Longjun Ci
Xiaohui Yang

Desertification and Its Control in China

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With 63 figures

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Preface

Desertification is defined by the United Nations Convention to Combat Desertification (UNCCD) as “land degradation in arid, semiarid and dry subhumid areas resulting from various factors, including climatic variations and human activities”. More than 100 countries on six continents and one-fifth of the world’s total population are affected by desertification. Desertification throughout the world expands at an annual rate of 0.5 million km^2.

China is one of the countries affected seriously by desertification. It is estimated that the areas of dryland and susceptible dryland in China (excluding hyperarid areas) are 357.05 and 331.70 million ha, respectively, and in 2004, 263.62 million ha had suffered or was suffering from desertification. The desertification affected area covers seven main dryland provinces and autonomous regions (Xinjiang, Inner Mongolia, Tibet, Qinghai, Gansu, Ningxia and Sha’anxi) and 12 main deserts and sandy lands (the Taklimakan, Gurban Tonggut and Kumtag Deserts, the Deserts in the Qaidam Basin, the Badain Jaran, Tengger, Ulan Buh and Qubqi deserts, and the Mu Us, Otindag, Horqin, and Hulun Buir Sandy lands). The direct economic loss caused by desertification is estimated to be upwards of 5.4 billion RMB annually, and thus desertification and desert expansion have become a bottleneck for sustainable development in the drylands of China. In the past 60 years, the Chinese government has made great efforts to combat desertification, and the tendency of overall expansion of desertification has been initially contained, although desertification continues to expand in some parts.

There are a large number of books available on desertification and related topics in China. This book is not intended to include all the desertification topics in China. We attempt to cover some key topics related to deserts and desertification characteristics and their distribution. We discuss the processes and features of wind erosion, water erosion, soil salinization and vegetation degradation in rangeland, and detailed measures used in the struggle against desertification at field scale. We also consider the eco-productive paradigms for sustainable dryland management at a regional scale.

Desertification is a global environmental issue, and its control needs collective efforts from international societies, including techniques transfer and information exchange. We hope international societies can better understand the seriousness of desertification problems in China and some successful experience and techniques can be shared through this book.

This book stems from the long-term accumulation of scientific knowledge and experience by all the authors. At the same time, a large number of valuable published books and research papers as well as unpublished documents enrich this book. We are indebted to both those who are cited and those who are not cited in this book.

This book was written and complied by Prof. Longjun Ci and Dr. Xiaohui Yang. To maintain a systematic, uniform style, they reviewed and synthesized the contributions by the varied authors while preserving as much as possible their original style and thoughts. A brief introduction to the main authors of each chapter is presented in the Contributors.

We would also like to thank Higher Education Press and Springer for encouraging and supporting this endeavor. We are indebted to Youlin Yang and Prof. Victor Squires for their collaborative work. Thanks are extended to Xiaoli Li, Sanda Chang, Hong Yu and Yange Wang for their efforts in editing, and the assistance of the Edanz Group in copyediting. Sincere thanks are also given to all the authors and staff involved in putting this book together. It was only with their energy and diligence that this book could be completed successfully. This book was also supported partly by the State Key Sci & Tech Support Project (2006BAD26B05) and the National Nature Science Foundation Projects (30671722, 30571529).

Finally, we would like to thank our family for their love, support and understanding.

Due to the inherent limitations of knowledge of the contributors, it is possible that errors may occur in the book. Any criticisms and corrections would, therefore, be much appreciated.

Longjun Ci
Xiaohui Yang
Beijing, 2009

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1 Concept and Global Status of Desertification

Longjun Ci, Xiaohui Yang and Youlin Yang

Desertification is a major economic, social, and environmental concern in the international community. It seriously constrains global food security, eco-security and socio-economic stability, as well as sustainable development. Desertification has had catastrophic effects on the global environment and people's lifes in many developing countries.

Combating desertification is a shared obligation of the global community. It involves sophisticated engineering and biological control measures such as planting of vegetation restoration, of desert-oasis protection systems, afforestation, transformation and restoration of natural desert forests over large areas, abiotic sand-fixing, and other measures specific to different regions. The results of current and historical projects have been positive, but many people still suffer from the misery caused by environmental deterioration, land degradation, climatic change and poverty.

The United Nations Convention to Combat Desertification (UNCCD) has provided adaptive, mitigative and rehabilitative guiding principles for global desertification control. It has established a center for global action to foster international cooperation and partnership in combating desertification and mitigating the impacts of drought. It has also drawn attention to the common responsibilities of governments and international organizations. Overall, this convention is a significant milestone in combating desertification.

1.1 Concept and scientific connotations of desertification

Located in the central and western parts of each continental land mass are the arid climatic zones. These geographical zones are mainly desert and grassland, and their climate is controlled by the general high-pressure air circulation and cold ocean currents. They have a climate of moisture scarcity and a corresponding landscape, vegetation patterns and ecosystem. Desertification, i.e., land degradation caused by human activities and climatic variations, with effects that include sandification, soil erosion, salinization and land productivity decline, is the main process that constrains the eco-environment and sustainable socio-economic development in arid zones. The world's drylands cover an area of about 5.55 billion ha, accounting for 37% of the earth's total land area, of which over 75% is threatened by medium intensity desertification. In China, 332 million ha, or 34.6% of the country's territory is dryland (CCICCD, 1997; Ci et al., 1997).

1.1.1 Definition of desertification

The UNCCD has given desertification a definition based on the causes and the scope of the problem. The definition of "desertification" means **land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities.**

"Land degradation" means reduction or loss, in arid, semi-arid and dry sub-humid areas, of the biological or economic productivity and complexity of rained cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical and biological or economic properties of soil; and (iii) long-term loss of natural vegetation.

"Arid, semi-arid and dry sub-humid areas" means areas, other than polar and sub-polar regions, in which the ratio of annual precipitation to potential evapotranspiration falls within the range from 0.05 to 0.65 (INCD, 1994). The United Nations Environment Program (UNEP) has suggested that the Thornthwaite Method be used worldwide to calculate potential evapotranspiration (MI). Based on the above mentioned definition of arid, semi-arid and dry sub-humid areas, the classifications of climate type where desertification is a risk are listed in Table 1.1.

Table 1.1 Bio-climatic zones and classification criteria

Bio-climatic zone	Humidity criteria
Hyper-arid zone	< 0.05
Arid zone	0.05–0.20
Semi-arid zone	0.20–0.50
Dry sub-humid zone	0.50–0.65
Humid zone	> 0.65

Desertification types

The major external forces that cause desertification are used to classify the types of desertification. These five types are as follows:

(i) Desertification caused by wind erosion and aeolian processes;

(ii) Desertification caused by water erosion and alluvial processes;

(iii) Desertification caused by soil salinization/alkalization and waterlogging;

(iv) Desertification caused by freezing and melting processes on cold plateaus;

(v) Desertification caused by other interacting factors (resultant factors).

All desertification types are also classified based on their effects on different land-use types, and consequently the effects of desertification on various land uses are presented with emphasis on the direct threats of desertification to human life. The effects of desertification on common land-use types are: degraded rangelands, degraded croplands and degraded woodlands.

Desertification is different from the definitions of Desert, Sandy Desert or Sandland.

Desert refers to a zonal geographic unit which is found in arid area and is characterized by a dry climate, very low precipitation levels, high evaporation rates and poor vegetation.

Sandy Desert refers to dry climate regions where the ground is covered with a loose accumulation of quartz and other fine mineral particles, which can form under the effect of air movements.

Sandland generally refers to the wind swept sandy landscapes formed due to the comprehensive disturbance of various types of sandy or gravelly ground due to natural and human factors. Sandlands are found in semi-arid, dry semi-humid, humid areas and the beaches and banks of their seas, rivers, lakes, etc.

1.1.2 Theoretical background to desertification

Desertification is a major chaos phenomenon in dryland areas. The chaos phenomenon is omnipresent in nature and determines the complex and unhalting creative and destructive forces in nature. Physical processes prevail in dryland areas. Considering thermodynamics, the molecular thermodynamic movement always trends towards increasing chaotic states and intensified disorder, i.e., entropy will increase. However, the degree of organization and order can be increased by inputting negative entropy from the outer environment into an open system which is in a non-equilibrium state. For instance, green plants absorb CO_2 from the atmosphere and nutrients from the soil, utilizing a non-equilibrium system formed by solar radiation, which allows the negative entropy (energy and matter) to enhance the self-organizational capacity of organic matter. Therefore, the real world is a system combining the coexisting processes of order and disorder, certainty and randomness, simplicity and diversity. It is the chaotic process that provides the rules and non-chaotic organization from complexity and order, where new modes and structures are created to promote the continuous flow of matter and energy.

Desertification mainly occurs in arid, semi-arid and dry sub-humid areas. The arid areas on the earth are a chaotic system encompassing the environment, with its physical characteristics of water scarcity and hydrothermal non-equilibrium, and the bio-community that has selected, adapted and evolved to that environment. Within an arid environment exists the increase and decrease of positive and negative entropies of matter and energy, incrustation and overlapping of chaotic and non-chaotic processes, and the evolution and degeneration of living and non-living matter, which forms a boundless universe, in which an equilibrium state and a non-equilibrium state coexist. As a chaotic system, one of the basic characteristics of arid areas is that the evolution of the system is extremely sensitive to the initial conditions, minute differences in which may cause a large systematic change, such as the degeneration of the arid environment and ecosystem (land and bio-community), i.e., "desertification". Initial activities conducted in a fragile and sensitive arid area (desert and grassland), such as inappropriate farming reclamation, overgrazing, over-cutting, and mining, as well as land surface destruction from traffic, tramping, etc., may result in a series of manifestations of desertification. These can include vegetation destruction, loose surface soil, shifting sand movement, instability of sand dunes, soil erosion, gully incision, secondary salinization, brushwood sparseness, land overgrown with weeds, declined productivity, and other similar effects. Therefore, desertification is a chaotic process in which the land ecosystem, under the effect of external factors such as climatic changes and human activities, undergoes an increase in system chaos and disorder, entropy increase and the decomposition of the systems self-organization. Research indicates that desertification initially occurred before the rise of human civilization, and thus there existed the classification of primitive desertification which occurred in the geological period. This classification is chronologically followed by ancient desertification which has occurred since the rise of human civilization, and modern desertification which has occurred since the Industrial Revolution. Primitive desertification and refers to the desertification which resulted purely from the climatic variations geological processes. Desertification in the historical and modern periods has been caused by inappropriate human activities against a background of arid climate and climatic changes (Fig. 1.1).

Desertification is one of the factors in the earth's environmental degeneration. At present, it is difficult to distinguish the natural factors from the human ones that cause desertification. However, considering the effects on matters, the artificial effects are irreversible, while the natural system is a typical self-regulating system, and is therefore relatively stable. Nonetheless, a stable state cannot be maintained indefinitely because it contains potential uncertainties that can be affected by human activities (Hare, 1983). Rainwater, atmosphere, soil pollution, deforestation, soil erosion, and climatic variations are all important factors in desertification, while desertification plays an important role in the loss of global diversity, especially in the cen-

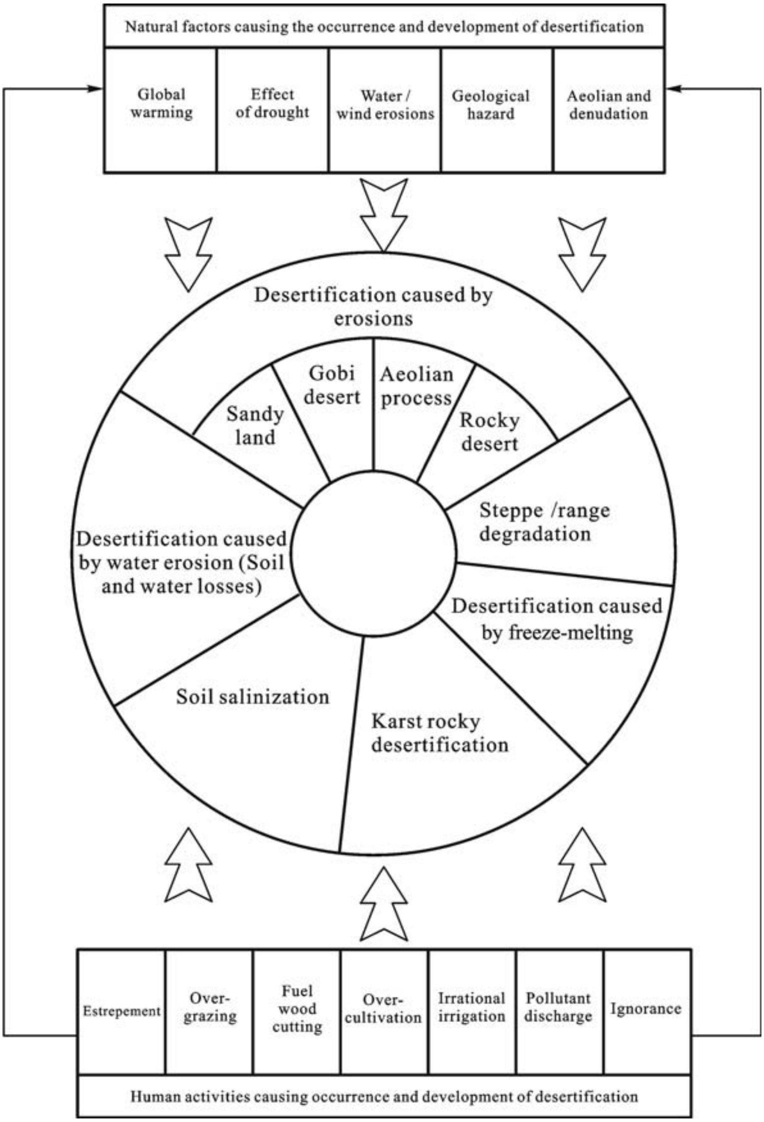

Fig. 1.1 Block diagram of formation of desertification

tral regions of the world's main crop species. Desertification aggravates the loss of the earth's biomass and bio-productivity and depletes the global soil humus reserves, thus affecting the global bio-geochemical cycles, particularly by decreasing the land area available for global carbon dioxide sequestration. Through increasing the albedo of the land surface, desertification adds to the global climatic changes, increasing the potential severity of such changes by decreasing the evapotranspiration capacity, changing the earth's surface energy estimation and adjacent air temperature, and increasing dust and carbon dioxide levels in the atmosphere. The pressure to control desertification comes from the fact that desertification can bring about horrifying social, economic and environmental consequences (UNEP, 1992).

Drought is a natural factor for the formation of desertification. The revolving earth is unevenly heated and large-scale downdraughts in the atmosphere occur at the latitudes of the subtropical zones, where arid areas are formed. In these regions desert (sand) can always be found. Therefore, the causes of desert formation of the arid and semi-arid areas in most subtropical zones should be related to natural factors. Because desert climates are extremely harsh, with low rainfall and extreme temperatures, few organisms can exist there. On geological time scales the causes of the relatively ancient desertification changes were completely natural factors, but subsequent changes are probably related to human influence, or unwise human activities which have worsened the situation.

Analysis of climatic factors shows that changes to the regional physical climate, caused by the change of land surface characteristics, can have an impact upon the dynamic climate through a feedback process. This, in turn, can have an effect on a larger region, an entire continent or even the entire planet. The analysis of artificial factors shows that inappropriate land use initially has an effect on the physical climate at a regional scale, i.e., local climate or microclimate. The process of desertification relies on the combined actions of two factors, which are the macroscale dynamic processes in the atmosphere which control the macroclimate, and the complicated regional effects caused by the physical processes of land surface change affected by human factors which change the local climate. It is the natural and artificial causes that change the dry ecosystem and cause it to degenerate, thereby changing the land surface albedo, roughness and hydrothermal conversion rate. As a consequence of the eco-environmental change, the bio-productivity (the capacity of the bio-community to convert solar energy and precipitation into the matter for self-use) declines, and a sandy desert comes into reality.

Before the Pleistocene Epoch, due to earth's internal and external forces, the crustal plates, under the arid climatic zones, underwent processes of uplift, subsidence, folding, distortion, and fracture. This formed the particular multi-layered structures of geology-geomorphology, climate and bio-community that we see today. The macropattern of forest, grassland, desert, etc., formed because of the differentiation of climatic zones. The stacked structure of mountainous regions, piedmont sloping plains and alluvial plains in the mountain-basin systems was formed due to the differentiation in geology and geomorphology, as well as the corresponding ecosystem. These spherical and layered structures are a series of orderly and self-organized systems which are formed under the effect of the randomness in the chaotic systems in arid zones — landslide and collapse, flooding, wind erosion with alternate heating and freezing, accumulation and deposition, and the nonlinear geophysical effects such as climatic and terrane zonality (geological and geomorphological zonality) of non-climatic zones areas that coexist in arid areas.

In an arid chaotic system, the key strange attractor is the "water-heat relationship" characterized by water scarcity. The water-heat relationship features various combinations (the expansion and convolution of strange attractors result in diversified ecological types within the arid areas) of biome, ecosphere and vegetation type, etc., on different scales. Due to the induced moisture scarcity in arid climates, the mountain uplift resulting from plate collision and extrusion does not normally develop into luxuriant mesophytic forest or vegetative meadow cover. In arid areas, as the degree of dryness increases, the degree of vegetation cover decreases and sedimentation accumulation increases. Riverbeds become congested with superfluous load, and their water-carrying capacity declines. This decrease in water-carrying capacity of riverbeds is especially severe after an intensified arid season, when the ensuing concentrated rainfall results in the maximum load of riverbed sediments. This process is stated in the famous theorem on Central Asian arid areas put forward at the beginning of last century by Huntington (1907), hence the repeatedly occurring rule of chaotic processes of arid areas.

The orderliness or regularity of an arid area is also embodied by the sphericity and zonality (Obruchev, 1911) in its geological and geomorphological structure. The differentiation in radiation or heat zones result from the difference of the solar incidence angle along the earth's latitudinal direction, or the zonality of continentality or the degree of roughness caused by the sea-land distance along the longitudinal direction, or the hierarchy of climatic-vegetation vertical zones caused by rising altitude and descending air temperature in a mountainous region or plateau. Regardless of causes, the orderliness is related to the sphericity and zonality of the chaotic system in arid areas. An important physical factor in arid areas is wind, which is caused by non-equilibrium thermal effects, or heat convection which causes pressure difference and therefore wind. Wind is frequent, inevitable and recurring in an arid chaotic system. Wind is also unsteady and non-linear, i.e., it is a chaotic force, of which the occurrence, path, strength and duration are difficult to predict accurately. Fortunately, the birth of satellite cloud imaging is making it possible to predict such an uncertain factor, to a limited degree. In the central part of the arid zone areas in Central Asia, i.e., areas near the anticyclonic high pressure centers, strong gales frequently occur, especially on the desert surface which has scarce vegetation, and wind erosion is the major force for land surface erosion, creating a large area of aeolian geomorphology and groundmass, on both micro and macro scales. In 1895, Obruchev published his *Aeolian Theory*, which illustrated the distribution frequency of the weathering products in the arid areas in Central Asia. The *Aeolian Theory* identified that at the central areas with the maximum wind power (annual average wind speed > 5 m·s^{-1}) there was the stony and gravel Gobi Desert.

Cen Shen, a frontier poet of China's Tang Dynasty (A.D. 618–907), once described the Gobi Desert, in Luntai, southern Xinjiang, as: "On an expansion of plain strewn with gigantic gravels, driven by the wind, all the rock travels". Such lines can well be considered to be an accurate portrait of the Gobi Desert. Sand accumulates at the fringe of the Gobi Desert with lower wind speeds (3–5 $m \cdot s^{-1}$), forming sand dune landforms or sandlands of diversified shapes. Finally, in areas with an average wind speed lower than 2–3 $m \cdot s^{-1}$, which have a topographic counterguard, such as a mountainous region or a region confronted with reverse monsoon or other air current, the dust carried in the air descends and deposits, forming a primary loess accumulation (Ci, 1997).

The geomorphological concentric structure in an arid playa is also a spherical and zonal structure peculiar to arid areas. To a large extent these structures are the result of formations caused by water superposed with aeolian effects. From the mountain watersheds, the solid matter carried by rivers, floods or debris flows to pediment exits slows down because of the abruptly widened topography and accumulates and deposits in inclining bajada, alluvial fans or estuarine deltas. Due to the hydrodynamic separation effect, the macrograined stone blocks, gravel and grit form the gravel or grit Gobi on the upper layer of the fan-shaped terrain; the sandy loam and loamy sand deposit in the medium layer of the fan; and the clay soil deposits in the lower layer of the fan, forming the salinized fan-fringe zone. The fan-shaped terrain stretches downward to border the ancient alluvial plain at the bottom of the playa. Such fans are normally surrounded by sandy loamy desert, with desert vegetation of *Haloxylon ammodendron* and *Reaumuria soongarica*. The central part of the playa is occupied by the sandy desert, comprised of semi-fixed sand dunes, sand ridges and sandlands. The water and salt catchments, such as lakes or dry lake basins are located in the lowest part, the playa. Such a concentric desert mountain-basin structure lays the foundation for the eco-productive paradigm of mountain conservation in arid areas, desert oasis agriculture, grassland animal husbandry and wild ungulate animal conservation.

1.1.3 Scientific basis for combating desertification

Ecological restoration, biodiversity conservation and sustainable agriculture in drylands are the main methods used to combat desertification, and are also the main methods used in the sustainable development of the drylands (Reynolds et al., 2007). However, these methods vary distinctly among the different regions and geographic zones. The reasons for this variation relate to climatic variations within the different zones and landscape differences that result from different geological structures and landform features. For instance, an alpine area may feature combined landscapes with significant vertical climate-vegetation belts, while a desert plain consists of the combined arrangements of oases, fan edge zones, desert plains, sandy deserts and basins. Human activities can also result in great changes to the landscape, such as the construction of oases, towns, traffic networks and wilderness areas. Therefore, considering the economic development and scientific and technological level, a series of principles and technical measures for the best or most feasible methods of ecological restoration and conservation, sustainable agriculture, forestry and animal husbandry, need to be adapted to the different climatic zones or to different landforms and geological features within the same zone. These principles and measures will involve a series of engineering solutions considering the ecosystem structures and landscape patterns which must be conducive to both conserving and improving the eco-environment, and the promotion of economic development. This is the so-called "optimized eco-productive paradigm". The essential factors of the "optimized eco-productive paradigm" are shown in Table 1.2, below:

Table 1.2 Diagram of optimized eco-productive paradigm in drylands of China (Zhang et al., 2003; Yang et al., 2008)

Optimization	Ecology	Production	Paradigm
Eco-friendly	Desert	Arable farming	Ecosystem management
Environment-friendly	Grassland	Forestry and fruit industry	Regional landscape pattern
High quality and yield	The Loess Plateau	Grassland animal husbandry	Combined configuration in functional areas
Energy and water-saving	Agricultural pastoral transitional area	By-product, processing and service industries	
Cost-effective	Alpine	High-tech industries	

1.2 Current status of global desertification

At present, 30% of global land in more than 100 countries in the world is affected by desertification. Worldwide, desertification-prone land covers 36 million km^2 and desertification is increasing at a rate of 50,000–70,000 $km^2 \cdot a^{-1}$. Desertification is causing large areas of land degradation in Africa, Asia, Latin America and the Caribbean and the Northern Mediterranean regions. In Africa, desertification is spreading rapidly and desertification-prone land covers 77.8% of Africa's drylands. In Asia, desertification-prone land covers 83.7% of the total dryland areas and the arable land affected by desertification is as much as 1,341 million ha. Desertification is the number one cause of declines in biological productivity in Asia, with China and India most severely affected by desertification. In other countries, such as Mongolia, the Islamic

Republic of Iran, Kuwait, and the Central Asian countries, the spread of desertification is also seriously accelerated.

Drylands are mainly distributed in the central and western parts of the earth's continental land masses and in subtropical high-pressure zones, covering a total area of about 61.50 million km^2 and accounting for 41% of the total land area in the world. According to the data from UNCCD, 70% of the world's drylands (excluding hyper-arid deserts), or some 3,600 million ha, are degraded (UNCCD, 2008). Africa's drylands comprise 13.1% of the total land area of the world, Asia's drylands comprise 13.0%, that of North America comprise 4.9%, South America 3.6% and Australia 4.4%. The percentages of the drylands on each continent are as follows: the drylands cover 75% of Australia total land area, 66% of Africa, 46% in Asia and 33% of both North America and South America.

Dryland ecosystems are very fragile. Under the huge pressure of population growth, dryland areas are being excessively cultivated, and in particular, the agricultural development of marginal land areas has resulted in serious consequences. Overgrazing has destroyed the vegetation cover and brought about topsoil erosion; over-reclamation of cropland has caused soil infertility; and inappropriate irrigation has led to the decline of underground water tables and soil salinization. To make matters worse, barren wastelands have been inappropriately opened for development, cultivated, and reclaimed for crop farming. This inappropriate development has brought about a vicious cycle of worsening poverty and then further reclamations, and consequently, desertification and land degradation have become widespread. With a view to alleviating global climate change and improving the environment, combating desertification is a common global obligation.

