotton-growing area significantly affected the spatial pattern of water demand (Hu et al. 2013).

A total of 44.2 billion m³ water was withdrawn for irrigation in year 2010. Larger amounts of water were consumed for crops in Northern Xinjiang and Tarim River basin than in Qilian-Hexi region.

Irrigation water requirement reaches its maximum in July and August. It is revealed that the critical period for water supply is during April and May through comparing the monthly irrigation water requirement with water availability, i.e., river discharge. Even though the annual water resources are much larger than the requirement, for some basins, there is severe physical water shortage during the critical water use period in April and May. The water resource supply is expected to be facing more difficulties in the future.

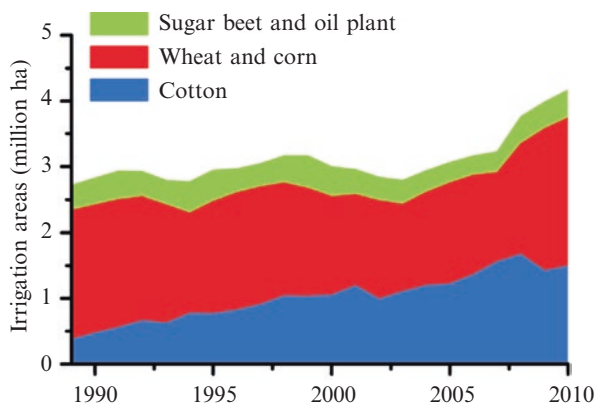
The irrigation water requirement in 2010 has reached 44.2 km³, with a net increase of 12.9 km³ compared with that in 1989. Among the five major crops, cotton was the most water-consuming crop in the region. The irrigation water demand for cotton reached 20.7 km³ in 2010, accounting for 46.8% of the total water consumption. In terms of water irrigation intensity, sugar beet consumed the most with 7,100 m³ ha⁻¹ year⁻¹, followed by cotton, corn, wheat, and oilseed crops with 6,700 m³ ha⁻¹ year⁻¹, 4,920 m³ ha⁻¹ year⁻¹, 4,560 m³ ha⁻¹ year⁻¹, and 3,520 m³ ha⁻¹ year⁻¹, respectively (Shen et al. 2013).

10.3.3 Crops and Cropping Pattern

Abundant radiation and heat resources in this region make it an ideal place for thermophilous and photophilous crop growth, so it becomes an important high-quality and also high-yield cotton production zone (Xu et al. 2011). Other crops like wheat and corn are also widely cultivated in this region. All arable cropland is in artificial oases established at the edge of the deserts through which inland rivers flow. Oases rely on surface water and groundwater for irrigation (Shen et al. 2013). At the end of 2010, the total area of farmland was 4.9 million ha, effective irrigation reached 4.682 million ha, and the total crop growing area amounted to 5.55 million ha. Cotton-growing area was 1.5 million ha, and its acreage and production accounted for 31% and 42.7% of the country's total, respectively. According to the Bureau of Xinjiang Water Resources (2011), the annual withdrawal for irrigation reached to 48.83 billion m³, accounting for 91.3% of the total water consumption in Xinjiang in 2010.

The irrigated area in northwestern arid regions increased from 2.7 million ha in 1989 to about 4.4 million ha (Fig. 10.3) in 2010, and the fastest increase goes to cotton-growing land. In the irrigated farmland, wheat- and corn-growing acreage was about 2 million ha, with little change in the total over the past 20 years. Beet and oilseed acreage was approximately 0.4–0.5 million ha, which slightly declined in recent years. The cotton-growing area showed the fastest increase, from only 0.4 million ha in 1989, mainly distributed in Tarim River basin, to 1.5 million ha by 2008. In 2010, the cotton-growing area slightly declined to 1.3 million ha, still accounting for about one third of the total cropping areas.