1.2.1 Introduction to distribution of global desertification

There are approximately two billion people, representing nearly 40% of total world population, who dwell and live on drylands. The total area of drylands in the world is approximately 54 million km^2, or about 40% of total global land area. Africa is comparatively the driest continent on earth, while in South America, well-known for its rainforests, the drylands cover one third of its terrestrial land. In Asia, drylands are widely distributed, with arid and semi-arid zones in Central Asia and Western China occupying 39% of the total land area of the Asia region. The largest population centers in the world are on drylands, particularly in Asia, where 1.3 billion people subsist on drylands. Of the human population living in drylands, 42% are in Asia, 41% in Africa and less than 20% are spread over the other continents. Almost all of these populations are living in semi-arid and dry sub-humid areas. The countries with high population densities in drylands face the risk of further land degradation. Some huge cities, like Beijing, Cairo, Lima and Dakar, are situated in drylands. Extreme arid zones, which are not included in scope of drylands, cover 9.9% of the global terrestrial land areas (Fig. 1.2, Table 1.3, Table 1.4, and Table 1.5). Land degradation is caused by several complicated factors, including natural, socio-economic and political factors. Population pressure adds to these factors and can accelerate the intensity of land degradation. UNEP data show: (i) 25% of terrestrial land area on earth is affected by desertification, and this is spreading at an accelerated rate; (ii) 20% of the global population is threatened by desertification, and 135 million people are at risk of losing their remaining land in the near future; and (iii) nearly 800 million people worldwide who live on drylands do not have sufficient food. Additionally, according to UNEP Human Development Report in 1997, desertification in the world's drylands is closely interlinked with poverty, and poverty is much less severe in humid zones than in the drylands. For instance, in ten countries in the Sahel region of Africa, the poverty index of populations in humid zones is 25%, compared with 61% in drylands. In view of the population distribution and areas of desertification, Asia is the continent with the largest population severely affected by desertification (Table 1.6).

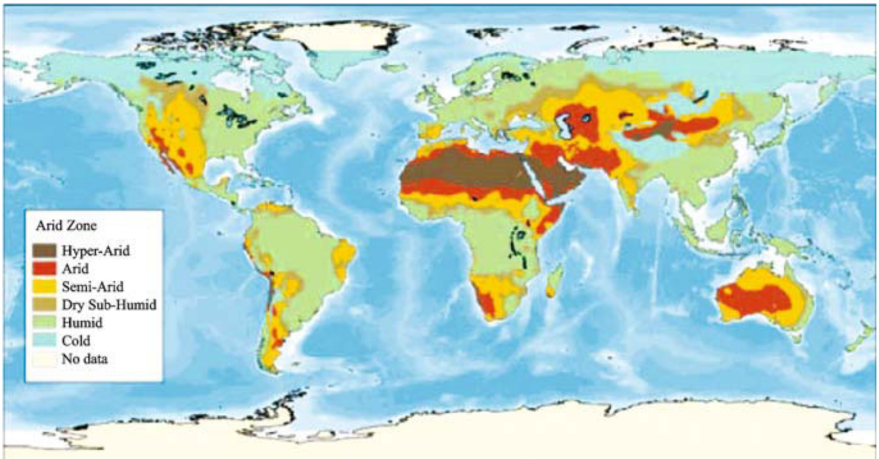

Fig. 1.2 Arid zones of the world(UNEP, 1992, with permission from UNEP)

Table 1.3 Extent and distribution of susceptible drylands by continent (UNEP, 1992)

Region	Area (10^6 ha)	Percentage of continental land mass (%)
Africa	1,286	43
Asia	1,672	39
Australia	663	>75
Europe	300	31
North America	732	33
South America	516	29
World total	5,169	40

Table 1.4 Extent of drylands in different continents of the world ($10^3 km^2$) (India, 2001)

Continent	HA	%	A	%	SA	%	DSU	%	TD	MSUU	%	C	%	GT
Africa	8,099	27	5,052	17	5,073	17	2,808	9	12,933	9,171	30	0	0	30,203
America & Caribbean	268	1	1,201	3	7,113	17	4,556	11	12,870	16,926	41	11,577	28	41,641
Asia	2,744	6	6,164	13	7,649	16	4,558	9	18,371	15,026	31	12,082	25	48,223
Australia	0	0	3,488	39	3,532	39	996	11	8,016	1,019	11	0	0	9,035
Europe	0	0	5	0	373	7	961	17	1,339	4,059	71	289	5	5,687
World total	11,110	8	15,910	12	23,740	18	13,879	10	53,529	46,512	34	23,948	18	134,789

HA: Hyper-arid; A: Arid; SA: Semi-arid; DSU: Dry sub-humid; TD: Total drylands (Arid, semi-arid + dry sub-humid); MSUU: Moist sub-humid +humid; C: Cold; GT: Grand total.

Table 1.5 Population distribution in drylands in different continents of the world (Population numbers are in 10^3) (India, 2001)

Continent	HA	%	A	%	SA	%	DSU	%	TD	MSUU	%	C	%	GT
Africa	58,068	9	40,503	6	117,649	18	109,370	17	267,522	326,129	50	0	0	651,719
America & Caribbean	4,387	1	19,081	3	100,753	14	581,201	8	701,035	510,820	73	10,359	1	1,226,601
Asian-Australian	29,506	1	161,554	5	625,411	18	657,899	19	1,444,864	1,942,210	56	29,902	1	3,446,482
Oceania	0	0	275	1	1,342	5	5,318	19	6,935	20,447	75	0	0	27,382
Europe	0	0	629	6	28,716	5	115,216	20	144,561	417,026	74	8,573	2	570,160
World total	91,961	2	222,042	4	873,871	16	1,469,004	17	2,564,917	3,216,632	60	48,834	1	5,923,344

HA: Hyper-arid; A: Arid; SA: Semi-arid; DSU: Dry sub-humid; TD: Total drylands (Arid, semi-arid + dry sub-humid); MSUU: Moist sub-humid +humid; C: Cold; GT: Grand total.

Table 1.6 Status of desertification in some selected regions and countries (Lu, 1998)

Region/Country	Terrestrial area (10^4 km^2)	Dryland area (10^4 km^2)	Area of desertification (10^4 km^2)	Arid	Semi-arid	Dry sub-humid
World		5,169.2	3,618.4(70%)			
Africa		1,286	1,000(77.8%)			
Namibia	82.5			22%	70%	8%
Mali	124.1					
North America		732.4	79.5(10.9%)			
South America		516	79.1(15.3%)			
Australia		663.3	87.5(13.2%)			
Europe		299.7	99.4(33.2%)			
Asia		1,671.8	1,400(83.7%)			
India		255.1	107.4(42.1%)			
China	960	331.7	262.2 (79%)			
Pakistan	88			80%	12%	

Region/Country	Extent of desertification (10^4 km^2) (% of area of desertification)			
	Slight	Medium	Severe	Extreme
World	427.3 (11.8%)	470.3 (13%)	130.1 (3.6%)	7.5 (0.2%)
Africa	118 (11.8%)	127.4 (12.7%)	70.7 (7.1%)	3.5 (0.4%)
Namibia				
Mali				
North America	13.4 (16.9%)	58.8 (74.0%)	7.3(9.2%)	–
South America	41.8 (52.8%)	31.1 (39.3%)	6.2(7.8%)	–
Australia	83.6 (95.5%)	2.4 (2.7%)	1.1(1.3%)	0.4 (0.5%)
Europe	13.8 (13.8%)	80.7 (81.2%)	1.8 (1.8%)	3.1 (3.1%)
Asia	156.7 (11.2%)	170.1 (12.2%)	43 (3.1%)	0.5 (0%)
India				
China	91.2 (34.8%)	64.1 (24.4%)	103 (39.3%)	
Pakistan				

1.2.2 Regional features of desertification-prone lands and strategies to combat desertification

1.2.2.1 Regional feature of the affected regions in the world

(i) Desertification-prone lands in North America are mostly comprised of revegetated, degraded land; unused deteriorated pasture and grasslands; and scattered, distributed, mobile sandlands and sand dunes. Following the experience of the well-known "Dust Bowl" caused by reclamation in the Western US in the 1930s, vegetation protection in North America is recognized by both state and federal laws.

(ii) Desertification-prone lands in South America occupy one third of its terrestrial land. The Atacama Desert is one of the most extreme arid deserts in the world and desertification-prone lands are distributed along coastal areas and inland valleys and river basins.

(iii) Desertification-prone lands in Sahelian Africa are complicated and comprise various types. Africa has experienced prolonged droughts and extreme weather events, which influence the wide distribution of highly mobile aeolian sand dunes. Uncontrolled destruction of natural vegetation has left a lot of land exposed without any biological protection. Ancient fixed sand dunes have been reactiviated on a large scale because of uncontrolled collection of fuelwoods and timber and this is particularly severe in the Sahara-Sudan belt. Oases have a scattered distribution and are located in low depressions and dried river valleys in this vast region and most are surrounded by shifting sands. Desertification-prone lands in southern Africa are mainly found in Botswana, Namibia, South Africa and neighboring countries, and the landscapes mainly comprise mobile dunes, shifting sands, fixed and semi-fixed sandlands, exposed and barren lands, forest-pasture land, Savanna, steppe, and desert steppe. The drought that occurred in the 1970s accelerated the spread of desertification on the African continent and the situation went from bad to worse.

(iv) Desertification-prone lands in Asia and the Pacific region: The United Nations Economic and Social Commission for Asia and the Pacific (UN-ESCAP) sponsored the High Level Regional Meeting of the World Summit for Sustainable Development (WSSD) in Phnom Penh, Cambodia in November 2001. The Conference adopted the "Phnom Penh Regional Platform on Sustainable Development", which identified that land degradation is still a key issue in the Asia-Pacific region, particularly in areas with fragile ecosystems. Soil erosion intensity is worsening on a different scale in each region and the total area of land degradation in Asia-Pacific region covers more than 80% of its total land area. The issue of land degradation concerns a wide range of the various subregions of the Asia-Pacific region. In Northeast Asia, rangeland and steppe degradation and dust and sandstorms are the priority issues. In South Asia, water and soil loss and soil salinization are the main problems. In Southeast Asia, deforestation and unsustainable agricultural development are causing serious problems. In Central Asia, the degradation of desert oases and mountain ecosystems is being rapidly accelerated, while in the South Pacific, increasing drought threatens small developing islands and topsoil loss is becoming worse causing negative environmental effects.

1.2.2.2 Ecological and environmental crisis caused by desertification

Climate variation and inappropriate human development activities on land, and the related socio-economic elements are the leading factors resulting in modern desertification. The detailed factors are described below:

(i) Climate change

Regular severe droughts are catastrophic to humans and are becoming increasingly common with the spread of desertification. Both desertification and global climate change are obstacles to achieving the Millennium Development Goals of poverty alleviation and sustainable environmental protection. However, global cooperation on alleviating climate change and combating desertification has the potential to improve this situation. Rehabilitation of degraded land, control of soil erosion and revegetation are helpful in reducing greenhouse gas emissions and improving the self-regulatory capacity of natural systems (documents of Beijing International Conference on Combating Desertification, January 2008).

(ii) Soil deterioration

The deterioration of soil resources is a global issue. It is estimated that during the last five decades more than 50% of the total land area in both China and India has experienced medium to severe soil deterioration. At present, the area of global soil deterioration is 1.2 billion ha, or 11% of terrestrial land area of earth. Loss of soil nutrients has caused soil deterioration over vast areas of agricultural land due to the use of inappropriate irrigation systems, secondary soil salinization occurs frequently. Degradation caused by chemicals, water erosion, or wind erosion is the manifestation of soil deterioration, and consequently, land productivity is reduced or lost. In the past, dryland ecosystems recovered rather easily following long droughts and dry periods. Under modern conditions, however, they tend to lose their biological and economic productivity quickly unless they are sustainably managed (UNCCD Fact sheet 1, www.unccd.int).

(iii) Loss of biodiversity

Desertification and land degradation are two of the major causes of the serious loss of biodiversity. Desertification causes the degradation of natural ecosystems, which results in changes to the structure of biological community, and accelerates the loss of biodiversity in the affected regions. This occurs particularly because desertification and land degradation bring about the devastation of species that live in drylands. The drylands are the origins of the main crop species of wheat, barley, sorghum and maize and are important gene banks for biological development of those species in future. Humans have conducted over-reclamation, overgrazing, inappropriate water resource utilization and management, and energy development to sustain their livelihoods. These economic activities contribute to desertification and a loss of biodiversity. Consequently, biological habitats are becoming smaller, the quality of the habitat is declining, the adaptability of species is reducing, the distribution of species is reducing and finally, the loss of earth's biological potential and biological productivity is accelerating.

(iv) Decline of vegetative coverage and exposure of land increasing frequency of erosion

When vegetation, which plays an important role in protecting land from erosion and deterioration, is destroyed by overgrazing, over-collection of fuelwoods, collection of herb medicines and other forms of deforestation, ecological disasters will be caused locally or at distant locations. The loss of rangeland resources, including the acreage and nutrient value of the rangeland, threatens the capacity and potential of the rangeland for sustainable livestock production. According to United Nations Food and Agriculture Organization (FAO) estimates, a total of 1.5–2.0 billion people worldwide consume fuelwoods for heating and cooking and the rate of reforestation is far behind the rate of man-made deforestation. It is estimated that fuelwoods consumption in Sudan is 70% higher than the total acreage of the rehabilitated or reforested areas, in Nigeria it is 75% higher, 150% higher in Ethiopia and 200% higher in Niger. Under the pressure of this plunder-like development, forests and savanna have been deteriorated and turned almost into wastelands or barren lands.

(v) Appropriate policy approaches

Good policies are the key to fighting land degradation and desertification in the drylands, and can include: (i) laws and regulations, rules and ordinances (including treaties and laws, rules and licenses); (ii) financial and governmental approaches (including price policies, taxation and penalties and management skills); and (iii) direct public investment and management approaches (including research, institutional capacity and infrastructure and service facility installation).

1.2.3 Status of desertification and activities to combat desertification in most affected developing countries

Population growth and inappropriate land use planning and management are the driving forces behind the accelerating spread of desertification. The sustainable development of natural resources in the drylands of the world is closely related to the lack of water resources, the fragility of dryland ecosystems and the pressures of both human and animal populations. Globally, the annual economic loss caused by desertification is approximately US$42 billion (UNCCD Fact sheet 8, www.unccd.int), which makes desertification the most expensive cause of land degradation in drylands of the world.

1.2.3.1 Status of desertification in some affected developing countries in Africa

According to the data and information from UNEP, in Africa, arid, semi-arid and dry sub-humid zones cover 43% of the terrestrial land on the continent and 73% of farmland is degraded. In the Sahel region, the productivity of grains, sorghum and peanuts has been low since the prolonged drought in 1970s and is still declining. Compared with the productivity levels during 1930–1935, productivity has declined by about 50–80% and the mean annual loss of farm crop income is about US$5.7 million.

(i) Status of desertification-prone land and its controlling measures in Niger

Niger is one of the African countries most severely affected by desertification, and two thirds of the total land area is composed of deserts. The southern part of Niger is an agricultural region and has a high population density. The northern part of Niger is a grazing and livestock raising area and the population is mainly composed of nomadic groups. It is a typical example of marginal land in the region. The annual precipitation varies from 200 to 400 mm and landscapes are composed of interspersed red soil uplands and hills, which are covered by ancient sand dune chains, inter-dune depressions and ancient dunes. Each inter-dune depression averages 100 ha in size. Ancient dunes, denuded sediments and aeolian sand deposits are widely distributed along river valleys and basins. The vegetation coverage is mainly composed of savanna species. On the sand dunes, *Acacia raddiana*, *Acacia senegal*, and *Balanites aegyptiaca* are the dominant species, while on the red soil uplands and rocky hills, *Acacia ehrenbergiana*, *Balanites* spp., *Combretum* spp., *Maerua crassifolia* and *Boscia senegalensis* are the main species. In the inter-dune depressions, *Acacia nilotica*, *Acacia seyal* and *Ziziphus mauritiana* are interspersed along ancient river courses of varying sizes. Herbaceous plants include *Cenchrus biflorus*, *Aristida* spp. and other annual plants. The perennial plants include mainly *Panicum turgidum* and *Cymbopogon schoenanthus*. These plants grow widely in the country on sand dunes and at the peripheral areas of the red soil uplands. This vast region is characterized by crop farming and livestock breeding, with un-irrigated farming being the main agricultural activity. There are some small scale traditional irrigation systems in the country. Domestic livestock are mainly ruminants, including camels, cattle and goats.

The issues of desertification and land degradation in Niger are some of the most important issues facing the government since its independence. Two thirds of governmental expenditure in the environmental sector was used for combating desertification. The government of Niger has developed and formulated its Economic Recovery Plan in 1996, in which several key projects for combating desertification were formulated and endorsed. At present, these projects are being implemented.

Recently, Niger has established a special project to improve traditional technologies. Wastelands without any agricultural development value were claimed for reforestation or plantation in fish-scale pits. The first phase of the project has improved and transformed 5,800 ha of wastelands or degraded lands. These improved wastelands are offered to local farmers to grow new crops or new cereal species. This practice is well popularized throughout the country. Fish-scale pits are a simple and convenient technology that needs little investment and an individual farmer, family or collective group can implement the project independently. The depth of each fish-scale pit is 15–20 cm and 20–30 cm in diameter. The surplus soil dug out from the fish-scale pits can be used to shore up the dykes of the fish-scale pits and some manure should be buried at the pit bottom to ensure the healthy growth of root systems and to fertilize soil. These fish-scale pits will collect runoff or rainwater during rainy days and farmers can make full use of the accumulated runoff to grow cereals and sorghum after they have harvested the runoff or rainwater.

(ii) Desertification-prone land and efforts to combat it in Namibia

The total land area of Namibia is 825,000 km^2. The country is bounded by the Kalahari Desert in the east, Namibia Desert in the west and the Khalu Desert in the south. Namibia is the driest country in the Saharan subregion of Africa. Drylands cover 22% of the total land territory and 70% of the drylands are covered by semi-arid lands. A high variation in rainfall is the leading factor in the environmental fragility in Namibia. Namibia has a total population of approximately 1.6 million, 70% of whom are engaged in subsistence farming. Therefore, the shortage of water resources and land degradation are serious issues facing the entire country. Sixty percent of the Namibian people live in the northern part of the country and are engaged in un-irrigated farming, but the land area in this part of the country comprises only 18% of the total. In comparison to the above data, only 7% of the total population lives south of Windhoek, the capital of Namibia, in area which comprises 32% of the total land area and has a mean annual rainfall of less than 250 mm.

Desertification-prone lands in Namibia are characterized by deforestation, rangeland deterioration, soil erosion, soil salinization, vegetation degradation, and the widespread growth of low bushes and shrubs. Faulty policies and planning related to drylands in tropical and sub-tropical zones are also factors leading to desertification in Namibia.

The National Action Programme to Combat Desertification (NAP) of Namibia is focused on promoting sustainable development, fairly and rationally utilizing natural resources, controlling desertification processes, benefiting current Namibians and preserving the environment for future generations.

Namibia has established a National Committee to Implement the National Action Programme to Combat Desertification and the National Coordination Body is composed of the Ministry of Agriculture, Water Resources and Rural Development, the Ministry of Environment and Tourism, the Ministry of Land, Settlements and Relief, the Ministry of Regional and Local Governments and House Building, the Namibia Desert Research Foundation, the Namibia Agriculture Association, the Namibia Development Trust Foundation, the Namibia Economic Research Bureau, the Namibia National Farmers Association, the Namibia Non-Government Forum and Namibia University.

1.2.3.2 Status of desertification and its control in some affected developing countries in Asia

The results of investigations by UNEP/UNSO show that the area of drylands in Asia is the largest in the world, and the population relying on drylands is approximately 1.3 billion, which accounts for three fourths of the total population relying on drylands in the world. These populations rely almost entirely on the natural resources of drylands. Furthermore, the population density of drylands in Asia is 3.7–4 times that in Africa, Latin America and the Caribbean regions. There are 1.949 billion ha of drylands in Asia, which represents 46% of the total land area in Asia, or 32% of the total land in the world. According to the data of UNEP's World Atlas of Desertification, 370.4 million ha of land was recorded as degraded in 1992 and 35% of arable land was severely affected by desertification resulting in greatly reduced grain yields. These affected lands include 35% of all irrigated lands, 56% of un-irrigated farmland and 76% of rangeland and steppe. The UNEP/GRID data from 1991 identified that the rates of irrigated farmland, un-irrigated farmland and degraded rangeland and steppe affected by land degradation worldwide were lower than in Asia, by about 30%, 47% and 73%, respectively.

According to the UNEP estimation, the area of arable land affected by desertification in Asia is 1.341 billion ha. The decline of productivity caused by desertification in Asia is the highest in the world. In China, the population affected by desertification is approximately 400 million, and in India about 300 million people are affected by desertification. Desertification processes in China, India, Mongolia, the Islamic Republic of Iran and Central Asia are caused by development in recent decades. Other Asian countries also face severe land degradation on a large scale caused by socio-economic and natural factors, such as wind erosion, water erosion, natural denudation and chemical deterioration, including excessive collection of fuelwoods and deforestation, and unsustainable agricultural practices. Table 1.7 shows the areas of desertification-prone land, and population densities in some affected developing countries in Asia.

Table 1.7 Areas of desertification-prone land and population density in some affected developing countries in Asia

Country	Terrestrial Land (10^4km^2)	Area of desertification (10^4km^2)	%	Total population (10^6)	Population density (persons·km^{-2})	Arable land per capita (ha)
China	960	267	28	1,280	120	1.2
India*	328	173.6	52.9	1,012	324	2.7
Kazakhstan	271.1	162.7	60	16.9	6.2	32
Mongolia	156	64	41	2.3	1.5	2.4
Turkmenistan	48.8	32.5	66.5	4.2	8.6	5.25
Uzbekistan	44.7	26.5	59.2	21.7	48.5	3.15
Pakistan	79.6	41.4	52	131.6	165	2.4
Syria	18.5	13.9	75	14.3	77.3	6.3
Jordan	8.9	8.5	96	4.2	48	1.5
Iran	163.6	70.3	43	67.2	41	4.1

(Source: UNCCD, 1998: The Social and Economic Impacts of Desertification in Several Asia Countries. * India, 2000–2001 Statistics of population survey and data from the Ministry of Agriculture, 1996)

(i) Hazards of desertification and their control in India

India is one of the countries on the South Asia subcontinent seriously affected by desertification and land degradation. The total land area in India is 328.73 million ha, and the total land area used for agriculture, forestry and animal husbandry is 264.5 million ha. "With barely 2.5% of the total land area of the world, India has to support 16% of the total human population and about 20% of the total livestock population of the world" (India NAP, Foreword). The rapid growth of both human and livestock populations, the spread of poverty, and a developing economy put increased pressure on the limited land resources in India. These pressures have the dual effects of limiting the development of agriculture, forestry and animal husbandry, and also lead to negative effects on the development of local settlements and industrial development. These factors interact with each other and cause severe land degradation as a consequence.

It is estimated that 187.8 million ha of land in India, accounting for 57% of the total land area, is degraded. It is fair to say that a large percentage of land in India has been degraded, is experiencing degradation, or will be degraded in the future. Considering the types of land degradation, arable land is the most severely degraded and grazing land, grassland, forestland and wasteland are also being degraded. The area of non-arable land is being rapidly reduced. Land degradation in India has brought about incalculable environmental degradation and economic losses.

The types and severity of desertification and land degradation in India are mainly caused by inappropriate use of land resources and ill-considered changes in land-use types. For instance, reclamation of farmland from infertile or fragile wasteland, making full use of soil without any protective measures, inappropriate crop rotations, mis-use or inappropriate use of pesticides and chemical fertilizers, mis-management of water resources or failure of irrigation practices, and over-exploitation of groundwater are some of the elements causing desertification and land degradation.

There are seven million ha of wasteland in the arid state of Rajasthan in West India. Various sandlands and deserts occupy 49% of the land area, and rocky hills and terraces cover 23.7% of the total wasteland. Under the impacts of long-term erosion and weathering, these wastelands are unproductive. The Central Arid Zone Research Institute (CAZRI) was established in 1952 and made 310 ha of rocky desert available for conducting research, experimentation, demonstration and pilot projects for rehabilitating degraded land and combating desertification. There is a vast area of shifting sands and mobile dunes in Rajasthan and it is an arid area with serious water shortages. Since 1980, the forest department of the local government created, with technical support and substantial assistance from academic institutions and technical organizations, sand dune stabilization experiment stations or pilot demonstrations, which were aimed to exploit and develop measures and technologies suitable to sand dune stabilization and preservation in arid areas. Currently, 100,000 ha of shifting sand or mobile dunes have been fixed and rehabilitated in Rajasthan, which either protects the desert environment, or reclaims large areas of sandlands. These pilot projects have identified the necessary targets for practicing sustainable land development and reclaiming and transforming desert lands.

With substantial support from local government and the effective efforts of local people, more than 10,000 household-scale water cellars were installed in Rajasthan to meet the water consumption needs of the human and domestic animal population. This approach is economical and beneficial to the local people and has been popularized and expanded with satisfactory results at the grass roots level.

To enable the large scale utilization of runoff and rainwater, the local government encourages both installation of household-scale water cellars and the construction of water pools, water catchments, and flood blocking reservoirs on a large scale, through the involvement of villages and local communities and with investment from different sectors. This is aimed at increasing the development of agriculture, forestry, animal husbandry, and ecological improvement. For the purposes of avoiding silt and sand accumulation, anti-infiltration films, sedimentation pools, and erosion-proof mulching were used in the areas around or near the water catchments or reservoirs, with remarkable results in blocking sediment infiltration, storing water and controlling erosion. This technology has been widely extended and practiced in the western part of India.

India has created a series of biodiversity protection and improvement areas in different climatic zones, including arid zones and sand desert zones. The nature reserves include tree plantations, bushland and grass revegetation areas and other vertical multi-layered vegetation communities. The area of each nature reserve varies from 100 ha to 1,000 ha. After 5–6 years of protection and improvement, these nature reserves or biodiversity preserves will be rotationally grazed or harvested at a controlled rate to meet the needs of fodder, forage and fuelwoods of local villagers and farmers.

As well as protecting biodiversity, the creation of high-quality products using new varieties and specialty forest plants is another best practice in combating desertification and rehabilitating degraded land in India. Some cash crop varieties with high economic values have been introduced to India, such as *Simmondsia* Nutt. and fresh *Ziziphus jujuba*. The creation of orchards using specialty tree varieties and cash crops is popular among local villagers.

The demonstration projects are aimed at controlling soil loss, revegetation, and harvesting of runoff and rainwater, and replanting of community forests is another effective measure being undertaken. The advantage of this measure is characterized by the integration of mechanical approaches with biological measures and is supported by good policy. From 1954, 100,000 ha of soil erosion have been controlled.

(ii) Stabilization of shifting sands in Kuwait

The total land area of Kuwait is 17,818 km^2, rainfall is rare and northwest winds prevail from May to September. Scarce fresh water resources and abundant sand sources are the leading factors impacting negatively on the fragile ecosystem in Kuwait. Inappropriate use of natural vegetation and soil resources has brought about an occurrence of wind erosion. The main sand sources for wind erosion are the rocky materials downwind of the denuded areas on the alluvial plain of southern Iraq. The hazards of shifting sands caused by development and construction are severe and bring about environmental and social issues. Various measures for controlling and stabilizing shifting sands are widely used in Kuwait.

The frequency of dust storms and sandstorms which occur as direct consequence of the wind erosion process is very high in Kuwait. An arid climate, a vast open landform, and sufficient loose and mobile sediment materials which are easily eroded and transported by wind, are the main factors leading to wind erosion. The sand accumulation on land surface includes: (i) sedimentation caused by wind erosion; (ii) deposits of residual gravel materials; and (iii) sediments of dried salt lakes. Aeolian sand sediments cover 60% of the total land area of Kuwait.

At present, the negative effects of shifting sands and mobile dunes have been mitigated to a certain degree by applying some artificial measures. Some solutions, like vertical barriers to fix and prevent sand disasters, are used to block and accumulate sands along coastal areas, but similar efforts and initiatives are necessary in open desert areas beyond the coastal areas (Ci et al., 2005).

1.2.3.3 Status of desertification and controlling measures in Australia

Australia is a typical arid country with 75% of its land area occupied by arid and semi-arid zones. Land degradation, rangeland deterioration and dust and sandstorms are the prevailing hazards in arid and semi-arid zones in Australia.

(i) Desertification caused by dust and sandstorms

The central and western coastal areas of Australia are frequently hit by dust and sandstorms. There are typically five or more dust and sandstorms occurring annually in Australia. Dust and sandstorms have a distinct seasonality, occurring mainly in late spring (September to October) and late summer (February to March). However, in un-irrigated farming areas or adjacent regions in southern Australia, dust and sandstorms often occur later during the autumn season before the winter rainfall.

(ii) Droughts

The EI Niño phenomenon usually causes droughts in Australia. Most of the severe desertification processes caused by dust and sandstorms are related to drought. In 1993, a large scale serious dust and sandstorm occurred on the Eastern Plain of southern Australia and four continuous years of drought from the effects of an EI Niño condition and inappropriate agricultural development activities contributed to this event. The eastern part of Australia and New Zealand received deposited dust which extended for more than 1,800 kilometers. Very fine soil particles and dust grains were blown into the atmosphere where they circled the globe three times suspended in air currents. A similar phenomenon also occurred in 1994 when a dust and sandstorm engulfed Western Australia, South Australia and the western part of New South Wales. It is estimated that approximately 10–15 million tons of topsoil from agricultural land in the above mentioned parts of Australia were lost. The topsoil was blown up by strong winds to engulf and affect most parts of the Australian continent.

(iii) Land degradation in South Australia

South Australia is a big state with 984,000 km^2 of land area, located between 26°– 38° south latitude and 129°–141° west longitude and it is surrounded by four states and territories. The Northern Territory has a mean annual precipitation of 125 mm, and is a mainly arid area, while South Australia is a vast un-irrigated farming area. The northern part of South Australia is a vast grazing land and grassland where livestock raising is the main economic activity, while the southern part of South Australia is a cereal cultivation region. The summer season is hot and dry across South Australia. Due to the prolonged drought, cropland has been exposed for a long period of time and abandoned croplands are widely distributed.

The arid environment is the key factor causing desertification and grassland degradation. Precipitation is scarce in the spring, summer and autumn in South Australia and un-irrigated croplands have been abandoned leaving the topsoil uncovered. Due to the high stocking numbers and concentrated grazing, topsoil was heavily trampled and its structure has been completely destroyed which allows local sand movements to take place, thus creating conditions for dust and sandstorms. There are more than 10% of days with some wind erosion in South Australia (Table 1.8). According to recorded data, vast areas of South Australia, which is 800 km from east to west, are affected by dust and sandstorms. Many towns and communities in some regions are under threat due to poor visibility caused by dust and sandstorms. The losses caused by dust and sandstorms are considerable. The direct effects include: (i) accidents in transport and communication; (ii) destruction of electricity lines and cut-off of electricity supplies; (iii) closing of airports and postponement of flights; (iv) interruption of highway and railway transportation; (v) loss of topsoil, soil infertility and reduction of soil productivity; and (vi) increased incidences of asthma, other respiratory diseases and eye ailments.

Table 1.8 Annual frequency of wind erosion disasters in South Australia

Regions	Intensity of wind erosion		
	Severe	Medium	Dust suspension
Adelaide	0.10	0.22	8.18
Kangaroo Island	0.05	0.10	3.83
Rongangkapaka and Fuoluruo	0.10	0.22	8.18
Yorke Peninsula	0.10	0.30	8.95
Northern low land	0.10	0.19	7.41
River region	0.10	0.37	12.01

Continued

Regions	Intensity of wind erosion		
	Severe	Medium	Dust suspension
Molimali	0.10	0.37	12.01
Port Lincoln	0.10	0.57	17.13
West Coast	0.10	0.57	17.13
Whyalla	0.10	0.57	17.13
Port Pirie	0.10	0.65	19.17
Flinders Ra	0.10	0.19	7.41
North end	0.10	2.27	60.58

(Calculation was based on 20 years visibility data of Meteorological Bureau)

(iv) Approaches to prevent dust and sandstorms and to control desertification

On the basis of many years of experimentation and research, scientists have identified the following approaches for preventing dust and sandstorms:

i) Perfection of a monitoring system to combat desertification; improvement of technological knowledge; improvement of agriculture and animal husbandry management; and adjustments to land-use practices.

ii) Popularization of agricultural economics and implementation of soil preservation processes; protection of vegetation; prevention of farmland and grassland from wind erosion; and strengthening of the anti-wind capacity of the land.

iii) Development of cultivation systems suitable to infertile soils; and the introduction of drought-resistant, anti-wind erosion and salt-tolerant plant varieties which are suitable to local conditions.

iv) Organization of training seminars and workshops for government officers, service technicians and supporting staff.

v) Summation of knowledge relating to new and relevant technologies for combating desertification, controlling rangeland degradation, alleviating wind-sand disasters and practicing sustainable agriculture and animal husbandry development.

vi) Acceleration of education and raising awareness of various sectors at different levels; and investment in related scientific research.

vii) Support for weather prediction, particularly promotion of the reliability of meteorological data and the accuracy of weather forecasting.

1.2.3.4 Status of desertification and its restoration in USA

The United States of America experienced the severe and disastrous "Dust Bowl" in the 1930s, and since then great importance has been attached to combating desertification and restorative land degradation. After several decades' efforts and initiatives, a series of measures, methods and experiences have been brought together and summarized for managing the land and for controlling land degradation. In the US, all applied measures for controlling land degradation and combating desertification are focused on the enclosure of degraded lands with artificial plantings and on water and soil conservation systems. Sound natural resource management practices and optimum water management systems are the key to the success of the US in preventing land from further erosion and responsible utilization of land resources.

The key experiences to control land degradation and combat desertification in US, are briefly summarized below:

(i) Protection and improvement of rangeland and revegetation of degraded grassland to increase the carrying capacity of grazing land.

(ii) Legislation of land use, introduction of land management rules, and the encouragement of water-saving or water preservation development initiatives including house building designs.

(iii) Continuity of scientific research and ground experiments for promoting and improving land management skills.

(iv) Through administrative initiatives, further popularization of soil conservation, improving statistics.

(v) Reinforcement of legal instruments like the "Water Law".

The detailed technologies for desertification combating popularized in USA are described as follows:

(i) Drip irrigation and sprinkler technology

The US practices advanced techniques in drip irrigation and sprinkler irrigation. These modern irrigation techniques are widely used in urban landscaping, city greening and national park construction, and in agricultural land. This technology is characterized by: (i) advanced new and high-value agricultural techniques with wide ranging application and effectiveness; (ii) the project of diverting water from the north to the south along the Colorado River and the special water-saving system; and (iii) advanced irrigation techniques and fertilization system and the sustainable development strategy for water resources.

(ii) Economic forests projects

Forest projects in the US are focused on: (i) improving environmental quality; (ii) development of recreation facilities and serving the tourism industry; and (iii) promotion of high efficiency economic forests. For instance, in the semi-arid desert region in California, environmental conditions are harsh and it is unreasonable to reforest on large scale because it is neither economically feasible nor efficient. The Forest Service, Land Management Agency and Nature Preservation Organizations in the US cooperate closely to popularize irrigation projects, like drip irrigation, sprinkler irrigation, leaching irrigation and wet-root system irrigation, to enlarge commercial forests and orchards in different regions with different soil textures, landscapes and water supplies, such as vineyards, walnut, pistachio and almond tree plantations. This is undertaken with technical support and guidance from technical institutions, in line with the construction and creation of national parks, nature preserves and tourism spots.

(iii) Greenhouse technologies

Greenhouse agriculture techniques in the US can be defined as an "integrated agricultural technical system", which means it makes full use of solar energy wherever possible; reuses as much of the surplus warm water and gas from city works wherever possible to increase soil temperature in the winter season; avoids, wherever possible, the over-consumption of water supplies; reduces the use of pesticide and fertilizers which are harmful to soil; and encourages advanced techniques which lead to high efficiency. The principles of greenhouse production include (i) provide out of season produce; (ii) offer markets superior quality of green produce; and (iii) produce high economic value products where the ratio between input and output should be no less than 1:2. The key technical points of greenhouse agriculture are:

i) Full use of solar energy or surplus heat from urban utilities;

ii) Improvement in seedling quality and control of disease insects through greenhouse plantation and nursery cultivation;

iii) All vegetables, flowers and fruit products are well-known and superior quality varieties;

iv) Automatic control systems and fertilization by drip irrigation systems (irrigation water and N.P.K fertilizer ratios are all controlled automatically by computer programs) with production systems to control the greenhouse microclimate (lighting, temperature, moisture and ventilation are all automatically controlled by computer);

v) Automatic grade sorting, wrapping and refreshing systems; the cultivation, harvesting, processing and marketing are systemized.

(iv) Developments in wind and solar energy

i) Windmill electricity;

ii) Solar energy utilization in greenhouses;

iii) Urban and household uses of windmill energy;

iv) Solar sterilization is used to control disease insects. By using plastic mulching in summer, all insects and pests in soil can be controlled and destroyed when the soil temperature reaches 60 °C. The advantages are that the plastic does not contain any chemical residues is highly effective, and this method has low operating costs and operational methods are simple and convenient.

1.2.3.5 Artificial solutions and measures to combat desertification

Combating desertification is a common obligation the global community. The UNCCD came into force more than ten years ago. Some efforts have been made to combat desertification with some successes. However, many people are suffering from disasters caused as a consequence of environmental worsening, land degradation, climate change and poverty. People need:

(i) To require all UN agencies to offer equal importance to the UNCCD, UNFCCC and CBD and commit substantial financial resources and other forms of support to undertakings to combat desertification.

(ii) To upgrade and improve the both the Regional Action Programme (RAP) to implement the UNCCD and the National Action Programme to Combat Desertification (NAPs). Leaders and decision makers at both national and local levels should concentrate their efforts on initiatives to implement the UNCCD and NAPs, including their targets and tasks to rehabilitate degraded land.

(iii) Social participation and community involvement in the project implementation at various levels should be actively encouraged. The effectiveness of combating desertification should be honored and rewarded as good governance practice at decision making levels.

(iv) Policy development, reinforcement of legal instruments and a system of reward and penalty should be further improved and promoted.

(v) Appropriate utilization of resources in arid, semi-arid and dry subhumid zones to develop other industries with careful protection measures for alleviating poverty in affected regions.

(vi) Apply new and advanced technologies and best practices to deal with the priority issues on combating desertification and rehabilitating land degradation. Multi-disciplinary approaches must be emphasized in scientific and technical solutions;

(vii) Most importantly, to transfer techniques from the laboratory to the field and encourage experts to work for the grass roots level objectives.

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2 Natural Background of China's Drylands

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The determination of dryland in China was delimited with various reference indices by different experts and organizations; the commonly-accepted classification method is the aridity index (RIG-CAS, 1959), which was formulated with emphasis on the accumulative temperature and has been used in past years (CGPGC, 1984; CCPG-CAS, 1985).

In the late 1990s, as a follow-up action to implement UNCCD, an aridity index based on the ratio of precipitation and the Thorthwaite PET method was adapted to define dryland, especially susceptible dryland in China by the China Committee to Implement CCD (CCICCD, 1997; Ci and Wu, 1997). Accordingly, the total area of dryland in China was found to be 3.317 million km^2, in which arid area, semi-arid area and dry sub-humid area are 1.427, 1.139 and 0.751 million km^2, respectively.

2.1 Deserts, Sandlands and the Gobi

China's drylands are widely distributed with large areas of desert, sandland and the Gobi (Fig. 2.1). China's deserts, including the sand dunes and wind eroded areas, account for a total land area of 712,900 km^2, while the total area of the Gobi is 569,500 km^2. The sum of the areas of the Gobi and desert is 1.2824 million km^2, which accounts for 13.36% of China's land. The major deserts and sandlands are mainly located in Xinjiang, Inner Mongolia, Gansu and Ningxia. The largest among them is the Taklimakan Desert, located in the Tarim Basin of southern Xinjiang, covering an area of 337,600 km^2. Table 2.1 shows the areas of the major deserts and sandlands in China, and the distribution of the deserts and sandlands in different provinces are discussed in Chapter 4.

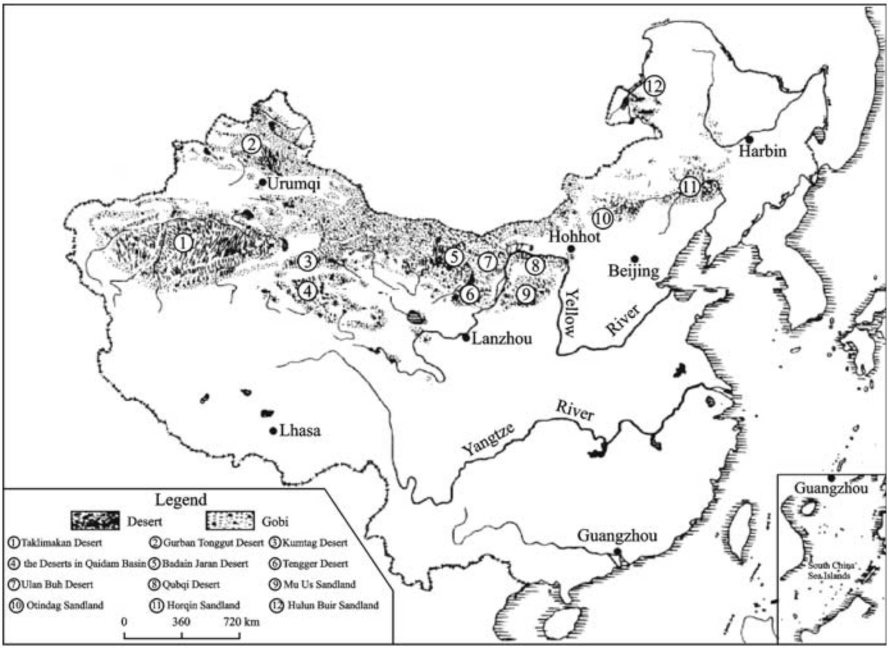

Fig. 2.1 Desert distribution map in China (Zhu et al., 1980; Wu, 2009, with permission from authors)

Table 2.1 Areas of the main deserts and sandlands in China

Name	Area (10^3 km^2)	Name	Area (10^3 km^2)
Taklimakan Desert	337.6	Otindag Sandland	21.4
Gurban Tonggut Desert	48.8	Kumtag Desert	22.8
Badain Jaran Desert	44.3	Ulan Buh Desert	9.9
Tengger Desert	42.7	Desert and the wind eroded region in the Qaidam Basin	34.9
Horqin Sandland	42.3	Qubqi Desert	16.1
Mu Us Sandland	32.1	Hulun Buir Sandland	7.2

2.1.1 Deserts

Taklimakan Desert: Located in the center of the Tarim Basin, the Taklimakan Desert is China's largest desert, and also the world's second largest mobile desert. This desert has three main natural characteristics.

(i) Mobile dunes are the dominant landform

The main part of the Taklimakan Desert, excluding Ma Yadage and the Luoshidage Mountains in the west, the northern Minfeng highland in the central-southern area and some patches along the rivers extending into the desert interior, is covered by sand dunes. Eighty-five percent of the sand dunes are mobile. Fixed and semi-fixed dunes occupy only 15% of the desert area, and they are mainly vegetated with *Tamarix* spp. These fixed and semi-fixed dunes are only found in the periphery of the desert, on plains near the piedmont and bordering the rivers which extend into the internal desert.

(ii) The sand dunes are huge with complex forms

The internal part of the Taklimakan Desert is mainly covered by exposed huge sand dunes, which are often 100–150 m high, with maximum of 200 m to 300 m. Within the desert, dunes of more than 50 m in height account for 80% of the total area of the mobile dunes, and some specific dune forms are unique and are not found in other deserts in China. For example, in the eastern half of the Taklimakan Desert, huge complex dune chains generally extend for 5–l5 km, with a maximum length of 30 km, and are typically 1–2 km wide. The leeward slopes are tall and steep while windward slopes are covered with secondary dune chains. The inter-dunes are flat with widths of 1–3 km extending for a considerable distance. These inter-dunes are segmented by low dunes which are vertical to them, forming some closed depressions with lakes scattered among them. In the center of the desert (82°–85° east longitude) and the southwestern desert, there are complex longitudinal sand ridges, which normally extend for 10–20 km, with a maximum of 45 km, typically parallel to the prevailing wind direction. The secondary dunes, above these ridges, are perpendicular to the main wind direction. The pyramidal dunes develop in regions with changing wind directions, distinct landform undulations, or adjacent to the mountains, the distribution of which can be isolated (such as between Yutian and Minfeng), or continuous irregular ridge-mounds (such as between Qiemo and Minfeng). In addition, there are tall dome-shaped sand dunes in the northern desert and scale-like dunes in the western and northwestern parts.

(iii) Plains within the desert have abundant water resources

Although the Taklimakan Desert mainly consists of mobile dunes, there are plains where the desert plant resources are abundant (mainly desert riparian forests — *Populus euphratica*, *Populus pruinosa* and *Tamarix ramosissima*). These plains are distributed in the river valleys in the desert interior, along the riverbanks at the desert edges and the front edge of alluvial-fluvial plains. Some rivers, such as the Hetian, Keliya, Niya, Andi'er and Yatongguzi rivers, flow into the desert interior, either flowing across the entire desert, or across two-thirds of the desert or 100–200 km into the desert. In the plains along these rivers, due to intermittent flooding, there is abundant shallow underground freshwater beneath the alluvial layer, which can be found 1–3 m below ground. In some areas, the spring outflows form small lakes in the interdune wadis or dry river beds. Hence, *Populus euphratica*, *Populus pruinosa*, *Tamarix ramosissima* shrubs and meadow reeds grow well. Other rivers, such as the middle and lower reaches of the Tarim River downstream of the Ye'erqiang and Che'erchen rivers, flow cross the desert's edge, have favorable water conditions for vegetation, and are currently being exploited with a number of new oases being established.

In addition, the solar resources are especially abundant and rank first in the usage of national desert areas. The frost-free period is especially long, typically 180–240 days, and the accumulated temperature greater than 10 °C is 4,000–5,000 °C, with annual sunshine of 3,000–3,500 hours. It is the only desert in the warm temperate zone and has great potential development and utilization values.

Gurban Tonggut Desert: The Gurban Tonggut Desert is located in the central Junggar Basin, and is the second largest desert in China. Its main features are listed as follows:

(i) The fixed and semi-fixed sand dunes are the major landform accounting for 97% of the entire desert, making the Gurban Tonggut Desert the largest of China's fixed and semi-fixed deserts. As the surrounding mountains are not completely closed, the mountain passes in the west and northwest, particularly, allow the passage of the humid westerly wind, and the precipitation can reach up to 70–150 mm annually which higher than the southern Tarim Basin. There are long standing snows in the winter, which can remain stable for 100 to 160 days, with a snow depth of more than 20 cm. Due to the relatively high precipitation rates, plants grow well in the inner desert with vegetation coverage reaching up to 40–50% on the fixed sand dunes, and 15–25% on the semi-fixed sand dunes. The abundant plant resources provide good winter pasture for the local herdsmen. There are more than 100 species of plants in the desert, including both Central Asian shrub desert flora and mid-Asian desert flora. Generally speaking, the Central Asian plant species are dominant in the eastern desert, and include *Haloxylon ammodendron*, *Ephedra distachya* and *Hedysarum scoparium*, while in the western and central parts of the desert, the mid-Asian desert plants such as *Haloxylon persicum*, *Artemisia santolina*, *Artemisia terrae-albae*, *Carex physodes* and other short-lived plants predominate.

(ii) The sand dunes in the desert interior form sand ridges, comprising 80% of the total area of the fixed and semi-fixed sand dunes. Normally, the bodies of the sand dunes are stable, and only the ridges of the semi-fixed sand dunes change direction following changes in wind direction. The distribution forms of the dunes are strongly influenced by the wind direction. In the western part of the desert with a prevailing northwest wind, most of the sand ridges lie in northwest-southeast directions. The bodies of the sand ridges are comparatively flat and straight, laid in straight lines, with some inverse crescent sand dunes also present. In the central and northern parts of the desert with prevailing north-northwest and north-northeast winds, the sand ridges lie in a roughly north-south direction as a result of the joint wind effects. The normal dune heights range from 10–50 m, distributed densely with dune chains extending for more than 10 km. The ridges have general features of dendritic morphology. In the central southern part of the desert with prevailing northwest winds, as well as northeast winds and the local piedmont-zone winds, there is also a distribution of secondary sand ridges at the inter-dunes, and honeycomb sand ridges are formed. The mobile crescent sand dunes and the dune chains are only found in the Akkum region in the northeastern desert and at the eastern end of the Huojingnielixin sand-belt in the southeastern desert.

Badain Jaran Desert:The Badain Jaran Desert is the third largest desert in China. The desert includes the region east to the Zongnai and Yabulai mountains, west to Gulunai Lake, north to Guaizi Lake, and south to North Mountain, and falls within Gansu Province, with a small portion within Ningxia Hui Autonomous Region. The main characteristics of the Badain Jaran Desert are:

(i) Tall sand hills are densely distributed, accounting for 68% of the desert area. These sand hills are mainly located in the center of the desert and most are 200–300 m high with a maximum of 500 m. They have three main morphological characteristics: The first is a complex sand hill with overlaid sand dunes on the windward slopes. The configurations of the overlaid sand dunes are varied, either sand chain dunes, horizontal sand ridges, or network dunes. The second are sand hills without overlaid dune chains on the windward slopes. The third are pyramid-shaped sand hills, mainly located at the south of the desert and near the windward sides of the eastern mountain areas. The sand dunes are extremely tall, because they are formed either on the ancient calcareous sand dunes, on the underlying eroded residual hills, or on the uplifting terrain. There are tall sand dune chains, normally between 20–50 m with some higher than 100 m, surrounding the sand hills. The inter-dunes are small without waterlogged depressions. The fixed and semi-fixed sand dunes are found mainly as shrub mounds, generally distributed around the Gulunai Lake basin at the edge of the desert.

(ii) The Badain Jaran Desert is mainly comprised of mobile sand, which occupies 83% of the desert area. However, on these mobile dunes and sand hills there exist some sparsely distributed plants. The plants are mainly located at the bottom of the windward and leeward slopes of the dunes, and can sometimes be found on the upper parts of the leeward slopes. In the west, the plants are mainly *Calligonum mongolicum*, *Meconopsis sphaerocephala*, *Hedysarum scoparium*, *Zygophyllum xanthoxylon*, *Ephedra* spp. and *Atraphaxis frutescens*, while in the east the plants are mainly *Meconopsis sphaerocephala* and *Phyllostachys propinqua.*

(iii) There are many small inland lakes distributed in the lowlands between the hills, mainly in the southeastern part of the desert, with a few in the north and west. Most of the water is too saline to be used for drinking and irrigation. However, springs can be found at the edge of the lakes, flowing into the lake center. The springs, fed by atmospheric precipitation and condensational water, have potable water quality with a mineralization of less than 1 $g{\cdot}L^{-1}$. The lakes are not only located between the high sand hills of the central deserts, but also found at the edges of the western and the northern parts of the desert on a comparative large-scale as the residues of the ancient river network.