Fig. 10.3 The variations of irrigated crop-growing area in the arid areas of China (Shen et al. 2013)



10.4 Climate Variability and Impact on Livelihood

Average temperature has risen above the global average. Over the past half century, the rate of temperature rise in the northwest arid area is up to $0.34\text{ }^{\circ}\text{C}/10\text{a}$, which is significantly higher than the global average by $0.12\text{ }^{\circ}\text{C}/10\text{a}$ (IPCC 2013). Analysis showed that a significant temperature rise occurred in the late 1980s. During 1960–1986, the average temperature increased to a lesser extent. In 1987, the average annual temperature in the northwest arid area showed an abrupt change, and the elevated rate of $0.517\text{ }^{\circ}\text{C}/10$ years showed an increasing trend to accelerate (Fig. 10.4).

Temperature experienced a “sharply” increase in 1997; however, this sharp increasing trend has turned to an apparent hiatus since the twenty-first century. The dramatic rise in winter temperatures in the northwest arid region is an important reason for the rise in the average annual temperature, and substantial increases in extreme winter minimum temperature play an important role in the rising average winter temperature (Chen et al. 2015).

In the arid region of China, temperature and precipitation were “sharply” increasing in the past 50 years. The precipitation trend changed in 1987, and since then, in a state of high volatility, during the twenty-first century, the increasing rate of precipitation diminished.

Glacier change has a significant impact on hydrology in the northwest arid area, and glacier inflection points have appeared in some rivers. The melting water supply of the Tarim River basin makes up a large portion of water supplies (about 50%). In the future, the amount of surface water will probably remain at a high state of fluctuation.

Under CMIP5-RCP scenarios of RCP 2.6, RCP 4.5, and RCP 8.5, both air temperature and precipitation are showing increasing trends in the arid region of China, and warming trend is more significant. In 2046–2075, the temperature will increase by $1\text{--}2\text{ }^{\circ}\text{C}$ in Southern Xinjiang and by more than $3\text{ }^{\circ}\text{C}$ in Northern Xinjiang compared with that in the historical period of 1971–2000. Annual

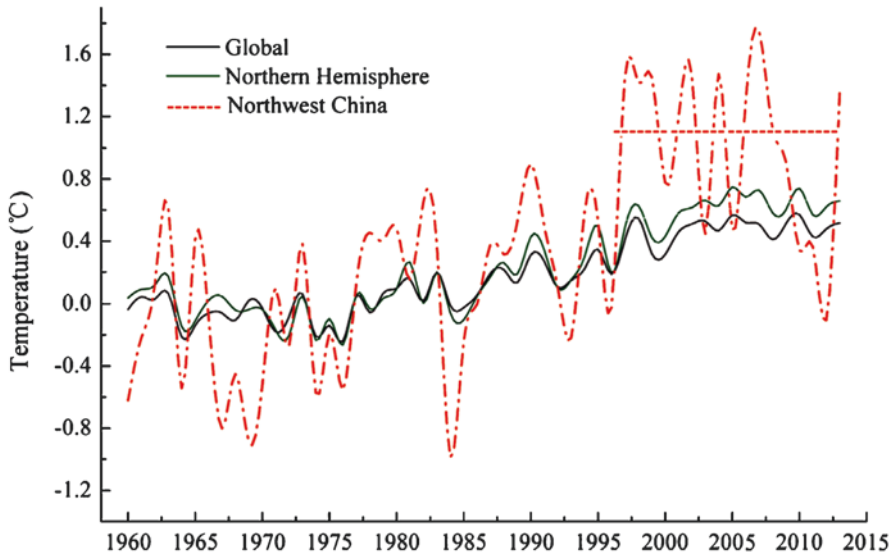


Fig. 10.4 Trends of temperature in the global, Northern Hemisphere, and arid region of Northwest China during 1960–2013 (Chen et al. 2015)

precipitation will also increase from 120 mm in the past (1971–2000) to 155–165 mm (Guo and Shen 2016).

The air temperature will increase in two terms of the twenty-first century in the whole arid region of China. The average annual temperature in the arid region of China was 6.1 °C during 1971–2000, which will increase to 7.9 °C, 8.0 °C, and 8.3 °C during 2016–2045 and 8.4 °C, 9.1 °C, and 10.3 °C during 2046–2075 under RCP2.6, RCP 4.5, and RCP 8.5 scenarios, respectively. Warming trend is more significant under the high emission scenario than under the low emission scenarios. Compared with the temperature in the historical period, the predicted temperature under the highest emission scenario in the middle term of the twenty-first century in the ARNWC increased by 67% (Guo and Shen 2016).