Tengger Desert: The Tengger Desert lies in the south-eastern part of the Alxa region, between the piedmont plain of the Helan Mountains and the Minqin Oasis, and is the fourth largest desert in China. Its main characteristics are:

(i) The desert interior comprises dunes, lakes, mountains, plains and monadnocks, with the dunes occupying 71% of the desert, lakes 7%, mountain remnant hills and plains 22%, and monadnocks 9%. Seven percent of the dunes are fixed or semi-fixed, especially in the southwestern part of the desert where the ridges are oriented in a north-south direction. Except for the mobile sand on the top of the hills, the bodies of the hills are sandy soil, mostly covered by plants such as *Ephedra przewalskii* and *Meconopsis desertorum. Artemisia* spp. grows well in the central and northern parts of the wadis. In the mobile sand dune regions, which comprises 93% of the whole sand region, sparse vegetation can be found on the leeward sides of the dunes and on the inter-dunes including *Calligonum mongolicum*, *Hedysarum scoparium*, *Phyllostachys propinqua*, and *Meconopsis sphaerocephala*. The mobile dunes are mainly network dunes and network dune chains, which are typically 10–20 m high. There are some complex dune chains, and higher dunes, which can be 50–100 m high or more, and these are only found in the center of the desert. The sand dune chains are mainly located at the edge of the desert. There are some hill remnants that have not been covered by mobile sand in the desert. As these hills have been denuded and eroded over a long time, they are low, typically about 50–200 m. The plains of the desert interior are mainly located between Chala Lake and Tonghu forest farm, where the topography is relatively flat, with a number of small salt lakes distributed among them.

(ii) Lake basins are widely scattered in the desert interior, except for the northern and southwestern regions. Most of the lake basins have little or no water and are vegetated with grasses. Mobile dunes lie outside the lake basins and fixed and semi-fixed sand dunes are at the edge of the lake basins (mainly vegetated with *Nitraria tangutorum* on the sand dunes, and sometimes including *Achnatherum splendens*, *Phyllostachys propinqua*, and others). The groundwater is generally 1–3 m deep, with mineralization of 1–2 $g \cdot L^{-1}$. Most of the lake basins are comprised of meadow soil except for some waterlogged areas. In some areas, dry lakes form saline meadows and the groundwater table is only 1 m deep with a high mineralization.

Desert and wind-eroded regions in the Qaidam Basin: Lying in the northwest of Qinghai Province, the Qaidam Basin is a huge inland basin in the northwest of the Qinghai-Tibetan Plateau. The basin is about 2,500–3,000 m above sea level, and is the highest desert region in China. The east of the basin is desert steppe, and the west is desert. The basin comprises a mosaic landscape of wind-eroded land, sand dunes, Gobi, salt lakes and saline soil plains. Its main characteristics are:

(i) The dunes have a relatively scattered distribution, and are interspersed with Gobi on the piedmont diluvial plains. Most of the dunes are found in the Qimantage Mountains, and the northern part of the Shasongwula Mountains which are located to the southwestern of the Basin. These dunes form a discontinuous sand belt in a northwest and southeast direction. Most of the dunes are mobile, which occupy 70% of the whole area of the sand dunes in the basin, and are mainly comprised of crescent sand dunes, sand ridges and sand dune chains, which are typically 5–10 m high. There are also small areas of high complex sand dune chains (20–50 m high). The fixed and semi-fixed sand dunes are mainly located at the front edge of the piedmont plains of the northern Kunlun Mountains with a high groundwater table, especially in Xiarihatiegui in the eastern basin. The sand dunes are mainly covered with shrubs, which are normally 3–5 m high, although some are 5–10 m. The most common plants are *Tamarix ramosissima* and *Haloxylon ammodendron.*

(ii) The wind erosion area occupies 67% of the desert and wind-eroded regions in the basin, and is mainly located in the northwest of the basin, beginning at the east by the Mahai and Nanbaxian regions and extending west to the Mangya district, and north to the regions between Lenghu Lake and Eboliang. In this region, a short-axis anticline structure constructed with Tertiary terranes (mudstone, siltstone and sandstone) is well developed in the northwest and southeast direction. The terranes here are loose. The hard terranes interleave with the soft terranes, along bluffs and joints. When the wind direction and the geological structure direction are similar, the strong wind-erosion and the mechanical weathering effects form wind-eroded ridge dunes and wind eroded badlands that have the same orientation as the geological structure and are parallel to the main wind direction. These wind-eroded landscapes vary from 10–15 m high, with some higher than 40–50 m. Their lengths vary from 10–200 m, with some more than several kilometers long. On the windward slopes of the wind-eroded lowlands and the wind-eroded hills, mobile sand accumulates, forming sand ridges or crescent sand dunes. However, the area of mobile sand is quite low, occupying only 5% of the whole wind-eroded area.

Kumtag Desert: The Kumtag Desert is located in the eastern part of Xinjiang, extending north to the Lop Nur lowland, south to the A'erjin Mountains, and east as far as the western part of Dunhuang, Gansu. The desert is situated at the center of the inland region, and humid air does not reach this area which means that precipitation is very low, sometimes only 10 $mm\cdot a^{-1}$. The desert is so arid that the vegetation coverage is sparse and the sand dunes are mobile. The desert is incised with many valleys oriented in a north-south direction, which are typically 100–200 m deep, but sometimes extend as deep as 300 m. The sand dunes are mainly distributed on the slope surfaces. In addition to the main wind direction, the dunes are also influenced by the local airflow, which makes the tops of the dunes mainly pyramid-shaped. In the piedmont area, the sand dunes are mainly at the ridges and are influenced by the northeast winds, so the sand ridges extend in a northeast-southwest upslope direction. The sand ridges are segmented by low sand embankments, creating a distinctive featherlike sand dune landscape. The dune heights are normally around 10–20 m. Although the Kumtag Desert is mainly covered with mobile sand and has great landform undulations, springs break out at the headwaters of the north-south directed valleys in the east of the desert, with better vegetation, and human settlements can be found in the oases within the desert.

Qubqi Desert: The Qubqi Desert is located in the south of the Hetao Plain, in the middle reaches of the Yellow River, and is administered by Hangjin Qi (Banner) and Dalate Qi of the Inner Mongolia Autonomous Region. Most of the area is a semi-desert zone, although a small part in the east is desert steppe. Its main characteristics are:

(i) The desert is a relatively integrated geomorphological unit at the northern edge of the Ordos Plateau. There are a few rivers that cut through the desert in a south-north direction in the eastern part of the desert, making this area relatively fragmented.

(ii) Within the desert, the human population is relatively sparse, and the usage of the land is mainly limited to grazing on the fixed and semi-fixed dunes at the edges of the desert. Some of the fixed dunes in the northern desert near the Yellow River plains could be used as agricultural land, with irrigation from the Yellow River, after being leveled off.

(iii) Mobile dunes occupy the majority of the area, taking 80% of the total desert, and mainly comprising sand dune chains and network sand dunes, which are normally 10–15 m high, with a few reaching as high as 50 m. On the Yellow River plains at the northern edge of the desert, there are some sporadic, low (3 m) crescent sand dunes and sand chains with a relatively fast moving speed, which cause damage to the surrounding agricultural traffic. The fixed and semi-fixed sand dunes are limited to the edge of the desert, mainly at the southern edge, with *Meconopsis sphaerocephala*, *Caragana korshinskii*, *Agriophyllum squarrosum* and *Phyllostachys propinqua* grown on them. These plants are generally lower than 5 m. In addition, *Nitraria tangutorum* sand mounds (3 m high) are also found in this area (Zhu et al., 1980; Wang, 2003; Wu, 2009).

2.1.2 Sandlands

Horqin Sandland: The Horqin Sandland is mainly distributed in the diluvial plain in the downstream branches of the Xiliao River in the western part of the Northeast Plain. The northern part of the sandland is also distributed on the alluvial terrace-plains. The main features of the sandland are:

(i) As it is relatively close to the ocean, the Horqin Sandland is impacted by marine weather patterns. Its precipitation is comparatively higher than other deserts or sandlands in the country, with a rainfall of about 300–450 mm. In addition, the branches of the Xiliao River (such as the Xilamulun, Jiaolai and Laoha rivers) run across the sandland, which gives the Horqin Sandland the best water conditions of any of the deserts or sandlands in China. The majority of the sand dunes are covered by plants at a rate of 20–40%, and sometimes even higher than 40%. Most of the plants are *Caragana microphylla*, *Artemisia halodendron* and *Salix flavida*, and there are also scattered shrubs of *Armeniaca sibirica* and *Ulmus pumila*. Most of the dunes are fixed or semi-fixed, and these comprise 90% of the total sandland, with the mobile sand dunes comprising the remaining 10%.

(ii) Although the sand dunes of the Horqin Sandland are mainly fixed and semi-fixed, with a comparatively small distribution of mobile sand dunes, the distribution of these dunes and their characteristics vary significantly between the different regions. The sand dunes in the north of the Xinkai River are scattered across the plains downstream of the rivers originating from the Da Xing'anling Mountains, forming fixed sand dunes (mainly sand ridges) and a marshland mosaic landscape. In the valleys, formed by the low mountains near the middle reaches of these rivers, there are also strips of fixed and semi-fixed dunes extending along the river banks. For example, the sand strip in the Huhu'er River valley stretches intermittently for hundreds of kilometers along the river. To the south of the Xinkai River and the downstream areas of the Xiliao River, the dunes are scattered on the sandy alluvial plains which are crossed by ancient riverbeds with characteristics of fixed and semi-fixed dunes and riverbed billabongs. The sand dunes are mainly concentrated in the south of the main stream of the Xiliao River, from the Balin Bridge in the west to Shuangliao in the east, and this covers 60% of the area of the Horqin Sandland.

(iii) The exploitation of the Horqin sandland has a long history. This sandland has been fully utilized for agriculture and animal husbandry. The relatively flat sandlands are used as crop land, while other sandland areas are used for grazing. Most of the meadows are utilized for grazing and mowing, and some have been reclaimed for cropping, especially the smooth sandy meadows, where the black soil is comparatively thick and loose, with a good nutrient status that provides a high productivity. However, with loose topsoil, the land is easily eroded by the wind, and therefore, shelter belts need to be constructed.

Mu Us Sandland: The Mu Us Sandland is a main component of the Ordos Plateau. Its main features are:

(i) The water resource is abundant compared with deserts west of the Helan Mountains, with an average precipitation of 400–440 $mm{\cdot}a^{-1}$. The precipitation rate decreases from east to west, but still amounts to as much as 250 $mm{\cdot}a^{-1}$. Therefore, the vegetation grows well. However, precipitation occurs in intensive events, usually in the form of rainstorms, and rainfall rates are so variable that the rainfall in a wet year could be two to four times as much as in a dry year. This variation leads to drought and flooding, with dry years occurring more frequently than wet years. In the Mu Us Sandland, not only the precipitation but also the surface water and groundwater are abundant. There are several main rivers (including the Kuye, Tuwei and Wuding rivers), that cross the southeast of the sandland and flow into the Yellow River. In addition, there are several lakes in the interior of the sandland, most of which are sodic lakes (such as Chahan Nor, Bayan Nor, and Nalin Nor) and lakes containing chloride (such as Yanchi). There are also a few freshwater lakes (such as Daotu Lake). In the Mu Us Sandland, there are many rivers formed from sandy springs. These springs are artesian, rushing out from the dunes and the underlying bedrock and becoming the main water supply during the drought seasons.

(ii) There are many plant species which thrive in the Mu Us Sandland. On most of the dunes, *Meconopsis desertorum* communities are dominant comprising more than 20 plants, with a total coverage of 40–50%. *Meconopsis desertorum* and *Caragana microphylia* are the main association types of shrubs and xerophilous grasses and *Sabina vulgaris* plants are sometimes found in this community. In the inter-dune areas and floodplains, there are meadows, saline meadows, and *Salix* spp. woodlands. The three types of important shrubs which grow in the *Salix* spp. woodland are mainly *Salix mongolica*, *Salix psammophila* and *Hippophae rhamnoides*. These plants create unique scenery in the Mu Us Sandland, becoming a natural oasis in the sandland. The *Salix* spp. woodland not only can be used as a good meadow but also has the potential to reduce wind speed, stop the movement of the edge of the mobile sand and regulate water conditions in the inter-dunes and floodplains.

(iii) The interior of the Mu Us Sandland is not only covered by dunes but also with some floodplain and valley terraces, which form one of the unique scenic areas of this sandland, and these areas are also used for agriculture. This landscape is mainly distributed in the southeastern part of the sandland, where the area is broad and the soil contains humus levels higher than 2%, with only a light degree of salinization. Generally speaking, the top 10 cm of soil has a salinization rate lower than 0.8%. The floodplains can be classified as outflow floodplains and inflow floodplains. The outflow floodplains are generally distributed strip-like along the rivers, are low and wet, and liable to flood during the rainy season. The soil type is mainly meadow soil, with some shallow swamp soil. The inflow floodplains normally have a low degree of salinization and are comparatively small in size. The freshwater lake plains are mainly distributed in the east of the sandland, and have a low rate of mineralization, generally about 0–0.3 $g{\cdot}L^{-1}$. In the vicinity of the lake, the soil is mainly weakly salinized (sodic) meadow soil, while the soil distant from the lake is meadow soil or gley meadow soil, which is currently in agricultural use. The valley terraces are mainly located at the southeast of the sandland along the Hongliu River, the Hailiutu River and the Yulin River. These are the main agricultural areas in the Mu Us Sandland.

Otindag Sandland: The Otindag Sandland is located in the eastern part of the Inner Mongolian Plateau. The main features of the sandland are:

(i) Fixed and semi-fixed sand dunes predominate. The annual rainfall ranges from 250–400 mm, so the plants, most of which are species of Gramineae and *Artemisia* spp., have good growing conditions with coverage of 30–50% or more. Therefore, the sand dunes are mostly fixed or semi-fixed, accounting for 98% of the area in the sandland. There are regional differences between the eastern and western parts of the sandland. This difference is related to the precipitation, which decreases from east to west. In the west, most of the dunes are semi-fixed, with scattered mobile crescent sand dune chains, while in the east, the dunes are more fixed and there are typically more shrubs such as *Ulmus pumila*, *Malus baccata*, *Cerasus Humilis*, *Cerasus tomentosa* and *Spiraea japonica*, with *Picea meyeri* and *Pinus tabulaeformis* scattered around. The soils are a sandy chestnut soil and a chestnut-like sandy soil, reflecting the characteristics of steppe soils.

(ii) The broad lowland, which is known as Tara locally, has good conditions for plant growth. The vegetation coverage is usually around 50%, and is mainly pasture. There are many small lakes scattered through the lowland area forming various landscapes. The lakes are supplied by groundwater, most of which has been discharged from underground runoff. Therefore, the water quality is good, and most of the lakes are fresh water. There are a few lakes which have a lakebed formed from the Tertiary red clay layer. This rock layer is waterproof and therefore affects water drainage, making those lakes saline. In terms of the lake basins, the water content is varies so that the outside edge is swamp, mainly dominated by *Carex* spp. and *Phragmites australis*, with free water in the center of the lake basin. The area outside the lake basin is meadow, with the groundwater depth greater than 1–1.5 m. The main plants in the meadow are *Salix microstachya* and *Achnatherum splendens* shrubs. Currently, these lake basins are used as pasture. The lakes with a large area such as Ku'erchagan Nor and Dali Nor are found at the northern edge of the sandland. The formation of the lakes is closely associated with tectonic processes.

(iii) Although the fixed and semi-fixed sand dunes are dominant, their formation varies. Most of the fixed sand dunes are in the form of sand ridges which are arranged in a west-northwest direction and an east-southeast direction, showing the main wind influences. The dunes are typically 15–20 m high, with some as high as 25–30 m. Normally, the vegetation coverage rate is about 30–40% on the sunny slopes, and up to 60–70% on shady slopes. The semi-fixed dunes are scattered, around the fixed dunes resulting from vegetation destruction. Therefore, the semi-fixed dunes are located comparatively close to the herder's settlements, and only a few have been gradually formed from moving sand dunes which have been fixed with vegetation.

Hulun Buir Sandland: The Hulun Buir Sandland is located at the northeastern end of the Inner Mongolian Plateau, and its features are:

(i) Sand dunes scattered in the alluvial plains are formed from lake beds, with some small lakes scattered among the sand dunes.

(ii) Mainly fixed and semi-fixed sand dunes. The Hulun Buir Sandland is the only sandland with natural *Pinus sylvestris* var. *mongolica* forest, and there are *Padus racemosa*, *Rosa davurica* and other shrubs in the understory vegetation (Zhu et al., 1980; Wang, 2003; Wu, 2009).

2.1.3 Gobi

Gobi mainly refers to the flat and undulating ground that is composed of gravel with sparsely growing plants. Gobi is normally considered as a type of desert and gravel land formed by denuded eluvial or diluvial phenomenon in desert areas. The Gobi is widely scattered in the northwest of China. This is a vast area, severely lacking in both water and soil with a sparse population, and has always been treated as a place unfit for human existence.

2.1.3.1 Gobi size

The Gobi of China is mainly distributed in the northwestern regions, including the provinces or autonomous regions of Xinjiang, Gansu, Inner Mongolia, Ningxia, Qinghai and Tibet. According to the census results in 1994 by the former Ministry of Forestry, the total area of the Gobi was 710,730.5 km^2 (Table 2.2) with the Xinjiang Uygur and Tibet autonomous regions containing the largest areas of Gobi, comprising 41.16% and 25.86% of China's Gobi areas, respectively.

Table 2.2 Distribution and dynamic change of China's Gobi areas (km^2)

	Xinjiang	Gansu	Inner Mongolia	Ningxia	Qinghai	Tibet	Total
1994	328,084.9	85,467.1	65,419.1	2,064	45,911.9	183,763.5	710,730.5
1999	307,008.6	61,379.2	69,436.4	1,160.5	40,852.5	184,157.6	663,994.7

When the State Forestry Administration conducted the second national survey of desertification in 1999, the area of China's Gobi had reduced to 663,994.7 km^2, which means that the area of Gobi in China reduced by 46,735.8 km^2 compared to the 1994 data. Gobi in Inner Mongolia and Tibet increased in area, while Xinjiang, Gansu, Qinghai and Ningxia all showed reductions in Gobi areas, with the largest reduction occurring in Gansu Province (Table 2.2).

2.1.3.2 Gobi types

The types of Gobi are classified, based on the geomorphology and the ground material composition, into a denudation (erosion) type and an accumulation type, which can be further divided into other sub-categories.

(i) Denudation (erosion) type of Gobi

This type of Gobi is mainly located in the central and western parts of the Mongolian Plateau and the mountains at the edge of the Plateau. This region has been uplifted continuously since the Cretaceous era, has not experienced marine inundation or violent crustal movement, and has remained relatively unchanged for a long period of time. Compared with the accumulation type of Gobi, the ground surface here is coarse, with larger undulations. The bedrock is often exposed, and there is a thin accumulation of gravel. The angularity of the debris is relatively apparent. This type of Gobi can be divided into two sub-categories:

i) Denudation (erosion) rock Gobi

This sub-category is mainly located in narrow strips in mountains and piedmont at the edge of the Mongolian Plateau such as in the Mazong-Beishan Mountains. There is a distinct quasi-plain phenomenon and the ground is almost Gobi. There is little or very little accumulation of gravel, and most of the Gobi is exposed bedrock (the gravels are either formed by bedrock weathering, or transported from the nearby mountains). The nearby mountains are almost flattened, with only sporadic residual mountains present. The ground is flat with few undulations, and eroded valleys are widely distributed. The rivers are mostly seasonal and the groundwater table is more than 10 m deep. The soil is infertile, such as coarse gypsum brown desert soil and gypsum gray-brown desert soil. The vegetation is sparse, with coverage of less than 1%. The plant heights are lower than 30 cm, and often in a state of dormancy. Scattered *Reaumuria soongarica*, *Nitraria sphaerocarpa*, and *Ephedra Przewalskii* are the common plant species, and species such as *Haloxylon ammodendron* can be found mainly in eroded gullies or small sand dunes, where better plant growth occurs. In these areas the vegetation coverage is up to 5–10%.

ii) Denudation (erosion) diluvial coarse gravel Gobi

This sub-category is widespread in the central and western Mongolian Plateau, and also occurs in narrow strips in the southern piedmont of the Mazong Mountains, the southern piedmont of the eastern Tianshan Mountains, and at the margin of the Qaidam Basin and the Junggar Basin. The surface material is mainly composed of gravel with diameters 2–20 cm, formed from diluvial materials. The psephicity and sorting of the gravel are not good. Generally speaking, the thickness of the gravel accumulation is less than 1 m, and underlying the gravel is flattened bedrock. Further from the mountains, the accumulated particles are finer and thicker. The ground is basically flat, with a typical slope of $3°$ to $5°$. There are well developed eroded gullies and few continuous streams. The groundwater table often exceeds 10 m. The infertile soil here mainly consists of gravelly gray-brown desert soil (desert zone) and brown soil (desert steppe zone). The vegetation in this sub-category is mainly *Reaumuria soongarica*, *Nitraria sphaerocarpa*, and *Potaninia mongolica* with a general coverage of 1–5%.

(ii) Accumulation type of Gobi

This type of Gobi is mainly distributed around the edge of inland basins, such as the Tarim Basin, Junggar Basin, Qaidam Basin, and Hexi Corridor and piedmonts. This type of Gobi is mainly formed by water diluvial processes which transport large amounts of debris from the mountains around the inland basins (such as the Kunlun, Tianshan, Altai, Bayanhar, and Qilian mountains) to the piedmonts or the edge of the basins. The gravel has good psephicity and is well sorted. The accumulation type of Gobi can be divided into three sub-categories as discussed below.

i) Diluvial gravel and gravelly sandy Gobi

This sub-category is mainly distributed along the edge of the basins and the piedmonts. Sometimes the Gobi is present as large areas and sometimes more sporadic in distribution, with an obvious Gobi appearance. The Mazong Mountain, for example, is part of a section of the Precambrian Alxa platform, and is a stable uplift zone with low mountainous residues. The fault block effect of the tertiary Himalayan orogeny resulted in a series of east-west direction land hills, between which are sink regions. Gobi is located at the edge of the sink region, and is formed from the intensively weathered ancient bedrock and the nearby diluvial processes. The ground is basically flat, with a slope of 3° to 5°, and is formed from gravels and gravelly sand. The gravel is basically the same as the mountain bedrock, being mainly granite, gneiss, schist, and quartz, with a diameter of 3 to 10 cm. Due to black gravel surface, this Gobi is called "Black Gobi". The precipitation and surface runoff are scarce, and the groundwater is as deep as 10–20 m. The soil is mainly 50–60 cm thick gypsum brown desert soil. The plants are mainly drought-tolerant vegetation such as *Reaumuria soongarica*, *Nitraria sphaerocarpa*, *Sympegma regelii*, and *Ephedra przewalskii*, with coverage of less than 5–10%.

In the Qilian Mountains, the situation is quite different. The geological structure is a geosyncline, and has been extremely unstable since the end of the Paleozoic era. The Himalayan uplift effect formed a series of large mountains and inter-mountain basins in a northwest-southeast direction. Small areas of Gobi are formed by diluvium at the edge of the inter-mountain basins, where the average elevation is normally less than 2,200 m. The Gobi is composed of coarse gravel materials, the sorting effect is not distinct, and the material has a gray-black color, which is called "White Gobi". The slope is about 5°–10°. As the elevation is comparatively high, with more precipitation, the river network is extensive, and the groundwater depth is about 10–15 m. The conditions are good for plant growth with the coverage in some areas reaching 30%. The vegetation includes plants such as *Kalidium foliatum*, *Reaumuria soongarica*, *Ephedra przewalskii*, and *Nitraria sphaerocarpa*.

ii) Diluvial-alluvial gravel Gobi

This sub-category covers the largest area, and is geomorphologically equivalent to a piedmont fan. The majority of the ground surface is covered with gravel, which mainly consists of diluvium and alluvium formed in the Quaternary period. The gravel has good psephicity and is well sorted. The nature of the Gobi has shown regional differences. For example, in the tilted plain of the south Mazong-Beishan Mountains, where gravel sources are lacking, the Gobi occurs in a narrow east-west band. The gravel layer is about 10–20 m thick; the gravel diameter is about 2–10 cm on average. The gravels have sharp edges with paint surface, and most are composed of siliceous limestone, quartz schist, granite, quartz, and similar materials. The ground is basically flat, and tilts from north to south. Incised by erosion gullies, the ground has slight undulations. Surface runoff is lacking in the rainy season, there are fewer floods, and the water table is about 5–10 m. The soil consists of infertile gypsum brown desert soil. The vegetation is mainly scattered *Reaumuria soongarica* and *Nitraria sphaerocarpa*, and the overall vegetation coverage is less than 1%.

In the northern piedmont fan region of the Qilian Mountains, where the gravel material is comparatively abundant, the Gobi lies in the form of a wide northeast band. The general thickness of the gravel layer is about 100 m, with the gravel diameter 2–20 cm. The gravels have good psephicity, with a gray-black color, and are comprised mainly of limestone, marble and a variety of metamorphic rocks. The ground is basically flat, tilting from south to north, and a lot of rivers flow out from the southern edge of the Gobi, cutting into the gravel layer 20–30 m deep, and finally irrigating the oasis at the north edge of the Gobi. The erosion gullies are well developed, and the groundwater depth is 5–10 m. In this region there are many springs exposed at the surface. The soil type is mainly brown desert soil. Sandy loam within the gravel layer makes the Gobi suitable for cultivation. Plants here have better growing conditions than those in Gobi of the same type (e.g., in the Mazong-Beishan Mountains). Plant species are mainly *Reaumuria soongarica*, *Nitraria sphaerocarpa*, *Sympegma regelii*, *Ephedra Przewalskii*, *Asterothamnus centrali-asiaticus*, *Peganum harmala* and others, with coverage of 1%.

iii) Alluvial-diluvial gravelly sandy Gobi

This sub-category is distributed along modern and ancient riverbeds, such as the Shule River and the Heihe River, and the banks of the middle and lower reaches of other large rivers, and along other depressions in the Mongolian Plateau. The Gobi is scattered around the oases and the saline-alkali soil covering a small area. This sub-category has the most favorable natural conditions of the different types of Gobi. For example, the Gobi at the middle and lower reaches of the Shule River consists mainly of alluvial-diluvial gravelly sand with good horizontal layers, psephicity and sorting with gravel 1–5 cm in diameter. The river water can be used for irrigation, and the groundwater is less than 5 m deep, which is easy to dig for irrigation. The soil type is fertile alluvial soil with more clayey material and a thicker soil layer. The vegetation is comparatively lush, mainly comprising *Peganum harmala*, *Ephedra Przewalskii*, and *Nitraria sphaerocarpa*.

2.1.3.3 The characteristics of the Gobi

(i) Dry climate: The annual rainfall is 200 mm or less. Therefore, the land shares the characteristics of intensive climate variation between the winter and summer, with heat in the summer and autumn afternoons, abundant sunshine, strong winds and high evaporation rates.

(ii) The Gobi is the product of wind erosion: Sand particles within the thick diluvium in the piedmont are blown away by the wind, leaving gravel covering the ground. Eventually a "protective shell" that cannot be moved by wind is formed by the gravel, which protects the underlying sediments from further erosion.

(iii) The physical weathering in the Gobi region is comparatively strong although not as intensive as that of the exposed bedrock.

(iv) The Gobi has a high degree of permeability: In modern times, the scarce precipitation does not cause a comparatively large amount of surface runoff. Therefore, the runoff has only formed gullies several meters wide and up to dozens of meters deep in the piedmont near the rocky mountains.

(v) The ground composition is mainly coarse gravel or bedrock: On the rock Gobi formed by the quasi-plain function, the composition of the materials on the ground are largely flattened bedrock (sometimes covered by thick layer gravel and coarse sediments), with a severe lack of water and soil. The extreme lack of water makes plant growth very difficult and reclamation and utilization of the land problematic. On the coarse gravel Gobi covered by thick accumulations of gravel, the ground materials have different characteristics, but all have a degree of gravel. The water and nutrients are extremely scarce, and the temperature variation is great. Under the gravel, there is a solid impervious crust, making seed germination and development unfavorable. However, the gravel surface and the crust have a role in protecting groundwater and the underlying fine clayey soil.

(vi) The Gobi ground is very flat, even more than desert. There are some fluctuations, and the widely distributed eroded gullies provide relatively good water, soil and climatic conditions, and good conditions for plant growth.

(vii) The soil fertility is low, and soil types are mainly brown desert soil, gray-brown desert soil and brown soil. Normally, the soil is thin with a coarse texture. While the soil lacks moisture and nutrients, it contains abundant salt. As the biological processes are minor there is little humic material, and the soil humic content under the gravel is normally below 0.5%. Because of the dry conditions, leaching from the surface is extremely weak, and the mineral salts have different levels of accumulation in the upper layers. With intensifying drought, gypsum accumulates, normally found in the form of needle-like, fibrous, granular and honeycomb crystals.

(viii) The sparse growth of vegetation: The vegetation is even sparser than in the desert. Vegetation is characterized by shrub and semi-shrub desert and desert steppe, and only simple species, with coverage of 1%. In many places (such as the southern piedmont of the Tianshan Mountains in the Turpan Basin, the north piedmont of Kunlun Mountains in the Tarim Basin, and southern piedmont of Dangjin Mountains district in Qinghai's Qaidam Basin) the Gobi is bare. However, there are some regions (such as the Mazong Mountains in Gansu and the Qilian Mountains), with large shrubs, where the vegetation coverage can reach 20% to 30%. The natural conditions of Gobi in the desert and semi-desert zones are different. Generally speaking, the natural conditions in the desert steppe are good, with vegetation coverage of 5–10%. Ground is mostly covered with gravelly sand, and precipitation is about 200 mm, therefore some steppe species such as *Stipa gobica* and *Stipa caucasica* can be found alongside drought-tolerant small shrubs and semi-shrubs (Xinjiang People's Press, 1959; Wang and Chen, 2008).

2.2 Loess Plateau

There is no formalized definition of the scope of the Loess Plateau. In the 1980s the Comprehensive Management Scheme Group on the Loess Plateau believed that the scope of the Loess Plateau should involve the areas north of Qinling Mountains, south of the Yinshan Mountains, west of Taihang Mountains and the east of the eastern margin of the Qinghai-Tibetan Plateau, which accounts for an area of about 5.8×10^5 km^2. In the 1990s the Comprehensive Science Expedition Team came up with a similar definition to that

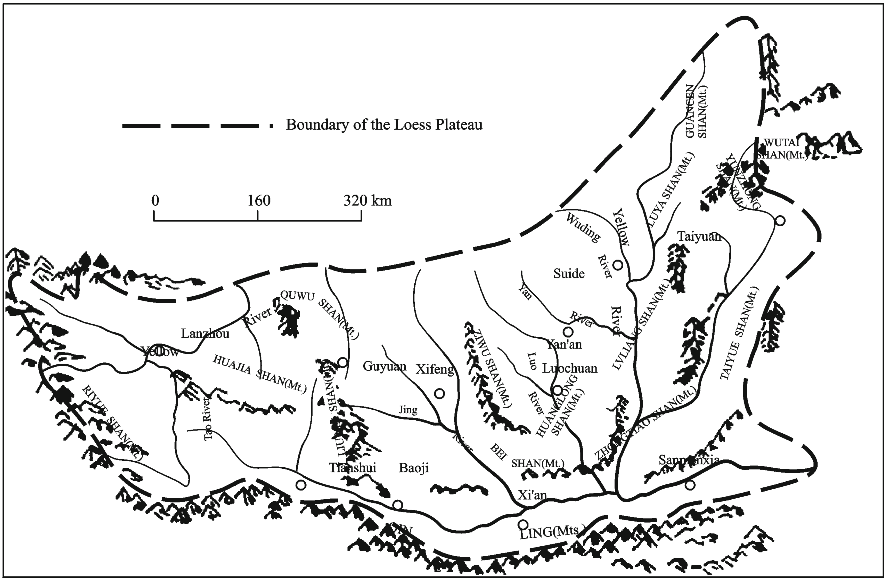

Fig. 2.2 The scope of the Loess Plateau in the middle reaches of Yellow River and the mountain landscape (ISSTLP-CAS, 1991b, with permission from China science and Technology Press)

given by the Comprehensive Management Scheme Group. The area identified by this team covers 6.268×10^5 km^2, with an area suffering from soil erosion of 4.3×10^5 km^2, including 138 counties (banners). The area suffering from severe soil erosion is 2.8×10^5 km^2, and the area suffering from extremely severe soil erosion covers 1.0×10^5 km^2(details on soil erosion can be found in Chapter 5). The scope of the Loess Plateau in the middle reaches of the Yellow River (commonly accepted as Loess Plateau in most references), as defined by Chen et al. (1988), is the western slopes of the Taihang Mountains and west of the Wushaoling Mountains and the eastern slopes of the Riyue Mountains, with northern and southern boundaries at the Great Wall sections and the northern slope of the Qinling Mountains, respectively (Fig. 2.2). According to the measurements, the area of this part of the Loess Plateau is about 3.8×10^5 km^2 (ISSTLP-CAS, 1991b; Li et al., 2008; Zhu et al., 2009).

2.2.1 Geomorphological features of the Loess Plateau

As a combined geomporphological type, the Loess Plateau is surrounded by a series of mountains, namely the Hengshan, Wutai, Taihang, Qinling, Riyue, Helan and Yinshan mountains. The Loess Plateau is actually a basin-like plateau, with a higher altitude in the north and northwest and lower altitude in the east and southeast. The continuous thick loess soil acts as matrix, and high, medium and low mountains including those mentioned above, and others such as Luliang Mountains and Liupan Mountains, form patchy mountainous landscapes within the Plateau.

The Loess Plateau is characterized by loess geomorphology. Loess geomorphology is derived from the common effects of wind-accumulated loess and water erosion. Loess tablelands, loess ridges and loess hills are the basic landscape elements constituting today's Loess Plateau. Most of these landscape elements are controlled by the underlying ancient landform. According to the underlying ancient landform, the loess tablelands can be divided into: (i) wide and gently inclined plains; (ii) high stream terraces; (iii) trapezoidal uplift mesas on both sides of the down faulted basins; (iv) hills with super wide tops. The loess tablelands are incised, forming relic tablelands or fragmented tablelands. Some examples of the typical loess tablelands include the Dongzhi tableland in Gansu, the Luochuan tableland in Shaanxi and the drought tableland in the Weibei region of Shaanxi. The loess relic tablelands and fragmented tablelands are mainly distributed in the regions from Daning to Xixian counties in the southwest of Shaanxi, Changwu and Bingxian counties in Shaanxi, and Pingliang and Qingyang counties in Gansu.

The most typical loess ridges are distributed in Longzhong Basin in the west of the Liupan Mountains, These can also be found in the north of the Hengshan, Yulin, Shenmu, and Fugu counties in Shaanxi, and in Wuqi and Zhidan counties in Shaanxi in the south of Baiyu Mountain. The loess hills are mostly secondary hills formed by erosion from the loess ridges. Therefore, they are distributed mostly in the regions with strong erosion activities, such as the Suide, Mizhi and Zizhou counties in northern Shaanxi. The primary hills are only found in Yongdeng, Gaolan, and other counties in the north of Lanzhou. They are formed from hilly bedrock covered with thin loess (Fig. 2.3).

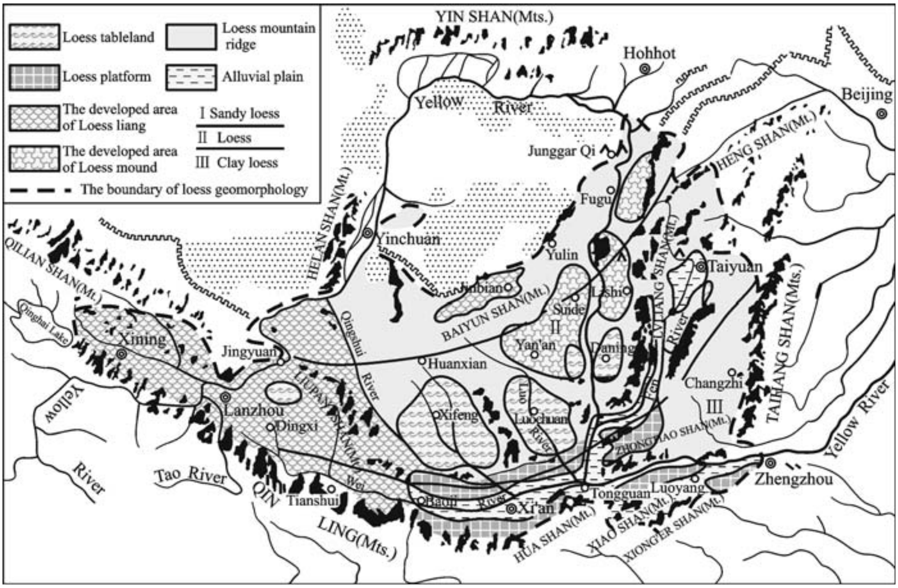

Fig. 2.3 The distribution map of geomorphic type of the Loess Plateau (ISSTLP-CAS, 1991b, with permission from China Science and Technology Press)

According to the characteristics of loess geomorphology, the Loess Plateau can be divided into three regions.

(i) The eastern region: This region is mainly mountainous and includes the Taihang, Luliang, Zhongtiao, Taiyue, and Yunzhong mountains. There are basins among the mountains, such as the Fenhe River Plain and the Guanzhong Plain which stretch westward along the Qinling Mountains. Basins among these mountains have broad and flat bottoms with an altitude higher than 400–500 m. At the edge of the basins and near the mountains, diluvial piedmont highlands are common.

(ii) The middle region: This region stretches from the western Luliang Mountains in the east to the Liupan Mountains and Longshan Mountains in the west, has a south boundary with the Guanzhong Plain and is bounded in the north by the Great Wall. This is the main area of loess tableland and loess hills. The tableland is mainly distributed on both sides of Ziwuling Mountains. Loess hills are mainly distributed to the north of the tableland.

(iii) The western region: This region extends from the west of the Liupan Mountains and Longshan Mountain in the east to the left bank of the Yellow

River in the west, with the Qinling Mountains as its south boundary, and connecting with the Qinghai Plateau in the southwest. The Longzhong Basin is located at the center of this region. Compared with the middle region, the loess hills here are more gentle. There are the Quwu Mountains and the low plain of northern Ningxia in the northern part of this region, the Xinglong Mountains and Maxian Mountains in the middle part, and multi-stepped alluvial, diluvial, or fluvial flat terraces among Lanzhou, Linxia and Lintao counties in the southwestern part (ISSTLP-CAS, 1991b).

2.2.2 Soil

The wide distribution of the loess and loess-like accumulation is the most important characteristic of the Loess Plateau. The types of loess are Holocene loess, Malan loess, Lishi loess and Wucheng loess. The soil of the Loess Plateau has mainly developed from these loess types which have profound impacts on soil characteristics. The soil of the Loess Plateau varies zonally, changing from the southeast to northwest, following the pattern of Lou soil→ black loessial soil, loess soil, and Sierozem → chestnut soil → brown soil → brown desert soil → aeolian soil (Fig. 2.4) (ISSTLP-CAS, 1991c).

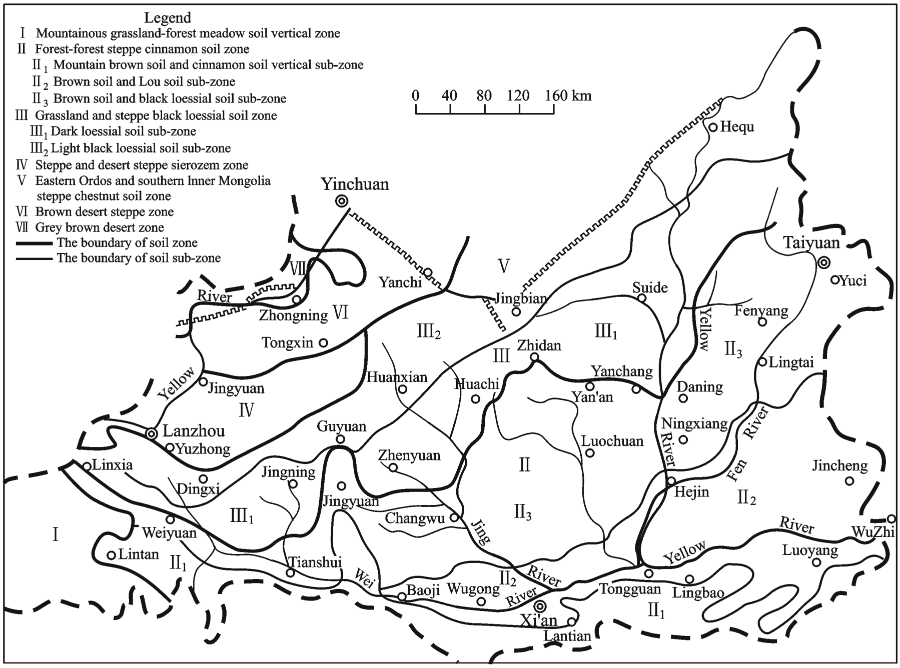

Fig. 2.4 Soil type zones in Loess Plateau (ISSTLP-CAS, 1991c, with permission from China Science and Technology Press)

In addition to zonal characteristics of soils on the Loess Plateau, there are azonal soils which are less clearly related to the climatic and biological conditions. These azonal soils mainly include hydric soil, cultivated soil, alluvial soil and soil formed by other factors, such as irrigation-silted soil, secondary saline soil and paddy soil which are widely distributed in the floodplain area. Additionally, there are fluvo-aquic soils which are widely distributed in the high-level river beaches and washlands. The area of this soil is comparatively small, but this also disturbs the regional distribution of the soil. Here is a brief introduction to the main characteristics of the different soil types.

2.2.2.1 Lou soil

The Lou soil is a type of old cultivated soil. It is formed from brown soil following long years of cultivation and the application of manure.

The texture of Lou soil is often referred to as heavy loam and the entire soil layer has good permeability, drainage and water holding capacity. This type of soil is suitable for arable use and can grow crops like wheat, cotton and corn.

2.2.2.2 Black loessial soil

Black loessial soil is one of the main zonal soils and is an ancient cultivated soil in the northwest. The development of black loessial soil is characterized by a cultivated layer, a humus layer, a carbonate deposition horizon and a parent material horizon. The intact soil profile only exists in less eroded tablelands such as the Dongzhi tableland, Luochuan tableland, Changwu tableland and Heshui tableland. There is a huge difference in the hydro-thermal conditions in the northern and southern areas where black loessial soil can be found. Black loessial soil, which is developed under steppe vegetation, has a unique soil forming process. Black loessial soil is good for crops like wheat, cotton, corn, cereal, sorghum and potato.

2.2.2.3 Loess soil

Loess soil is a kind of cultivated young soil formed directly on loess and loess deposits. The development of the soil profile is not clear. Because of its loose texture the anti-erosion capability of the soil is extremely weak. During the soil forming processes, there are two contrary processes. One is the cultivating and mellowing dominant soil forming process; the other is the soil erosion process. When the former is dominant, the soil fertility is raised gradually as the degree of mellowing increases. If the latter is dominant, the soil forming processes will not develop naturally, and the soil will remain in a partially developed state.

Suitable plants to grow in loess soil include wheat, maize, and millet. Most loess soil has a light loam texture, with good porosity and good permeability to water. The water holding capacity is comparatively low, which reduces the resistance of this soil to drought.

2.2.2.4 Sierozem

Sierozem is a kind of transitional zonal soil type which is found between the steppe and the desert. The landscapes where the Sierozem is located are mainly the Ordos Plateau, hills, low mountains, and alluvial and valley terraces. The formation of the Sierozem is part of the steppe soil formation procedure, which involves accumulation from the processes of leaching and deposition of carbonate. However, the speed of humus decomposition and mineralization surpasses that of the soil forming processes, so the accumulation process is comparatively minor compared with the weak humification process. The parent material of the formed soil is mainly sandy loess soil and sandy soil, with a soil profile thickness less than 1 m. The Sierozem which is located in Jingyuan and Huining counties of Gansu is a medium loam. Due to the presence of drought and sand-dust storms, rainfed agriculture is a very uncertain occupation. Development of water-saving irrigation in areas where conditions permit would facilitate the potential use of the Sierozem and play a role in increasing its fertility.

2.2.2.5 Chestnut soil

Chestnut soil is one of the main types of steppe soil on the Loess Plateau. The vegetation is typical of the steppe, and widely distributed. The formation of the chestnut soil is a dual process involving the accumulation of chestnut humus and a strong calcium carbonate deposition process. The humus layer, calcic deposition horizon and C horizon constitute the profile of the chestnut soil. Chestnut soil is utilized for both agriculture and animal husbandry. In the region of chestnut soil where drought and soil erosion coexist, these cause a huge threat to agricultural and livestock production. Therefore, in terms of increasing the soil utilization, we need to develop water-saving irrigation systems in well-developed regions, and also develop soil and water conservation measures based on local conditions to promote the sustainable development of agriculture and animal husbandry.

2.2.2.6 Brown soil

Brown soil is another main type of steppe soil on the Loess Plateau, and is also a kind of transitional soil that covers the area from the temperate steppe to desert steppe. The climatic condition in brown soil areas is the temperate continental climate type. The natural vegetation types are more arid desert steppe vegetation. The characteristics of the formation of brown soil are that weak light brown humus accumulates in the top layer, while calcium carbonate deposits in the lower layer. In addition, the surface soil is characterized by soil crustal processes. Located at the edge of arid desert, brown soil is lacking in moisture, and the soil is shallow and coarse which severely limits the development of agricultural production. Water-saving irrigation practices should be advocated in the marginal regions to promote the development of agricultural production. In most areas suitable for developing animal husbandry, attention should also be put on the scientific formulation of grazing systems and livestock numbers on the steppe to prevent degradation and ensure the sustainable development of animal husbandry.

2.2.3 Climatic characteristics of the Loess Plateau

The climate of the Loess Plateau is not only affected by its latitude and altitude but also the terrains. The Loess Plateau has typical continental monsoon climate characteristics, which mean that it is cold in the winter, and warm and humid in the summer with rain occurring during the warm periods.

There is a significant change between the winter and summer temperatures on the Loess Plateau, and also significant diurnal variations. The annual average temperature is in the range of 3.6–14.3 °C, with significant differences in different directions. The average annual temperature of Luoyang in Henan Province, in the southeast, is 15 °C, while in Hualong County in east Qinghai, the average temperature is 2.2 °C.

On the Loess Plateau, the differences in diurnal temperature range are also significant. In the southeast, the average diurnal temperature variation ranges from 10–16 °C, similar to that of the Huanghuai Plain. However, in the east, the diurnal temperature variation is up to 15–25 °C. In terms of the $\geqslant$ 10 °C accumulated temperature, there is a significant difference between the west and the east. The accumulated temperature $\geqslant$ 10 °C is 4,941 °C in Luoyang in the east, and only 955.6 °C in Hualong in the west, which is about 4,000 °C less than in Luoyang.

The annual precipitation on the Loess Plateau is 150–750 mm. The annual precipitation of the Fenwei Basin and the loess hills in southern Shanxi and western Henan in the southeast of the Plateau, is 600–750 mm, these regions have the highest rainfall regions on the Plateau. In the area along the Yellow River in Ningxia and Inner Mongolia, the western Ordos Plateau, and the Jingyuan-Jingtai-Yongdeng region in Gansu, in the western and northwestern parts of the Plateau, the annual precipitation is only 150–250 mm. The 400 mm precipitation contour cuts across the Yulin, Jingbian, Huanxian, and Guyuan regions, and divides the Loess Plateau into southeast and northwest sections. The annual precipitation gradually reduces from the southeast to the northwest. During the year, the majority of the rainfall occurs during the three months of July, August and September, and this accounts for 60–80% of the total precipitation. The precipitation in winter is normally about 5% of the total. The precipitation on the Loess Plateau has an uneven annual and seasonal distribution. Impacted by the monsoon climate, the relative variation of precipitation between years is 20–30%. The relative seasonal variation is even higher, normally 50–90%. The precipitation in wet years is often several times higher than the precipitation in the dry years. The torrential rains in this district are mainly focused in northern Shaanxi and western Shanxi provinces, and in the Junggar of Inner Mongolia. The rainfall intensity of the biggest storms can reach 2 mm·min^{-1}.

The annual evaporation on the Loess Plateau is generally higher than the annual precipitation, and is up to 1,400–2,100 mm·a^{-1}. The overall pattern is of low evaporation in the south and east, and high evaporation in the north and west. The variation in evaporation between years is highest at the end of the spring and the beginning of the summer, and lowest in the winter (Qian, 1991).

The climate resources of the Loess Plateau also provide both favorable and unfavorable conditions for agriculture, forestry and animal husbandry. One of the favorable conditions is that solar energy resources are abundant, which is good for photosynthesis and nutrient accumulation in plants. The total solar radiation in the region is 50.2–67.0$\times10^4$ J·cm^{-2}, with an increasing trend from the southeast to northwest. The solar radiation in the western and northwestern areas ranges from 58.6$\times10^4$ J·cm^{-2} to 67.0$\times10^4$ J·cm^{-2}, with an effective radiation 4.2–6.3$\times10^4$ J·cm^{-2} higher than on the North China Plain. Second, the diurnal temperature difference is huge. The crops accumulate abundant material during the daytime, and consume little at night, thus increasing crop yield. The third favorable condition is that the synchronization of rainfall and temperature meets the plants water and heat requirements, which allows for highly efficient utilization of the limited precipitation resources and the abundant energy resources. There are many unfavorable climate factors which can reduce the productivity of agriculture, forestry and animal husbandry. These factors are (ISSTLP-CAS, 1991a):

(i) Drought: This occurs due to the low precipitation, the inconsistent distribution of precipitation and high evaporation. There is a saying that "There are nine drought years in a decade";

(ii) Rainstorms: Frequent rainstorms occur during the rainy season, often causing dam breakages and the destruction of farmland;

(iii) Frost which is frequently intensive. The frost comes early, and can cause significant damage to crop yields;

(iv) Hail, which is often accompanied by strong winds and heavy rain.

2.2.4 Vegetation

The Loess Plateau should theoretically have three vegetation zones –forest, steppe and desert zones. The whole region can actually be divided into five vegetation zones as well as transitional vegetation zones: forest zone, forest steppe zone, typical steppe zone, desert steppe zone and steppe desert zone (ISSTLP-CAS, 1991d; Cheng and Wan, 2002). These zones are distributed from southeast to northwest in the order above, and can be seen in Fig. 2.5, below.