On a monthly scale, the temperature shows an increasing trend in all seasons, which is more significant in the summer and winter, most particularly in July. Under the highest emission scenario RCP 8.5, temperature will increase by more than 5 °C (Fig. 10.4). Spatially, the annual temperature shows a warming trend all over the arid region of China, which is more significant in the Northern and Eastern Xinjiang. In 2046–2075 under different emission scenarios, temperature will increase by 1–2 °C in Southern Xinjiang and by 3 °C in Northern Xinjiang and especially by more than 5 °C in some areas of the Tian Shan Mountains in Northern Xinjiang (Fig. 10.5).

Precipitation is one of the main water supplies to surface water resources and greatly affects the variation in water resources in the arid region of China. In a similar trend of temperature, annual precipitation will also increase in the two terms of the twenty-first century in the whole region. The increase trend is more significant

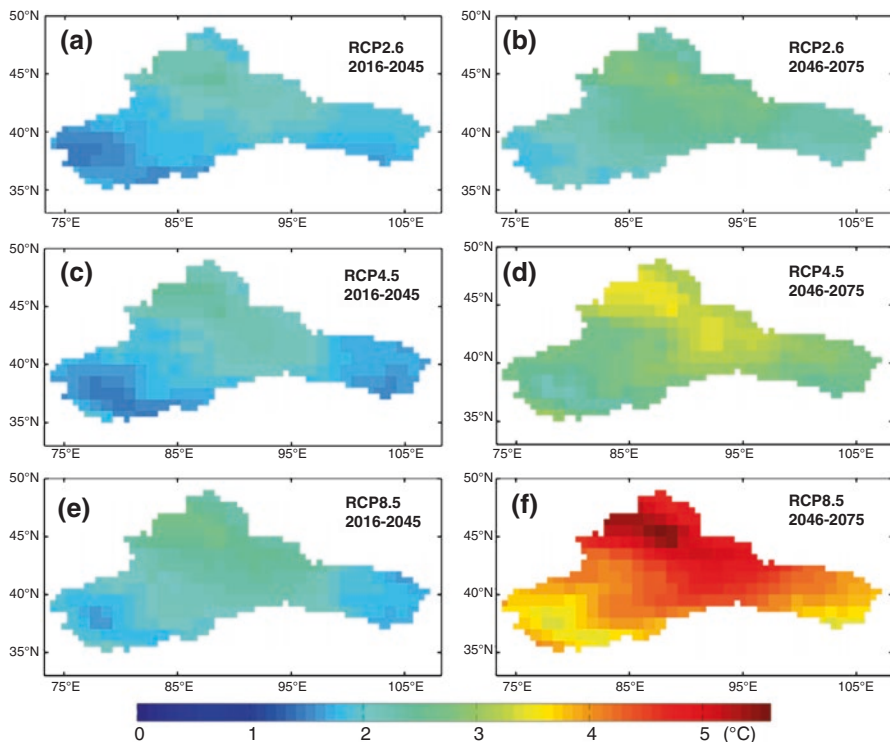


Fig. 10.5 Distributions of annual temperature change from 1971–2000 to the periods of 2016–2045 and 2046–2075 under three scenarios, respectively (Guo and Shen 2016)

under the high emission scenario than under the low emission scenarios and which is more significant during the period of 2046–2075 than that during 2016–2045. The average annual precipitation in the arid region of China is 120 mm during 1971–2000, which will increase to 141 mm, 145 mm, and 147 mm during 2016–2045 and 150 mm, 154 mm, and 165 mm during 2046–2075 under RCP 2.6, RCP 4.5, and RCP 8.5 scenarios, respectively.

From the seasonal variations, the precipitation shows an increasing trend in all seasons, which is more significant from January to August (Fig. 10.6). Spatially, monthly precipitation increases more significantly in the mountains, especially in the Tian Shan Mountains, the upstream of the Tarim River, and the Kunlun Mountains.

10.5 Recent Trends in Arid Lands and Future Scope

It is a commonly held belief that the rapid expansion of farmland (irrigated land, primarily cotton fields) and its subsequent abandonment or neglect would lead to increasing soil salinity and ultimately to desertification (Zhang et al. 2003; Ma et al. 2011).

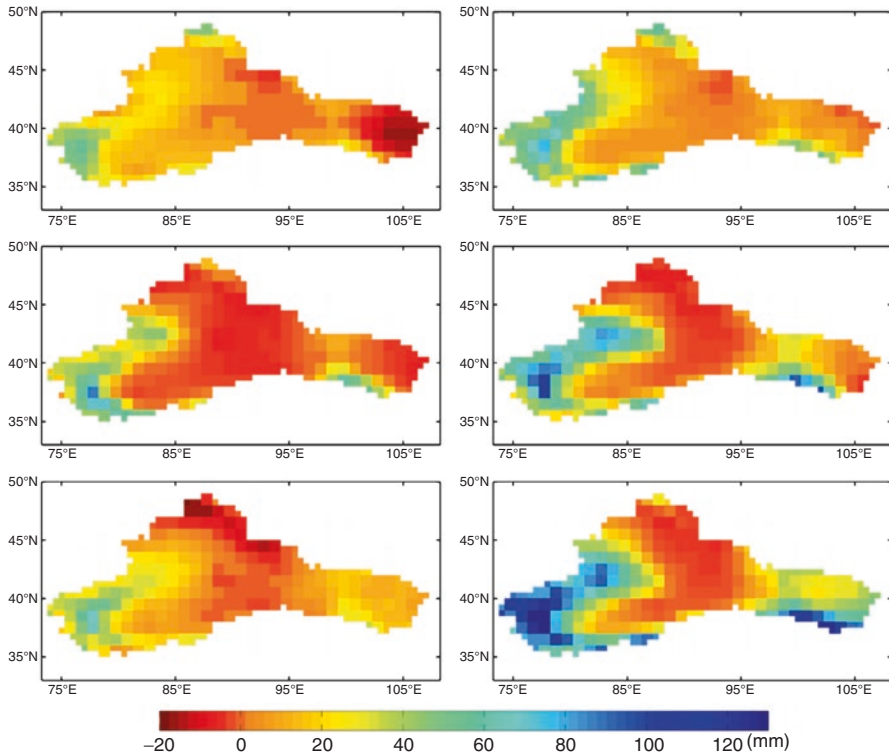


Fig. 10.6 Distributions of annual precipitation change from 1971–2000 to the periods of 2016–2045 and 2046–2075 under three scenarios, respectively (Guo and Shen 2016)

The mountain glaciers melt, and glacial retreat has been accelerated by climate change, particularly by the impact of winter temperatures. In the northwest arid area, runoff is dependent on glaciers. Moreover, since changes in glaciers have a significant impact on water resources and their annual portion of water supplies, glacier inflection points have appeared in some rivers. Rivers with comparative development of glaciers and more glacial melt water supply may have runoff of high volatility for a long period of time. In addition, glacier inflection points will appear, glacial melt water will reduce, glaciers' swap function will decline, and runoff variability will increase due to the impact of precipitation anomalies. In the context of global climate change, the frequency and intensity of extreme hydrological events in the northwest arid region are increasing, which affect the safety of the water system and increase water resource vulnerability and uncertainty (Chen et al. 2015).

Agricultural land in the arid areas of China mainly located at the oasis with irrigation sourced from river water, which mainly originated from snow/glacier melting and summer rainfall in mountain areas. Climate change has large impacts on not only the quantity of river discharge but also river hydrographs in the northwestern arid basins in China. The latter is more important with regard to water supply.