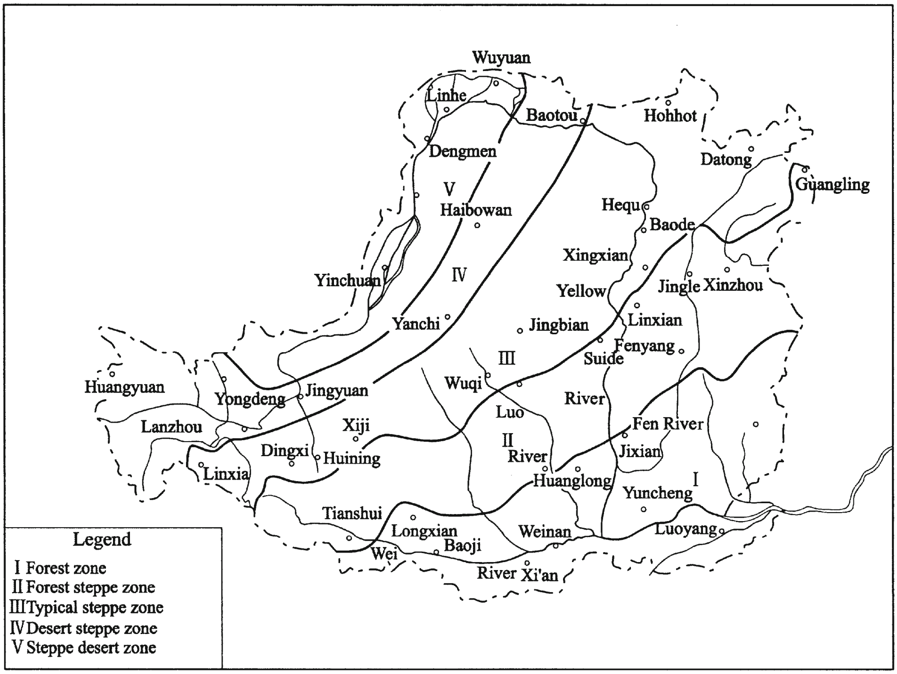

Fig. 2.5 The vegetation zones in Loess Plateau (ISSTLP-CAS, 1991d, with permission from China Science and Technology Press)

2.2.4.1 Forest zone

This zone is located in the southern part of the Loess Plateau. The typical vegetation in this region is broad-leaved forest, of which *Quercus variabilis* and *Quercus acutissima* are representative. In the warm coniferous forests there are mainly *Pinus tabulaeformis*, *Platycladus orientalis* and *Pinus bungeana*. The dwarf trees include *Morus alba* and *Ulmus pumila*, and the shrubs are represented by *Forsythia suspensa*, *Syzygium aromaticum*, *Vitex negundo* var. *heterophylla* and *Ziziphus jujuba* var. *spinosa*. On the slopes of the loess hills, there are *Chrysanthemum indicum*, *Spodiopogon sibiricus* and *Bothriochloa ischaemum*.

2.2.4.2 Forest steppe zone

This zone is located to the northwest of the forest zone and is bounded to the north by the typical grassland, and is a transitional zone between forest and steppe. The main landscape in this region is undulating loess hills. The main difference with the forest zone is that steppe vegetation becomes comparatively dominant on the loess hills. *Bothriochloa ischaemum* steppe, *Stipa bungeana-Bothriochloa ischaemum-Lespedeza davurica* steppe, *Artemisia giraldii-Stipa bungeana* steppe, and *Stipa bungeana-Lespedeza davurica* steppe are dominant vegetation associations. The shrubs are mainly mesic-xerophytes and xero-mesophytes, such as *Sophora viciifolia*, *Prinsepia uniflora*, *Tamarix ramosissima* and *Lycium chinense*. The middle and low mountains contain the most shrub developed regions. It is common to find *Ostryopsis davidiana*, *Spiraea salicifolia*, and *Rosa xanthina* on the shady slopes and *Hippophae rhamnoides* on the sunny slopes. Within this region, the forest vegetation is mainly found in the higher mountain areas and shaded valleys, with pure or mixed forests containing *Pinus tabulaeformis*, *Quercus liaotungensis*, *Betula platyphylla* and *Populus davidiana*.

2.2.4.3 Typical steppe zone

The typical meadow steppe zone is located to the northwest of the forest steppe zone, and bounded by the desert steppe in the north. The main feature of the vegetation in this zone is the dominant steppe vegetation, of which *Stipa bungeana* is most widely distributed, with *Artemisia giraldii* steppe also common. In the upper Huajialing Mountains, Baiyu Mountains and the top of the loess hills, small shrubs such as *Thymus mongolicus*, *Artemisia frigida*, and *Potentilla acaulis* associated with *Stipa* spp. compose the steppe. The shrubs in this zone are mainly *Caragana korshinskii* and *Caragana microphylla*. Sparse *Caragana intermedia* and *Artemisia ordosica* communities, dominate the sand-covered loess hills.

2.2.4.4 Desert steppe zone

This zone is located to the northwest of the typical steppe zone. The vegetation is dominated by different types of *Stipa breviflora* steppe. The northern part of this zone is a combination of relic loess hills and sandland. The relic loess hills are mainly covered with *Stipa breviflora* and *Stipa glareosa*, and the sandland is covered with sandy plant communities such as *Sophora alopecuroides*, *Glycyrrhiza uralensis* and *Pennisetum centrasiaticum*, and semi-shrub communities such as *Meconopsis desertorum*, *Meconopsis sphaerocephala*. In the sandland of the central Ordos Plateau, *Artemisia ordosica*, *Caragana korshinskii*, and *Caragana intermedia* are predominant.

2.2.4.5 Steppe desert region

This zone is located at the northwestern end of the Loess Plateau. The northern part of this zone is the Qubqi Desert, and the vegetation mainly comprises sparse semi-shrubs such as *Meconopsis desertorum*, *Meconopsis sphaerocephala* and *Calligonum mongolicum*. The southern part of this zone has a landscape of denuded low hills. Super-xerophytic shrubs and small semi-shrub communities including *Kalidium foliatum*, *Kalidium foliatum*, *Sympegma regelii*, *Sympegma regelii*, and *Anabasis brevifolia* are dominant.

2.3 Loess-desert transitional belt

China's loess is widely distributed in the mid-latitude regions, with a thickness, scale and distribution which are rare in the world. In this section, we introduce the relationship between deserts and loess formation, loess distribution and its physical properties in detail.

2.3.1 Role of deserts in the formation of loess

From the beginning of the 1950s, the Quaternary research team, lead by Mr. Dongsheng Liu, has undertaken a comprehensive study on the loess, considering both temporal and spatial scales. They have improved the "aeolian loess hypothesis" and also proposed the ideas that: the source material for the loess comes from the external desert and Gobi region; the loess started accumulating about 2.6 million years ago; and at least 37 climate cycles have been recorded. These remarkable results make the research into China's loess a world leading achievement.

Spatially, China's Gobi, desert and loess have significant band-like distribution, from the northwest to the southeast. This distribution pattern is the most powerful evidence for the "aeolian loess hypothesis", and also shows that there is an inseparable relationship between the loess and its material sources, the desert and Gobi. The formation of the loess includes production (the formation of dust material in the source area), entrainment (the process of dust being blown into the air), transportation (the dust removal by different airflows), deposition (the accumulation process downwind) and the loessification process (the formation of soil following dust accumulation).

Fig. 2.6 is a scientific generalization and illustration of the loess. Due to a new Ice Age following the Quaternary global cooling trend, glaciers in the northwest mountainous region are well developed. Due to the grinding effect of the glaciers and the strong physical weathering of the rocks, a large amount of dust and powdered materials are produced and eventually moved by water to the piedmont and the sedimentary basins. The climate in the arid and semi-arid regions is an important background to the formation of the loess and also needs to be considered. The climatic conditions in spring in East Asia area are extremely variable. Strong air currents frequently come from Siberia, as well as cyclonic air flows from Mongolia and active frontal zones. In addition to these factors, there is often dramatic geographical turbulence which forms cold fronts. At ground level, wind speeds can exceed 10 $m \cdot s^{-1}$, and dust can be raised to a height of 1,000 m above ground level. Following entrainment, the dust will be moved in a southeasterly direction near to the ground by the westerly turbulence. As it moves, the dust will deposit and eventually be accumulated. The entrainment, transportation and deposition processes that occurred with the original dust have been confirmed through observations of modern dust storms (Liu et al., 1981; Sun et al., 2000).

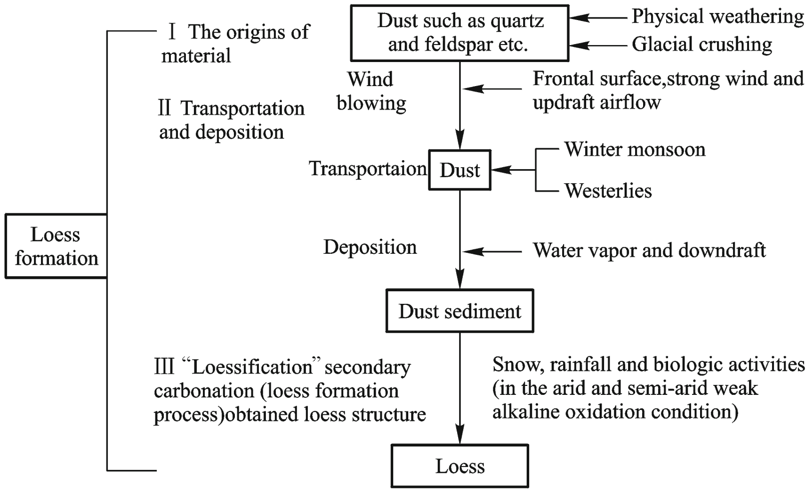

Fig. 2.6 The formation of the loess (Liu, 1985, with permission from author)

The accumulated dust is not loess. The process of converting dust into loess can only occur under specific environmental conditions. It is important to emphasize that not all the accumulated dust will be changed into loess because some of the dust is lost through erosion processes. Generally speaking, the limited precipitation in the loess accumulation areas not only maintains a certain level of surface vegetation which is helpful to dust accumulation, but also avoids the loose dust being completely eroded by rainwater. The weak alkaline environment of the arid and semi-arid steppe is conducive to secondary carbonate processes associated with formation of micro-aggregates and micro-assemblies. Secondary carbonate deposits form on roots and insect hole walls, and play a bracketing role in soil structure formation. This process in the arid and semi-arid biogeochemical environment is the loessification: the beginning of loess formation.

The emergence of the Loess Plateau is part of the complicated geological history of the Asian continent in the Cenozoic period. It is the integrated effect of a variety of geological forces. The development of an arid climate and the formation of desert and Gobi in the northwest region provide the material conditions for the formation of the Loess Plateau.

In the dry-cold periods, strong winter winds and northern branches of westerlies moving to the south provided the impetus for dust accumulation. After the dust was deposited in the Shanxi, Gansu and Shaanxi regions, the gently undulating hills and flat bedrock basins allowed the dust to accumulate. Meanwhile, the accumulated dust experienced a series of secondary changes, which lead to the eventual formation of the Loess Plateau landscape. This process can be also illustrated in a conceptual model (Fig. 2.7). The three main zones which are involved in the formation and distribution of the loess are described below.

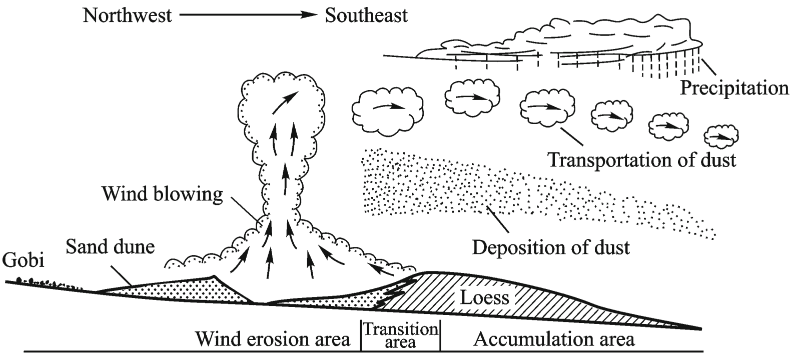

Fig. 2.7 The blowing, transportation and accumulation model

The wind erosion zone: In the northwest of the Gobi and desert, the wind is strong, the climate is dry, and the vegetation cover is poor. The year round surface wind disturbance leads to dust being carried in the lower atmosphere. Under certain climatic conditions, the dust can climb up to a height of several thousand meters above ground level, moved by the winter winds or the westerly to the southeast. Therefore, this region becomes a source of dust, and the erosion here is mainly caused by wind. The wind-eroded Yardang landform is widely distributed.

The desert-loess transitional zone: The loess accumulation scope is closely related to desert expansion and shrinking in this zone. When the climate was cold and dry and geological force of the wind was strong, the sand dunes expanded southward, and the northern boundary of the loess accumulation also moved to the south. When the climate turned warm and humid, and the geological force of the wind weakened, the loess accumulation boundary line advanced northward. An overlapping pattern of loess and ancient aeolian sand deposition layers can be seen in the geological profile, reflecting the repeated processes of desert expansion and contraction. The width of the transitional zone in a north-south direction is about 100 km.

The loess accumulation zone: To the southeast of the desert-loess transitional zone is the loess accumulation zone, which is characterized by rich air moisture and weak winter winds. Regardless of whether the conditions are cold Ice Ages or warm interglacial periods, loess is deposited in this zone. The loess accumulation zone can be further classified on the basis of geographical location. First, in the northwest part of the Loess Plateau, due to close proximity to the dust source zone and strong winds, the accumulation of the dust with coarse particles is fast, and the loess thickness can reach more than 400 m. However, during the peak of the cold Ice Age, discontinuities in deposition caused by wind erosion can be found in the loess profile. In the southeastern part of the Loess Plateau, the weaker winds and higher precipitation during the warm interglacial periods lead to discontinuities in deposition caused by water erosion in the loess profile. Compared with the northwestern and southeastern regions, the intensity of wind and water erosion in the central part of the Loess Plateau is low. The tableland that has the largest areas of loess and the most continuous loess deposition is also located within this region.

2.3.2 Distribution of the Loess

China's loess and loess-like rock lies in a belt-like distribution in the south of the Kunlun Mountains and the Qinling Mountains, and the south of Altai Mountains, the Alxa Plateau and the Xing'anling Mountains. The eastern end of the loess belt extends from the northern part of the Songnen Plain, to the middle and lower reaches of the Yangtze River, and is located between N 30°–49°. In the center of China's loess, located at N 34°–45° latitudes, the loess is the most developed in China. There are several notable features of the geographic distribution of the loess and loess-like rock in China which are controlled by the mountains and the climatic zones.

(i) Loess and loess-like rock is basically located in the northern part of China. The Qinling Mountains, the Qilian Mountains, and the Kunlun Mountains form a boundary line, and in addition to sporadic distribution to the south of this line, the loess and loess-like rock is mainly distributed between N 30°–48°.

(ii) The distribution of the loess and the loess-like rock extends in an east-west direction as a result of the mountains and terrain of the northern Chinese region as well as the belt-like features of the climate.

(iii) The loess and loess-like rock, desert and Gobi form a significant band arrangement from the south to the north (Fig. 2.8).

(iv) The loess and loess-like rock forms a band of sediment in an east-west direction cutting across northern China. However, the loess has many regional variations with loess-like rock. The loess is largely located at the center of this band, while the loess-like rock is mainly distributed at the eastern and western ends. We describe the loess and loess-like rock in four geographical regions from east to west, below.

2.3.2.1 Northeast

Loess is present in relatively small scattered areas located mainly to the west of the Xinkai River and the Xiliao River alluvial plain, and in the eroded middle and low mountains of the Rehe Mountains in the southwestern part of this region. Loess-like rock is widely distributed in the central, northern and southern parts of this region.

Loess in this region can be divided into loess and sandy loess based on particle size. The loess is mainly located in the south of the Wengniute Qi,

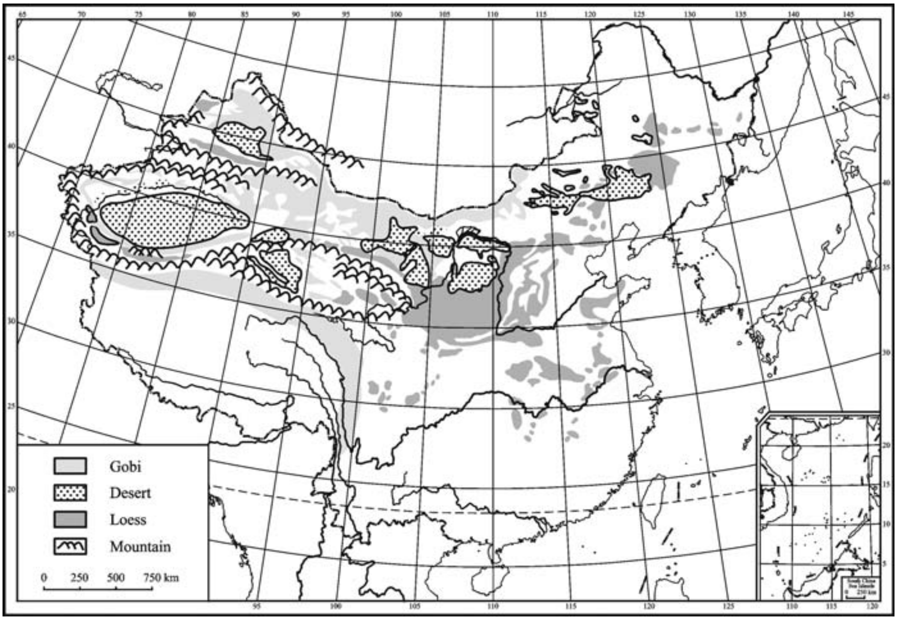

Fig. 2.8 The distribution of Gobi, desert and loess in China (Sun, 2004, with permission from author)

Chifeng, Bianjiangqiang and Guojiatun and sandy loess is found to the north of these locations. The loess-like rock is widely distributed in the Songnen Plain other than in a few swamps and valleys, and in the north of the Liaohe River Plain and the north of Shenyang, with a scarce distribution in the south. There are smaller areas of loess-like rock in the eastern and southern part of the Xinkai-Xiliao River and in the Rehe Mountains.

2.3.2.2 North China

The loess in the North China Plain is much more developed than that in the northeast region, but is less developed than that of the Loess Plateau. The loess-like rock distribution is less than in the northeast. The loess and loess-like rock extends in a belt-like distribution along the piedmont belt. The loess is mainly distributed on the piedmont foothills and mountainous slopes with high elevations, while the loess-like rock is mainly distributed in the swamps, plains and valleys. The loess in this region forms a less continuous surface layer than in the Loess Plateau, but comprises a relatively continuous and thin surface layer in the areas of Zhangjiakou, Pangjiabao, Xuanhua, Longguan and Huailai counties.

The loess in the North China Plain can be divided into Malan loess and Lishi-Wucheng loess.

The Malan loess is seen in the southern piedmont of the Yanshan Mountains, the eastern piedmont of the Taihang Mountains, the piedmonts of the

Taishan and Lushan mountains and the piedmonts and basins in the north of the Shandong Peninsula.

The Lishi-Wucheng loess can be seen along the Yanshan Mountains and the eastern piedmont of the Taihang Mountains. There are also small areas in the eastern piedmont of the Qinling Mountains and the piedmonts of the Taishan and Lushan mountains.

The loess-like rock is more widely distributed than the loess in this region. It can be seen along the southern piedmont of the Yanshan Mountains, the eastern piedmonts of the Taihang and Qinling mountains, and south central part of Shandong Province and the northern part of the Shandong Peninsula. Additionally, there are areas of loess-like rocks in the northern Hai River Plain and parts of the Yellow River plains.

2.3.2.3 Middle reaches of the Yellow River

The middle reaches of the Yellow River has the shape of a quadrangle surrounded by mountains, with the Helan Mountains in the west, the Yinshan Mountains in the north, the Taihang Mountains in the east, and the Qinling Mountains in the south. The loess is widely distributed within this quadrangle, covering nearly all the ground. From the Taihang Mountains westward, the loess is even more widely spread. This tendency ends at the Wuqiaoling Mountains in Gansu Province where the large areas of loess decreases. In this region, there is a wide distribution of loess in Gansu, Shanxi, Shaanxi and Henan provinces but not in Qinghai Province. In the region between the Liupan Mountains and the Luliang Mountains, particularly, there is a continuous coverage of thick loess covers over the Tertiary formations and other ancient bedrock in different forms. This area is the famous Loess Plateau, where loess cover accounts for 72% of the whole region.

The modern terrain in this region was formed after the movement of the Yanshan Mountains in the Cretaceous period. The Taihang, Luliang and Liupan mountains are the major tectonic belt in this region, while the loess is a slight modification to the ancient terrain. Therefore, the modern terrain in this region is basically a continuation of the ancient terrain, and can be divided into three sub-regions according to terrain and geomorphological differences.

(i) The western sub-region between the Wuqiaoling Mountains and the Liupan Mountains. The loess is widely distributed on the mountainous slopes, basins and the high terraces. The accumulation of the loess basically reflects the fluctuations of the bedrock topography.

(ii) The central sub-region between the Liupan Mountains and the Luliang Mountains. The loess here is continuous, filling most of the original valleys and basins. At the bottom of a few deep valleys, the bedrock can also be seen, with loess more than hundreds of meters deep.

(iii) The eastern sub-region between the Luliang Mountains and the Taihang Mountains. Here, the obvious mountain-basin geomorphology can be seen. The loess covers the basin margins and the river terraces. A thin loess layer can also be seen in the catchments among basins.

2.3.2.4 Northwest inland basin

The western part of Gansu, Qinghai and the Xinjiang Uygur Autonomous Region comprise China's inland basin in the west of the Loess Plateau. The loess is mainly distributed in the mountains to the west of the Junggar Basin, the Tianshan Mountains, and at the outer edge of the Tarim Basin, the Hexi Corridor and the eastern Qaidam Basin. The loess of the Junggar Basin is mainly distributed in mountains in the west of the basin and the Kupu Valley in the south of the basin. It is arranged with a belt-like formation along the southern piedmont of the Tianshan Mountains in the south of the basin. The loess of the Tarim Basin is mainly distributed in the northern piedmont of the Kunlun Mountains in the western and southwestern parts of the basin.

The loess-like rock is mainly distributed in the Junggar Basin, Tarim Basin and Hexi Corridor, with a small area in the Qaidam Basin as well.

2.3.3 Physical properties of the loess

The physical properties of the loess also vary in a belt-like form similar to the loess distribution, and including particle size, shear strength and collapsibility (Table 2.3). These properties determine the differences in the resistance of loess to erosion.

Table 2.3 Physical and mechanical properties of the Malan loess from different locations on the Loess Plateau

	Physical properties				
	Specific weight (ΔS)	Bulk density γ ($\mathrm{g{\cdot}cm^{-3}}$)	Average water content W (%)	Porosity (%)	Plasticity index W_n
Zone I: Sandy loess	2.691– 2.706	1.312–1.442	4.97–10.50	46.68–50.10	7.55–11.70
Zone II: Loess	2.698– 2.720	1.281–1.632	10.24–20.02	39.70–52.40	9.81–14.30
Zone III: Clayey loess	2.706– 2.738	1.367–1.618	17.45–24.70	40.40–49.40	10.44–15.70

	Mechanical properties			
	Comparative sinking index (I_n)	Average consolidation rate $C_v^1(\mathrm{cm^2{\cdot}s^{-1}})$	Inner frictional angle (degree)	Cohesion ($\mathrm{kg{\cdot}cm^{-2}}$)
Zone I: Sandy loess		3.20×10^{-4}–1.84×10^{-1}	28.7	0.128
Zone II: Loess	0.015 7–0.087 5	1.31×10^{-4}–5.50×10^{-3}	24.1–27.8	0.060–0.608
Zone III: Clayey loess	0.002 6–0.067 6	3.50×10^{-5}–7.85×10^{-3}	22.2–26.9	0.120–0.522

(Adapted from the data of Northwest Shaanxi Water Scientific Research Institute)

2.3.3.1 Particle size of the loess

China's loess is basically composed of particles smaller than 0.25 mm in diameter. Malan loess particles become gradually finer from the northwest to the southeast, and can be divided into sandy loess, loess and clayey loess around the Ordos Plateau (Fig. 2.9) (Liu, 1966).

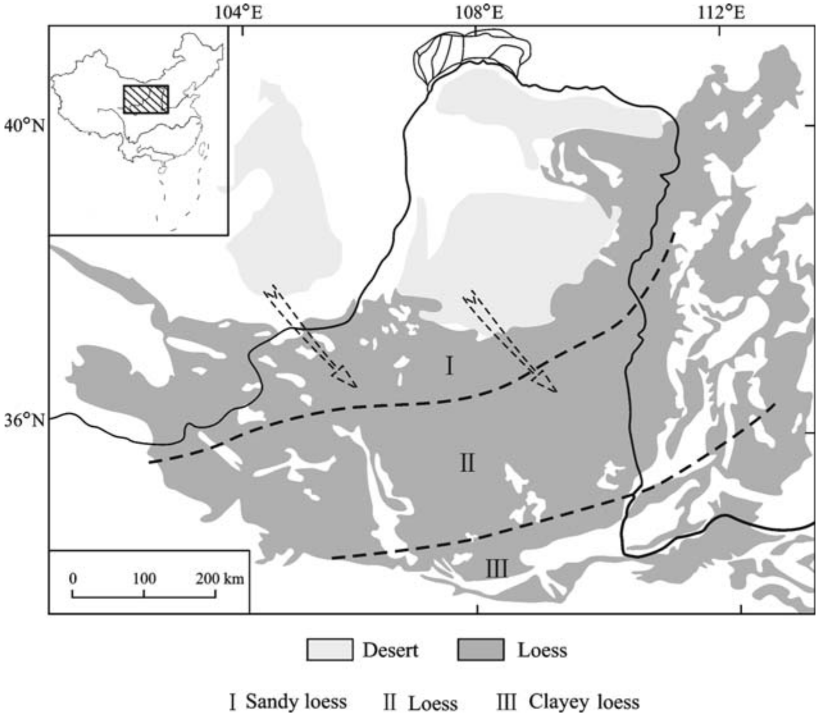

Fig. 2.9 The distribution of the loess (Liu, 1966, with permission from author)

(i) Sandy loess zone: The content of the fine sand is 23.6–72.4%, clay is 7.0–20.7%, and the median particle size is 0.026–0.076 mm. This zone with the Mu Us Sandland as the northern border, and Tongxin in Ningxia, Jiaxian in Shaanxi and Xingxian in Shanxi as the southern border.