In some river basins, even though the annual water resource can meet the irrigation requirement, there are huge deficits in some critical water-demanding periods, such as in April, May, and even June in some specific river, i.e., Hei River. This kind of seasonal water shortage reinforced the water stress in the region. On the other hand, the unprecedented enlargement of the crop-growing area has resulted in rapid increase in irrigation water demand and already caused ecological degradation in the lower reaches of the rivers (Shen and Chen 2010), such as the terminal lake shrinkage and desiccation of the floodplain in down stream reaches of Tarim River (Chen et al. 2012) and Hei River (Zhao et al. 2007). It is urgent to call for wise water management such as water price regulation, crop planting pattern adjustment, as well as water-saving technologies in this hyper-arid region.

Irrational irrigation patterns and imperfect water infrastructure resulted in the inefficient utilization of water resources, coupled with the rapid expansion of crop acreage, creating huge agricultural water consumption. The demand for water resources has further expanded in recent years with the development of society and the economy and a rapid increase in population. Water shortage situations are becoming increasingly serious. Meanwhile, this region is the most sensitive area to global climate changes. Climate change will further exacerbate the uncertainty of the water supply and increase extreme hydrological events in this region, such as floods and droughts. Under the combined effects of climate change and human activities, this region's water resource system, which is based on snow and ice meltwater, has become very fragile. Rising temperatures caused seasonal variations in meltwater runoff, thus reducing the stability of the water cycle system and the renewability of water resources and increasing the frequency and intensity of extreme climatic/hydrologic events. Climate change and extreme hydrological events have increasingly impacted the water supply system and increased the instability of oasis agricultural production. Increases in temperature and the uncertainty of precipitation directly affect the evaporation and transpiration of croplands, thus increasing crop irrigation water demand (Shen et al. 2013; Wang 2010).

Meanwhile, climate change has affected cropping systems and the layouts of crop varieties (Piao et al. 2010), thus impacting the irrigation water demand. In recent years, the contradiction between water supply and demand has become more severe, which has affected agricultural production, restricted industrial development, and impacted on domestic water use. Water shortages have led to more vulnerable ecosystems in the context of climate change. Water shortages have become a major limiting factor of socioeconomic development and environmental protection in the arid areas of China (Liu et al. 2016).

Future climate change will present greater challenges to the regional water supply and demand balance. Therefore, predicting future climate trends and their impact on future water supplies and quantitatively simulating agricultural water demand (the largest water consumption sector) under future climate change and socioeconomic development conditions is very important to grasp future agricultural water demand changes and to improve future water allocation and management. Meanwhile, proposing effective adaptation strategies according to possible

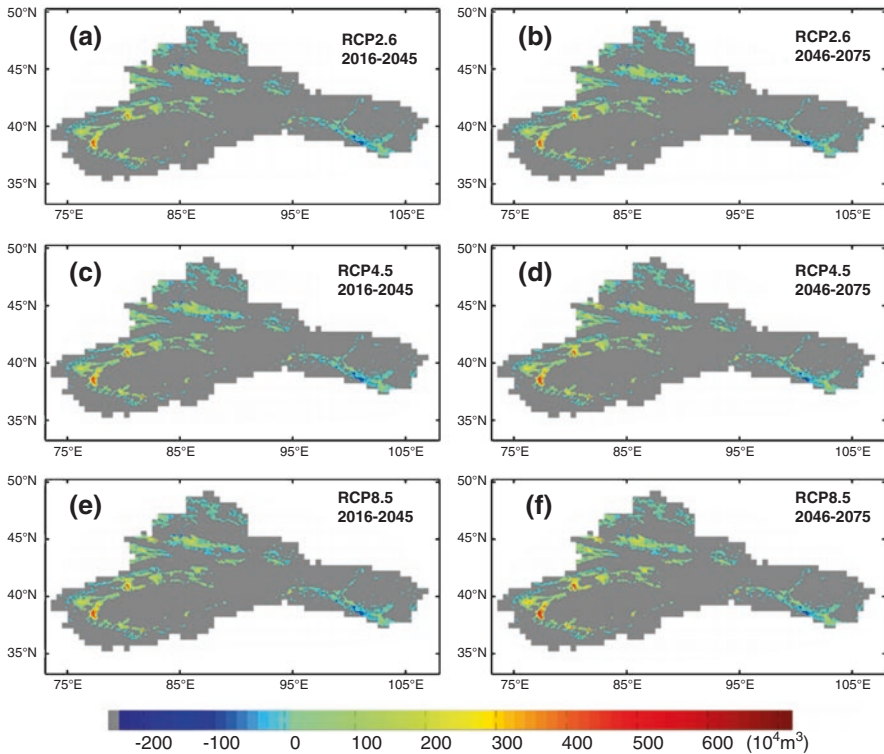


Fig. 10.7 Distributions of annual irrigation water demand (IWD) change from 1971–2000 to the periods of 2016–2045 and 2046–2075 under three scenarios, respectively (Guo and Shen 2016)

changes in the climate, water supply, and agricultural water demand has very important practical significance for the sustainable use and scientific management of water resources, sustainable socioeconomic development, and the restoration of the water and ecological environment in the arid areas of China.

The projections done by Guo and Shen (2016) showed that the irrigation water demand of five main crops (wheat, rice, maize, cotton, and oil crops) under future climate scenarios has an increasing trend and will reach 37.02–37.27 billion m^3 and 37.15–38.9 billion m^3 in 2016–2045 and 2046–2075, respectively. The amount increases by 4.27–6.15 billion m^3 compared with that in the past (1971–2000). Spatially, the largest IWD increases occur in Southern Xinjiang, the Ili River basin, and the Northern piedmont of Tian Shan Mountains (Fig. 10.7).

Annual runoff of the two future periods will only increase by 4.8–7.5 billion m^3 and 5.4–8.5 billion m^3 , respectively, which is equivalent to or even less than the increased IWD of five main crops, and runoff in some river basins even shows declining trends. The potential changes of water supply and demand indicate that the water shortage situation will be more severe in the future. In some basins, the water scarcity index will be over 1, which indicates that the water resources in the

basin will be unable to meet the water demand of the basin. The water crisis is also likely to bring about further deterioration of the ecological problem (Guo and Shen 2016).

Rational planning and effective use of water resources with adherence to “resource-saving” development is the only sustainable and basic ways for economic development and eco-environmental protection in these arid northwest regions of China. In this respect, there are many possibilities such as adoption of advanced irrigation techniques and development of water-saving agriculture. It has been proven that large-scale afforestation to fix shifting sand and the establishment of a protective forest network play a very important role in the control of sandy land desertification. The reversal of desertification in the middle reaches of the Tarim River basin and the Heihe River basin is a good example of these policies (Wang and Cheng 2000).

Land use policies are often designed with the intention of striking a balance between man and the natural environment and between economic development and ecological sustainability. In reality, the implementation of land use policies is affected by various economic, social, political, and environmental changes. Consequently, the outcomes of these policies may not be as intended, and the impact of land policies on environment can be either positive or adverse. Hence, monitoring and understanding the effects of land use policies on environmental issues are theoretically and practically important (Xu et al. 2016).

Climate change affects both the water resource system itself and the social, economic, and environmental changes that are caused by changes in water resource systems and human demand for water resources (Arnell 1999). Global warming will accelerate the process of atmospheric circulation and the hydrological cycle, subsequently affecting the spatial and temporal distribution of water resources and exacerbating water shortages, especially in arid regions. The irrigation water demand depends on evaporation and transpiration during crop growth periods, which are impacted by changes in temperatures and rainfall (Wang et al. 2012).

The expansion of agricultural oasis is a type of land use and cover change (LUCC), which greatly changes the vegetation distribution and surface biogeochemical and biophysical processes, leading to dramatic changes in the water cycle and ecosystem productivity. At the same time, water is the most limiting resource for sustaining crop production in agricultural oasis due to high water demands of the increased cropland area and population (Luo et al. 2003). To address this concern, the effects of expansion and associated management practices in agricultural oasis on regional carbon and water budgets have not been examined quantitatively (Bai et al. 2014).

Water, largely originated from the mountain areas, has been the most critical factor to drive the energy and mass circulation in this region, which responds sensitively to the global climate change; thus, it plays a crucial role in future sustainable development. With the increasing concern of global environmental and ecological degradation, there has been an urgent need to investigate the related water cycle changes.

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