(ii) Loess zone: The fine sand content is 11.1% to 31.5%, the clay content is 8.1–30.4%, and the median particle size is 0.016–0.032 mm. This zone borders with the sandy loess zone in the north, and the southern boundary generally follows the Minhe in Qinghai, Lanzhou, Huining and Pingliang in Gansu, north Yijun and south Luochuan in Shaanxi province, and Xixian and Wucheng in Shanxi province. This zone is the main loess tableland zone.

(iii) Clayey loess zone: The fine sand content is 11.4–21.9%, the clay content is 18.0–27.8%, and the median particles size is 0.018–0.027 mm. This zone borders with the loess zone in the north, and the southern boundary line is along the Qinling Mountains and Funiu Mountains.

This belt-like distribution of particle size can also be found in the inland basins of the southwest, northeast, and in some places in north China. For example, at the southern edge of the Junggar Basin, loess becomes finer from the northwest to the southeast, as the particle sizes change from sandy loess to loess. At the south edge of the Qaidam Basin, the size of the loess particles becomes finer from west to east. The characteristics of the loess particle size distribution provide strong supporting evidence for the aeolian deposition hypothesis of the loess.

2.3.3.2 Collapsibility of loess

The collapsibility of loess refers to a characteristic where a sudden subsidence can occur in the loess after being wetted by water without additional pressure. If the subsidence occurs due to its own weight, it is called a self-collapsible phenomenon. If the subsidence is caused by an additional weight load, it is called as non-self-collapsible phenomenon. The particles of self-collapsible loess are coarse and porous, with obvious variations in particle size. The particles of non-self-collapsible loess are fine, with low porosity and have even particle size.

The Liupan Mountains can be considered as a boundary between these two types of loess, i.e., there is self-collapsible loess to the west of the mountains and non-self-collapsible loess in the east of the mountains.

2.3.3.3 Shear strength of loess

The shear strength is determined by the soil formation factors, soil composition and the climatic conditions. The shear strength is closely related to soil moisture. Under different pressures and temperatures, the inner frictional angle of the loess varies from 5° to 31°, and the cohesion is 0–0.042 MPa. The inner frictional angles of the loess in northern China are normally about 27°–28°. Generally speaking, the inner frictional angle becomes smaller from the northwest to the southeast.

In short, the structure and composition of the loess, and the climate all vary regionally, making the mechanical characteristics of the loess vary regionally as well. The density, water content and shear strength increase from the northwest to the southeast, while the collapsibility and the permeability decrease.

The mechanical characteristics also vary with loess formation time. Normally, the newly deposited loess has a comparatively low density and higher porosity, and relatively high collapsibility. The mechanical characteristics of late Pleistocene loess are similar to the newly deposited earth, in that it has comparatively low structural intensity, and is greatly influenced by soil wetting. Landslides and soil erosion are typical in this kind of loess in the middle reaches of the Yellow River. The loess of the mid-Pleistocene era forms the majority of the loess stratum, and is composed of a mosaic of loess, ancient soil layers and calcium accumulation layers. The characteristics of loess soil are high bulk density and non-collapsibility or slight collapsibility. The early Pleistocene loess has a thin stratum. Compared to the mid-Pleistocene loess, it is denser and less collapsible.

The changing trends in loess mechanical characteristics coincide with the regional changes in the loess geological structure and the material composition from the northwest to the southeast.

The northeastern part of the Loess Plateau is adjacent to the Gobi and desert and close to the material source region for the Malan loess (i.e., the wind erosion area). The accumulated particles are coarse. In terms of the physical and mechanical properties, this loess has comparatively high porosity and inner frictional angle, and low bulk density, plasticity and cohesion. The above characteristics describe the loess with poor resistance to erosion in this region. Wind tunnel experiments have shown that the composition of the surface material particles is an important factor in the soil's erosion resistance ability. In terms of the particle constitution, the most erosion-prone soil has clay content of less than 10% (Pye, 1995). The results of the particle size analysis for loess particles from different parts of the Loess Plateau show that the clay content of the loess in the northwestern part of the Loess Plateau is lower than 10%. On the particle size map (Fig. 2.10), it can be seen that

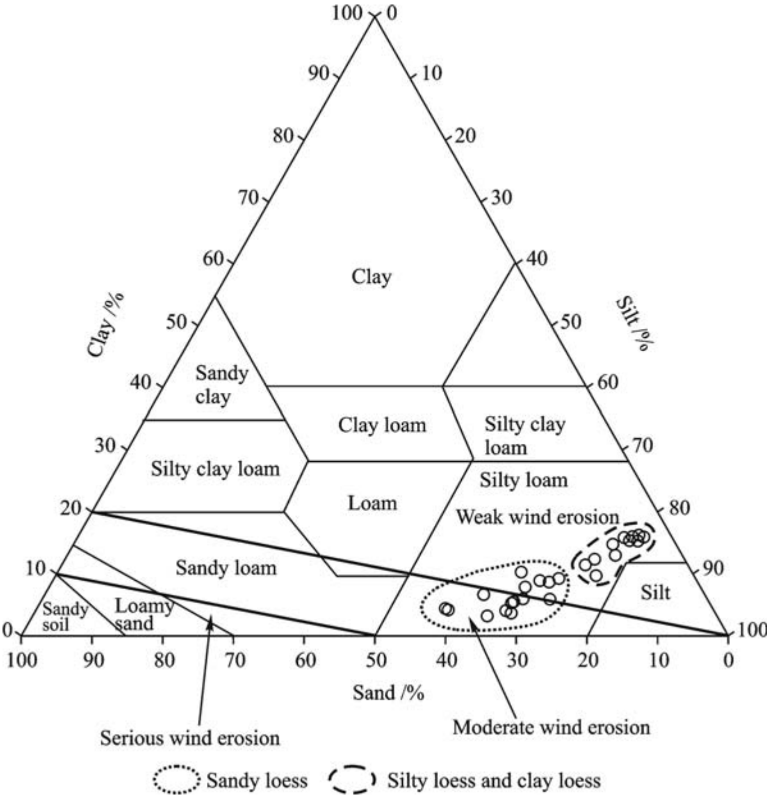

Fig. 2.10 The soil particle characteristics of the northwest Loess Plateau which prove this region is wind-erosion prone area

most of the surface particles are readily prone to wind erosion. Loess in the northwestern part of the Loess Plateau has high porosity, low cohesion and low shear strength, and is prone to water erosion. There are numerous secondary and tertiary river tributaries in this area making this place a key water erosion area in the Loess Plateau. Therefore, the loess in the northwestern part of the Loess Plateau is at risk of wind and water erosion, and this region should be considered as key soil erosion control area.

The southeastern part of the Loess Plateau is long distance from the wind erosion (source) region, and the accumulated particles of the Malan loess are finer, which is advantageous for the soil formation process. In addition, the climate conditions in this region are more humid than in the northwestern part, and vegetation is well developed. After accumulation, the Malan loess has been subject to wind erosion, biological processes and precipitation. Over time, the Malan loess becomes finer and finer, the clay content gradually increases. The porosity, and inner frictional angle decrease, and the specific gravity, bulk density, plasticity and cohesion increase. Therefore, the likelihood of soil erosion in this region is relatively low. However, the precipitation here is higher than that in northwestern area, with rainfall mainly occurring in July, August and September. This intensive rainfall can easily cause soil erosion and gully erosion, and therefore, this region is also one of the key regions for water erosion control.

2.3.4 Loess-desert transitional belt

Although the Gobi and deserts in the northwest provide rich materials for loess deposition in China, only the Mu Us Sandland shares a direct border with the Loess Plateau. This area is the loess-desert transitional belt, and within this belt, the aeolian sand is interleaved with loess and ancient soil, forming a typical aeolian sand – loess – ancient soil sequence. The formation of this unique sedimentary sequence is related to the advance and retreat of the desert caused by cyclical climatic change during the Quaternary period. During the last glacial maximum, the Siberian high pressure systems were strong, with frequent and intensive outbreaks of cold air, resulting in poor vegetation growth, and the summer monsoon had a short duration and low intensity. During this time, the Mu Us Sandland extended southeastward into the Loess Plateau. The ancient aeolian sand layer found in the soil sequence was formed as the southerly weather patterns advanced a sand layer which was later buried by loess and ancient soil. In contrast, during the non glacial maximum of the Ice Age period, the winter winds were mainly dry and cold, but weaker than those during the glacial maximum, and the conditions for vegetation growth were reasonably good so the loess-desert transitional belt is mainly accumulated loess. During the warm interglacial period, the strength of the Siberian high pressure system weakened gradually and summer monsoon activities increased. The surface vegetation density increased, and the blown-sand activities decreased leading to a decrease in the rate of the dust accumulation, characterized by the soil formation process.

During field investigations among the aeolian accumulated materials at the loess-desert transitional belt, the most complete profile was found in the Shimao village of Hengshan County, Shaanxi. The profile was 74.5 m thick, overlying purple sandstone of the Cretaceous period. The profile is at least 580,000 years old (Fig. 2.11). There are 13 layers of ancient aeolian sand in this aeolian accumulated sequence, which proves that the Mu Us Sandland was formed at least 580,000 years ago, and since then, there have been at least 13 cycles of large scale desert expansion (Sun et al., 1999).

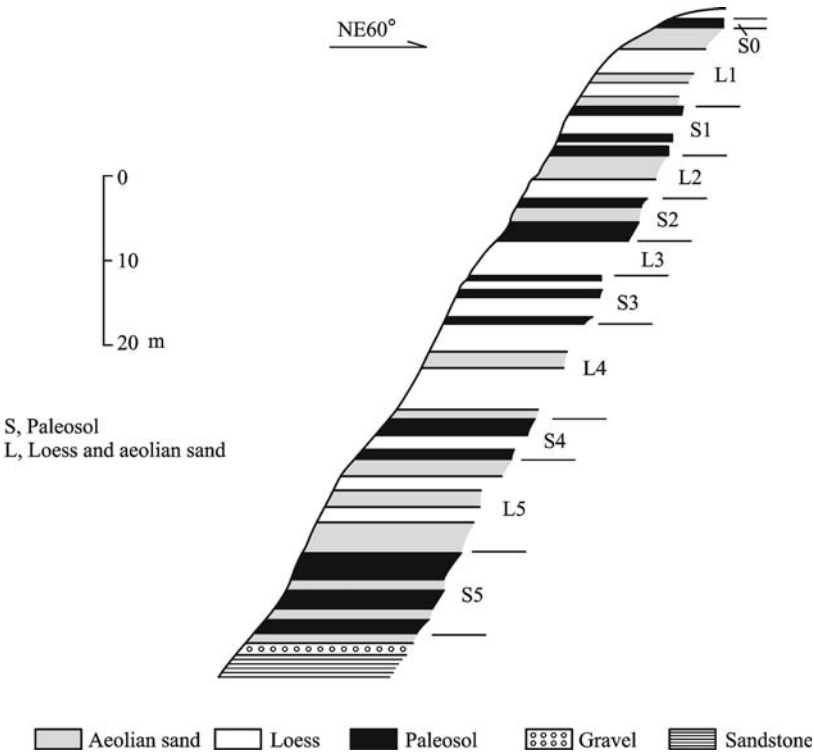

Fig. 2.11 The ancient-aeolian-sand, loess and ancient soil sequence at the profile of the desert-loess border (Sun et al., 1999, with permission from authors)

The unique geographical location of the loess-desert transitional belt has lead to this place being classified as one of the most serious sandy desertification areas. Sand-covered loess hilly terrain is a representative geomorphological feature. The desertification is related to the "ancient sand renovation" resulting from human activities and natural forces.

First, as identified previously, over the past 580,000 years there have been at least 13 layers of ancient aeolian sand recorded in the loess -desert transitional belt. The ancient aeolian sand should be the historical sand source for desertification, but this process does not occur as the ancient aeolian sand is deeply buried and well protected. The main sand source is three top layers of ancient aeolian sand which were buried only shallowly during the last glacial period (Sun et al., 1998).

Second, the ancient aeolian sand is comparatively thin in this region, limiting the available quantity of sand. The mobile sands are distributed in patches, covering various landscapes discontinuously, rather than forming large continuous areas of sand dunes. However, the damage from desertification is obvious. The human population is quite large, and over-reclamation, overgrazing and deforestation have made this region seriously at risk of desertification. Currently, low level industrial developments and poor management practices have accelerated the desertification process in this fragile transitional belt.

Third, the factors that influence desertification are even more complex in this belt, including not only human activities and wind related factors, but also water and gravity erosion. It must be noted that the ancient aeolian sands from the last glacial maximum are normally eroded together with the upper and lower loess layers. Therefore, we will briefly introduce the most common method of ancient sand renovation in the loess-desert transitional belt (Fig. 2.12).

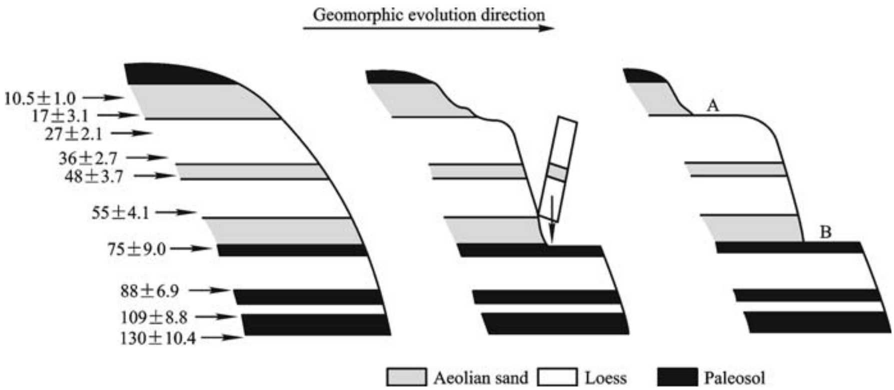

Fig. 2.12 The geological processes of “renovation of ancient sand” at the desert loess border (TL age, Sun et al., 1998, with permission from authors)

Fig. 2.12 (A) shows the renovation process of the ancient aeolian sand during the last glacial maximum. The thickness of the sand is 3–5 m, above which is Holocene black sand (layer S0). Because this layer is only shallowly buried, it is the key sand source in the belt. From the historical records it can be seen that excessive human activities cause wind erosion on the surface of the Holocene black sand layer. Currently, at the transitional belt of the Mu Us Sandland and the Loess Plateau, the ancient aeolian sand has been denuded, leaving individual residual mounds that are smaller than 1 m^2. Only one or two such mounds could be found in several square kilometers. Therefore, the ancient aeolian sand layer from the last glacial maximum has been renovated, leaving the Malan loess formed in the last glacial period as a wind-eroded tableland partly covered by sand. This forms a very eye-catching landscape in this area (Fig. 2.12 (A)).

The renovation of the ancient aeolian sand from the last glacial maximum period was followed by the ancient sand renovation in the middle of stages three and four during the last glacial period. This process was completed under the influence of human factors, and water, wind and gravity erosion. First, the water fragmented the surface with gullies, which further exposed older layers of ancient aeolian sand. Because the sand layer formed during the last glacial maximum has become completely denuded, the L1–2 to L1–5 layers of the Malan loess have become the main surface accumulation materials. The destruction of ground vegetation as a result of human activities has intensified the water erosion and wind erosion processes. The ancient aeolian sand at stage four has been partially removed owing to the strong near ground wind erosion. The layers above L1–2 to L1–4 have collapsed from the effects of gravity and water. When these processes occur continuously, the Malan loess becomes denuded and the ancient aeolian sand formed during stage four is exposed and gradually renovated. Above the S1 soil layer from the last interglacial period, wind eroded tablelands have also been formed in the landscape (Fig. 2.12 (B)).

There are still ten layers of ancient aeolian sand under the S1 layer, but the S1 layer has a thickness larger than 5 m, making these lower layers difficult to erode. Therefore, it will be hard to renew the ancient aeolian sand under S1 over a large area.

2.4 Droughts

Although droughts often occur around the globe, the arid and semi-arid climates in dryland areas result in high rainfall variabilities and more frequent and more serious droughts. As a natural disaster, drought has become a serious threat to economic and sustainable development in dryland areas.

2.4.1 Historical record of climate change and droughts

Dong et. al. (1990) analyzed the available scientific information and historical records from dryland regions in China. They believed that, except in arid and extremely desert areas, over the past 10,000 years the change between dry and wet conditions has occurred with high frequency and at short intervals. Li et al. (1996) made a comparatively comprehensive study on climate change over the past 3,000 years. Considering the glacial landscapes, lake and river landscapes, and tree rings it appears that the period from 1000 BC to the sixth century AD was generally a long cold and dry period, with a short warm-humid period from the end of the second century to the beginning of the third century AD. There was another warm-humid period between the 7th century and the 12th century, while the period between the 13th century and 19th century was comparatively cold and dry, known as the "Little Ice Age". Within the Little Ice Age, there are two particularly dry periods with very little precipitation (1685–1725, 1813–1889) and a moist period where rainfall was abundant (1726–1812). During the 20th century, the climate has warmed, but precipitation has been falling (Fig. 2.13). The Tibetan Plateau is comparatively sensitive to climatic variation, and the changes between dry and wet conditions here are basically consistent with the changes occurring in China's dryland region.

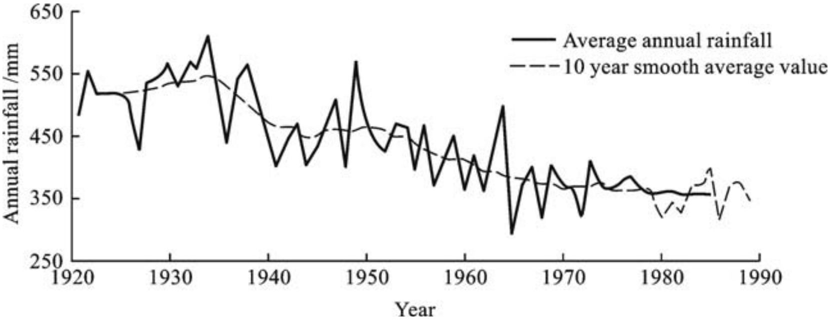

Fig. 2.13 The precipitation variation in the north China between 1921–1989 (Luo and Hao, 2001, with permission from Journal of Hohai University)

The direct consequence of droughts in dryland regions is the shortage of water resources. The differences in the degree of the drought can cause tremendously different effects and a serious drought could destroy the communities in a particular area. Historical research has clearly shown that many historical cultures have been destroyed by drought. In the dry climatic period between 600 BC and 300 BC, the ancient countries of Loulan, Qiemo, Luobupo, Niya, Keladun, Guminfeng and Jingjue ceased to exist. In the dry cold climatic period spanning the Wei Dynasty, Jin Dynasty, Northern and Southern Dynasties, the late Tang Dynasty, the Five Dynasties, the Ming Dynasty and the Qing Dynasty, many important ancient cities in the Hexi Corridor and neighboring areas were abandoned (Wang et al., 2003). Based on incomplete statistics from the Han Dynasty to 1949, there appear to be 17 periods when droughts caused more than 10,000 deaths, with a total number of direct deaths from drought over that period estimated at 3,470,000 (Table 2.4) (Li et al., 1996). There are more people who died from the famine and plague caused by droughts.

Table 2.4 Number of drought disasters and deaths from Han Dynasty to 1949

Number of deaths	10–20 thousand	30–50 thousand	60–100 thousand	110–200 thousand	210–500 thousand	> 500 thousand	Total
Number of droughts causing those deaths	9	3	1	2	1	1	17
Total number of deaths ($\times 10^4$)	11	13	10	33	30	250	347

2.4.2 Climatic change and droughts in modern times

Since industrialization in the late 19th century, industrial activities have had a great impact on climate variation, as demonstrated by greenhouse gas emissions. In recent years, because human activities have increased the concentrations of CO_2 and other greenhouse gases in the atmosphere, many scientists are convinced that the global average atmospheric temperature will increase by 1.5–4.5 °C over the next 50 to 100 years, which will also increase the frequency of droughts in the middle latitudes during the summer months (Ye, 1992). As a result of global warming, precipitation is expected to decline in most regions, and the increased temperatures will lead to increased evaporation. Surface runoff and soil moisture will be substantially reduced and the drought-prone areas will expand (Shi, 1996). In the mid to late 1980s and early 1990s, a distinct warming trend was observed worldwide. Variations in the annual average relative humidity between 1979 and 1983, and between 1987 and 1991 are listed in Table 2.5, below.

Table 2.5 Variations in annual average relative humidity between 1979 and 1983 and between 1987 and 1991 (%)

Grade	Time period	Urumqi	Jiuquan	Zhangye	Minqin	Lanzhou	Wudu
500 hPa	1979–1983	11.0	16.6	21.4	20.8	24.2	29.4
	1987–1991	15.2	17.2	19	13.0	17.6	31.2
	Difference	4.2	0.6	–2.4	–7.8	–6.6	1.8
700 hPa	1979–1983	12.6	20.8	23.2	22.2	23.6	27.8
	1987–1991	12.8	10.6	10.6	15.8	17.2	29.2
	Difference	0.2	–10.2	–12.6	–6.4	–6.4	1.4
850 hPa	1979–1983	28.4	29.2	38.8	25.6	–	24.4
	1987–1991	33.6	22.8	27.0	22.8	–	21.0
	Difference	5.2	–6.4	–11.8	–2.8	–	–3.4

It can be seen that at the northwest fringe of the southeast monsoon region (represented by Zhangye, Minqin and Lanzhou), in the lower and middle parts of the troposphere, the variation in average annual humidity is less in 1987–1991 than in 1979–1983, which indicates that there is a weakening trend in the summer monsoon. In the westerly zone (represented by Urumqi), there is no reduction of the relative humidity variation in 1987–1991 at any level of the troposphere (500 hPa, 700 hPa, and 850 hPa). At the eastern fringe of the westerly zone (Jiuquan), a reduction in annual relative humidity variation could be seen at levels of 850 hPa and 700 hPa, but not at the 500 hPa level. In the southeast monsoon zone (represented by Wudu, which is about 600 km from Zhangye), there is no reduction in the variation of the annual relative humidity in the lower troposphere (Zhang et al., 2000).

According to meteorological records, the temperature in northern China has shown an increasing trend, with a significant reduction in precipitation (Fig. 2.14 and Fig. 2.15). Droughts, especially serious droughts, often cause a

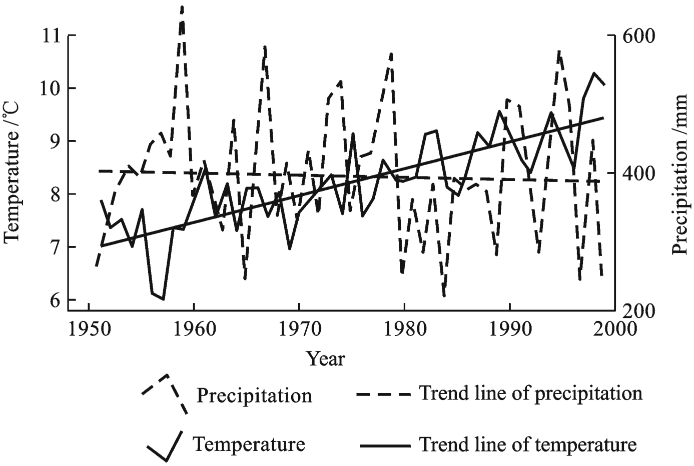

Fig. 2.14 Temperature and precipitation variation in Zhangjiakou in Hebei Province between 1950–2000

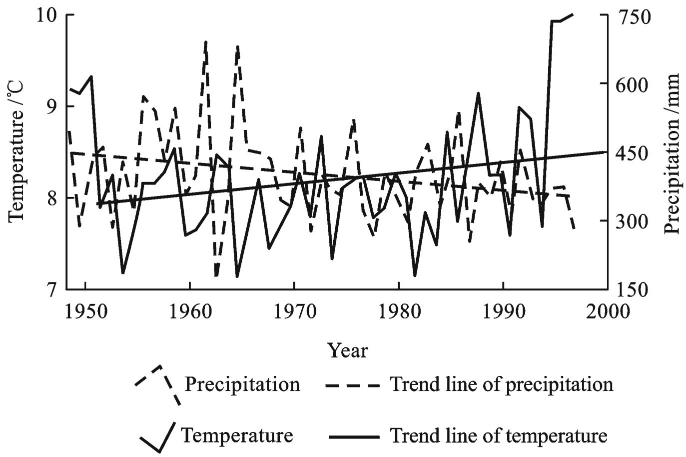

Fig. 2.15 Temperature and precipitation variation in Yulin in Shaanxi Province between 1950–2000

reduction in agricultural productivity, a water resources crisis, and even serious sand-dust storms. According to incomplete statistics, since 1960, China's northern region has experienced 13 incidences of severe drought (Peng, 2001), and the statistics on affected agricultural and livestock production are listed in Table 2.6.

Table 2.6 Summary of droughts in China's western region from 1960 to 2001 (Peng, 2001; Li, 1992; Yang and Li, 1997)

Year	Effects of the drought
1957	The drought in the Ningxia region affected 444,700 ha, with the loss of 29,100 livestock.
1960	The drought in the middle reaches of the Yellow River lasted for 110 days from March 24th to July 17th, with less than 13 mm of rainfall in that period. The thickness of the dry soil layer was about 1 m. 1,400 ha of corn fields and 5,800 ha of irrigated fields all died because of drought. The affected area covered 4,320,000 ha and a total human population of 11,480,000. Food crop yields were reduced by 2,220,000 tons.
1965	The drought in northwestern China lasted from November 1964 to April 1965. Over 171 days, the precipitation was only 26 mm. In May 1965, the rainfall was only 9 mm, and June, 15.8 mm. The severe drought caused widespread crop yield reduction.
1971	The drought in the Tongxin County of Ningxia affected an area of 444,700 ha, with a loss of 18,300 livestock.
1972	The drought in western China affected 4,370,000 ha of farmland areas reducing crop yields by 30–50%, 50–80% and 100%, or 2,270,000, 72,300 and 293,000 ha respectively.
1980	From September 1979 to May 1980, the continuous "two hundred day" drought in Shaanxi Province resulted in cracked soil and significant plant death, with food crop yields reduced by 3.337 million ton. From August 1979 to May 1980, a period of 245 days, the precipitation in the Tongchuan Region in Shaanxi Province was just 70 mm, which is the lowest in recorded history.
1982	The drought in the Ningxia affected 444,700 ha, with the loss of 22,000 livestock.
1983	A serious drought affecting the whole of Haiyuan County in Ningxia, lasted 150 days from the start of the summer, with an affected area of 2,730,000 ha. The crop yields were reduced by more than 80% over 77,000 ha, and 8,000 livestock were lost.
1985	The whole Shanxi Province suffered from a drought, which affected an area covering 1.9 million ha, accounting for half of the sown farmland area in Shanxi.
1987	The drought in Haiyuan, Tongxin and Yanchi counties of Ningxia affected an area of 1,672,000 ha, with a loss of 142,000 livestock.
1995	The drought in the Shaanxi Province from December 1994 to early July 1995, affected an area of 1.33 million ha. The autumn grain production was reduced by 31% compared with 1993.
1997	The North, Northwest and Northeast of China suffered from a serious drought affecting 33,514,000 ha, including 6.67 million ha of winter wheat. The lower reaches of the Yellow River dried-up 13 times from February 7 th to November, with a total dry time of 226 days, and over a length of 740 km.

Continued

Year	Effects of the drought
2001	The northern part of China experienced 13 severe sand-dust storms and summer droughts, affected an area of 28 million ha. 1.4 million ha of irrigated fields were affected. The drought caused drinking water problems for 22.6 million people in rural areas and 14.5 million livestock. After two consecutive years of drought, Inner Mongolia has suffered severe drought. There are 1,160,000 ha of farmland that could not be sown, and 31,070,000 ha grassland which could not turn green.

2.4.3 Possible trends in droughts

Research on the expected future climate change, and interactions between surface terrain characteristics, the atmosphere and solar radiation, can be used to predict future trends in climate variation in the dryland areas. Statistical analysis on drought and flood information, and the meteorological and hydrological data from the main recording stations of parts of Shaanxi and Gansu from Yan (1999), have identified that the current weather cycle is in an 11 and 50 year moving-average dry period as part of a 526 year time series. In the past 50 years, the average air temperature has increased by 0.3 °C, the average annual precipitation has decreased by 80 mm, and the surface runoff volume has reduced by 0.78%, all of which are indicators of aridification. According to the statistics from observations at 10 main weather stations, there is a negative correlation between the temperature and sunspot activities. Records show that the annual average temperatures of the 5 sunspot valley years are lower than the moving average value. The temperature variation is closely related to La Niña events, and most years with La Niña conditions were comparatively cool years. There is a relationship between the annual precipitation variation and EI Niño events. Excluding 1983, of the 14 recorded EI Niño years, low rainfall occurred in 11 of them. In contrast, La Niña years have abundant precipitation. The years with low sunspot activity are mainly rainy years, with the exception of 1986 (Fig. 2.16). According to the 5 year moving-average curve, in the next 20 years the northern region will see even less rainfall, and droughts will not be significantly reduced.

The warm-dry trend in the climate may cause a reduction in the average surface runoff of 0.14% (within 40 years), 0.34% (within 30 years), 0.5% (within 20 years), and 1.0% (within 10 years). Li (2001) researched the regional precipitation variation in the Xinjiang, Northwest China, Inner Mongolia, North China and the northeast regions based on weather data since 1949. According to his research, in terms of trends in precipitation variation, the precipitation has tended to decrease since the mid-1980s, with significant droughts observed in most regions except Xinjiang, where the rainfall has tended to increase. Since 1997 there has been an increase in the number of

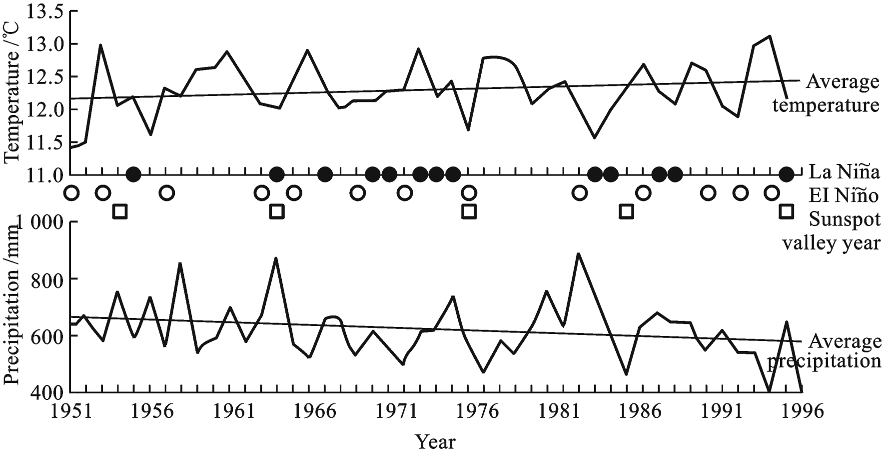

Fig. 2.16 Climate change in northern China between 1951–1996 (Yan, 1999, with permission from Journal of Catastrophology)

provinces suffering from drought, with the 1999 and 2000 droughts causing serious losses.

The reduction in precipitation is the decisive factor in causing droughts and the feedback mechanism between desertification and climate is one of factors that causes the variation in precipitation. Dong et al. (1990) undertook an in-depth study of the mechanism of feedback between desertification and climate. In terms of the balance of heat radiation from the land and the atmosphere, exposed or sparse vegetated sandy surface has a high albedo (0.25–0.30) in the desertification areas. Assuming the same total amount of solar radiation, the ground surface in the desertification areas reflects more short wavelength light than other surfaces such as water, grassland or forest. The sandy surface has a low thermal conductivity, low heat capacity and is dry. The temperature of the sandy surface will increase rapidly with absorbed solar radiation, reflecting the radiation into cloudless air more than other surfaces, which may cause low or negative value zones of radiation to form. The relatively high albedo of the sandy surface may also influence the regional atmospheric conditions, and decrease the precipitation, making the climate drier. Ye et al. (1979) analyzed the atmospheric circulation on the Qinghai-Tibetan Plateau, which indirectly confirmed the feedback relationship between the sandy ground and the atmosphere.

2.5 Sand-dust storms

High frequent sand-dust storms originating from the dryland are potential serious hazard. It was recorded that strong sand-dust storms have had an increased tendency to occur in the northwest region of China since the 1950s

(5 storms in the 1950s, 8 storms in the 1960, 13 in the 1970s, 14 in the 1980s and 21 in the 1990s). The sand-dust storms resulted in so much damage that they were being treated as “an alarm for the entire nation”.

2.5.1 Sand-dust storms and their main sand sources

2.5.1.1 Sand-dust storms definition and classification

In addition to public descriptions, sand-dust storms have a clear definition in meteorology. As a weather phenomena, sand-dust storms refer to situations where strong winds blow sand up from the ground and reduce the level of atmospheric visibility to less than 1 km.

(i) Strong sand-dust storms

A strong sand-dust storm refers to a storm where the wind speed is no less than 20 $m{\cdot}s^{-1}$ (17.2 $m{\cdot}s^{-1}$ in southern Xinjiang), and visibility is less than 200 m.

(ii) Extremely strong sand-dust storms

An extremely strong sand-dust storm refers to a storm where wind speed is no less than 25 $m{\cdot}s^{-1}$ (20.8 $m{\cdot}s^{-1}$ in southern Xinjiang), with a visibility less than 50 m.

A thick sand-dust wall often appears during the occurrence of strong or extremely strong sand-dust storms. Because the occurrence of sand-dust storms is closely related to terrain and climate conditions, different regions have different classification standards. The definitions of sand-dust storm intensity in India and some parts of China are compared in Table 2.7.

Table 2.7 Sand-dust storm intensity classification in India and some parts of China

Place	Light	Medium	Strong
India	Wind speed grade 4–6 Visibility 500–1,000 m	Wind speed grade 6–8 Visibility 200–500 m	Wind speed grade > 8 Visibility$<$ 200 m
China	Visibility $>$ 1,000 m	Visibility 500–1,000 m	Visibility $<$ 500 m
Gansu			Wind speed $>$ 25 $m{\cdot}s^{-1}$ Visibility $<$ 50 m
Wuwei, Gansu			Wind speed $>$ 22 $m{\cdot}s^{-1}$ Visibility $<$ 50 m, formation of sand wall
Ningxia			Wind speed $>$ 25 $m{\cdot}s^{-1}$ Visibility $<$ 200 m

At a given site, based on the instantaneous maximum wind speed and minimum horizontal visibility, the intensity of the sand-dust storm can be classified as extremely strong, strong, medium or weak. Table 2.8 shows the classification criteria for each level of intensity.

Table 2.8 Classification criteria for sandstorm intensity at a single site

Intensity	Instantaneous maximum wind speed	Minimum visibility
Extremely strong	$\geqslant 25\ m{\cdot}s^{-1}$	< 50 m
Strong	$\geqslant 20\ m{\cdot}s^{-1}$	< 200 m
Medium	$\geqslant 17\ m{\cdot}s^{-1}$	200–500 m
Weak	$\geqslant 10\ m{\cdot}s^{-1}$	500–1,000 m

Clearly, there is no unified standard on the classification of sand-dust storm intensities. The occurrence and development of a sand-dust storm is influenced by the current weather conditions, and also by the local surface conditions such as the moisture content of the soil surface and the wind conditions. Even under the same weather conditions and vertical convective conditions, the intensity and scale of the sand-dust storm will vary distinctly based on the terrain. Therefore, the occurrence and intensity of sand-dust storms depend on location and weather condition.

According to the definition of a sand-dust storm, the occurrence and the formation of sand-dust storms require three essential conditions: strong winds, strong convective instability (a vertical rise in air), and abundant sand materials. When loose and bare sand encounters strong winds and strong convective instability (atmospheric turbulence and updrafts), the sand will be lifted by the wind, thus forming a sand-dust storm weather phenomenon. When sand is carried a considerable distance by the wind, it then influences the weather conditions and geography of other regions.

2.5.1.2 Sand sources contributing to sand-dust storms in China

The world's major sources of sand-dust storms are mainly located in arid and semi-arid areas. In China, the main sand sources are located in north China's desertified and sandified areas, typically between E 75°–125°, and from N 35° to the China-Mongolia border.

The sand sources can be divided into original sources and intensifying sources depending on their relationship to the formation and transmission of the sand-dust storm. Original source refers to a place where the sand is first raised by a storm, and is the beginning of a sand-dust storm. An intensifying source is a location where sand can easily be added into the sandstorm by the action of the wind. There are no strict and exact boundaries for original sources and intensifying sources. Some places might act as an intensifying source in one sand-dust storm but act as the original source in another storm.

The main sources of China's sand-dust storms can be determined by analyzing the process of the sand-dust storm with the aid of meteorological satellites and ground-based weather observations.

Depending on the geographical location of a sandstorm, it can be classified as inside-territory or outside-territory source. There are two outside-territory original sources of China's sand-dust storms: one is the desert area in central southern and central eastern Mongolia; the other is located in the desert of eastern Kazakhstan and its related desertification area. The Mongolian sand source is the most important external sand source affecting China's sand-dust storms. The Kazakhstan sand source mainly influences sand-dust storms in northern Xinjiang, and its effects would only be transmitted to larger areas under strong weather conditions. The inside-territory sources are mainly the northwest deserts and the edge of the degraded steppe in the Hexi Corridor of Gansu, the Yellow River irrigation district of Ningxia, Hetian and Turpan regions of southern Xinjiang, the Qaidam Basin, the Alxa Plateau, the Hetao Plain, the Ordos Plateau of Inner Mongolia, and Yulin and the districts along the Great Wall in north Shaanxi. These areas are not only frequent sand-dust storms occurrence zones, but also provide some intensifying sand sources for sand-dust storms that pass over these areas, and can extend the influence of these sand-dust storms into eastern and southeastern China.

2.5.2 Factors influencing sand-dust storms occurrence in China

The formation processes and intensity of sand-dust storms are determined directly by the wind, temperature, precipitation, the vertical atmospheric instability and related ground surface conditions. The climatic conditions provide the kinetic conditions for sand-dust storms while the ground surface conditions provide the source materials for the sand-dust storms.

Generally speaking, the factors influencing sand-dust storm formation can be divided into natural factors and human factors. The natural factors are the influences of climate variation, landform and geomorphological features and the distribution of desert. The human factors include activities such as land degradation which is due to water overuse, overgrazing and inappropriate land use patterns, and global climate change resulting from greenhouse gas emissions.

Sand-dust storms often initiate in the spring in areas with a warmer temperature, low humidity, low vegetation coverage, and loose soil surface. When a relatively strong cold air mass passes through this area, the strong winds will easily raise the exposed and loose sand and cause a sand-dust storm. Certain terrains can have the effect of stimulating and promoting the formation of the sandstorm. For example, when cold air crosses the mountains and dives into lowlands or basins, it will sink rapidly, dramatically increasing the slope of the cold front and a large amount of potential energy will be changed into kinetic energy. Furthermore, the temperature in the basin or lowland will be warmer than the cold front which will cause an intensive convergence, further intensifying the pressure gradient and temperature differences. In this way, the weather system will be strengthened and cause the formation of a sand-dust storm. Another role that terrain can play in the formation of a sandstorm is when the terrain forms a narrow pipe such as the Hexi Corridor. When a cold air mass flows from the north into such a corridor, it will converge horizontally, and the pressure gradient and temperature differences will increase, strengthening the cold front, which assists in the occurrence of sand-dust storms.

Land degradation and desertification have provided abundant loose soil material for the formation of sand-dust storms. Modern economic and social activities occurring without control in inappropriate locations are the major human factors that impact the formation, development, and transmission of sandstorms.

With the current and anticipated global warming, there is an expectation that precipitation will decline in most dryland regions. This trend will be maintained over the next 30 to 50 years, and will further intensify drought conditions in the current arid and semi-arid regions while the current sub-humid areas may develop into semi-arid, or even arid areas. According to research by domestic and international experts, the climate in northern and northwestern China will become warmer with lower precipitation. This indicates that the predominance of sandstorms in north China is likely to continue, and could have a significant effect on most parts of China.

2.5.2.1 Characteristics of China's atmospheric circulation and monsoon climate

China is affected by the monsoon climate. The main features of China's monsoon climate are:

In the winter, the upper westerly jet stream divides into a southern branch and a northern branch, and the intensity of the jet stream increases to its maximum gradually. The entire Chinese continent is controlled by the westerly circulation pattern. The Mongolian cold high pressure system is also very strong, with the high pressure center located between E 100°–105° and N 45°–55°. In northern China, northerly and northwesterly winds prevail.

In the spring, from March to June, the southern branch of the westerly jet stream moves northward about 500 km. There is also little change of the intensity and the position of the northern branch of westerly jet stream. During this season, cyclonic activities in China are the most frequent. In the northern part of China there is the Mongolian cyclone, the northeastern cyclone and the Yellow River cyclone with associated small anti-cyclones. These lead to changeable spring weather conditions.

In the summer, western China is influenced by different continental subtropical high pressures systems, and the influence of the cold air mass is limited to a much smaller area. The climate is mainly controlled by the easterly and westerly simultaneously. Weather systems such as westerly troughs/ridges, cyclones, anti-cyclones, fronts, subtropical high pressure systems, intertropical convergence zones, easterly waves, and typhoons may occur.

In the autumn, the subtropical high pressure system remains in the upper atmosphere, while the surface is controlled by the cold high pressure systems. This leads to the characteristic that "the sky is high and the air is clear" in the autumn.

2.5.2.2 Major weather systems that impact the sand-dust storms of China

China covers a vast land area which includes a wide range of latitudes (north-south) and longitudes (east-west) and is therefore influenced by various aspects of the global climatic system. The climatic systems that influence sand-dust storms are local warm low pressure fronts which occur at southerly latitudes, and the East Asian cyclones and anti-cyclones, the Mongolian cyclones and other systems.

(i) Local thermal depressions

Local thermal depressions are formed by the uneven heating of the near-surface atmosphere which often occurs on warm continents. After exposure to heat, the land temperature rises unevenly, depending on the terrain and the surface topographical differences. The air in the region with the larger temperature increase will expand, and cause a pressure difference. Therefore, the isobaric surface will be raised, forming a gradient from the center of the high temperature area outward. Under the force of the pressure gradient, air is diverted to the surroundings, and causes a further reduction in the air pressure at the ground. The air pressure gradient forces air from the outside towards the center, forming an air convergence pillar which rises into the upper atmosphere and then diverts outward. Once the converging air begins to dominate the air pressure at the ground surface declines continuously. With the effort of the ground deflecting force, a closing cyclonic system will be formed from the local warm low pressure.

There are obvious daily variations in the intensity of these warm low pressure systems. During the day time, the low level warm air pressure increases as the ground temperature increases. In the afternoon, the pressure reaches the maximum, and will decrease in the evening along with the temperature decreases on the ground.

There is a limit to the heating ability of the underlying ground surface, so warm low pressure systems are not thick, normally less than 1.5 km.

(ii) Warm low pressure fronts

When air masses with different characteristics encounter each other, there will be a transitional region. When this region is small, it is called a “front”. A front refers to a narrow, tilting transitional region where cold and warm air masses meet. There are significant differences between the characteristics of the air masses on either side of the front, which means that the air mass close to the front is active. There is an intensive uplifting movement along the front, with an unstable air flow, which can cause dramatic air movement.

Warm low pressure fronts occur in the warm section of the cold front. Its formation comes not only from uneven heating, but also from the advection of warm air at the warm section of the cold front. It causes low pressure on the ground, and the warm advective air preceding the low pressure caused by the warm temperatures will increase. Warm low pressure fronts occur most frequently in desert and basin areas. When low pressure fronts develop to a certain point, they can cause strong winds and sand-dust storms.

(iii) East Asian cyclones and anti-cyclones

The cyclones of the East Asian region mainly occur in two areas. One area is located between N 25°–35°, which includes a large area of the Jianghuai Watershed, the East China Sea, and the ocean area south of Japan. The cyclones in this region are referred as southern cyclones, including Jianghuai cyclones and East China Sea cyclones. The other area is located between N 45°–55°, which is the boundary area between Heilongjiang, Jilin and Inner Mongolia and has frequent occurrences of cyclones. Customarily, cyclones in this area are called northern cyclones, including Mongolian cyclones, northeastern cyclones, Yellow River cyclones, and Yellow Sea cyclones.

The high frequency zone of anti-cyclones in East Asia occurs within a long northwest-southeast strip going from western Mongolia to China's Hetao region. Northeast and southwest of this strip has a lower frequency of anti-cyclones.

Mongolian cyclones occur or develop in the central and eastern Mongolian Plateau between N 40°–50° and E 100°–115°. The western and northwestern parts of this region are mountainous. Central and eastern Mongolia lies on the leeward side of these mountains, which is advantageous for the occurrence and development of the cyclones. During the spring and autumn, the cold and warm air is very active; the greatest number of cyclones occurs during these seasons. Some cyclones also occur during the winter. In the summer, the frontal region moves northward, and the warm air becomes dominant, so the number of cyclones decreases significantly. The Mongolian cyclone and the northeast low pressure system are the main climate systems that impact on sand-dust storms in China.

The most common path for Mongolian cyclones is one that crosses the west of the Xilinguole League, Inner Mongolia, moving in an easterly direction, then travels along the Northeast Plain, reaching the Songhua River. Two other common paths are to cross the Hulun Buir League, Inner Mongolia, in an easterly direction, or traveling northeast from North China and the Bohai Sea, passing around the Changbai Mountains and moving into North Korea. The weather caused by Mongolian cyclones varies, but strong winds are typical. The precipitation caused by a Mongolian cyclone is generally insignificant. This is because the warm air within the cyclone comes mostly from the areas northeast of the Qinghai-Tibetan Plateau and the Hexi Corridor, which are lacking in moisture. Normally, high cloud appears in most seasons but rainfall only occurs in the northern part of cyclone's center. Note that the Mongolian cyclones occur during all four seasons, but in the spring and autumn cyclones are stronger and more common than in other seasons.

The northeast low pressure system is similar to the Mongolian cyclone, being one of strongest developed cyclones in China. This low pressure system occurs throughout the year, especially in the spring and autumn. The weather it causes includes strong winds, heavy rainfall and thunderstorms.

The regions with a high frequency of sand-dust storms are the arid and semi-arid areas. The common characteristics of this region are drought and low rainfall, with frequent strong windy days. The formation of sand-dust storms and their intensity are directly determined by the characteristics of the wind, temperature, precipitation and the landscape features. In northern China, in the late winter and spring, as a consequence of the monsoon weather, the vegetation coverage becomes low, which allows for intensive reflection of solar radiation from the ground surface and makes the formation of low altitude high temperature and low pressure zones easy. During this period, the weather is influenced by cold air which comes from Siberia. When these two air masses meet, the pressure gradient causes intensive air disturbance and vertical instability, which can cause strong winds and a vertical uplift airflow. Because there is nothing to stabilize the exposed ground surface, dust and sand will be blown into the air and drift downwind, thus forming sand-dust storms.

2.5.3 Relationship between sand-dust storm frequency and desertification

Wind-eroded desertification is one of the main reasons causing sand-dust storms. Wind-eroded desertification occurs mainly in the arid and semi-arid regions and is the desertification type with the largest area and widest distribution in China (see Chapter 4). In the wind-eroded desertification areas, the vegetation is seriously degraded, and the exposed ground surface and rich sand materials provide appropriate conditions for the occurrence of sand-dust storms.

The normalized difference vegetation indexes (NDVIs) from July 1991 and July 2001 are shown in Fig. 2.17 and Fig. 2.18, which clearly indicate that vegetation is being degraded in China. This vegetation degradation is caused by climate fluctuations on the one hand, and also by inappropriate human activities and excessive use of the available water resources. The vegetation degradation is especially obvious in northern China.

In terms of the spatial distribution of the sand-dust storm occurrence regions, these are mainly located in regions with comparatively serious desertification. Fig. 2.19 shows the national distribution of the average sand-dust storm frequency at some of the meteorological stations over the past 40 years. It can easily be seen that sand-dust storms occur most frequently in the south of the Taklimakan Desert in southern Xinjiang, the central and western parts and the Hetao regions of Inner Mongolia, and the boundary area between Shaanxi, Gansu and Ningxia. The southern margin of the Taklimakan Desert, in particular, has averaged more than 20 sand-dust storms per year over the past 40 years. These regions are also desertified areas, and are regions with

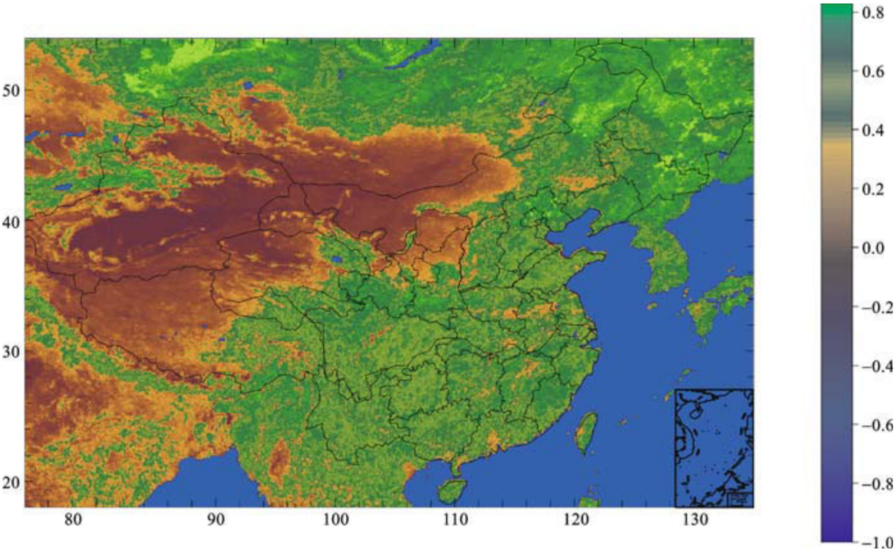

Fig. 2.17 The average vegetation index distribution in July,1991 (Gao et al., 2004, with permission from authors)

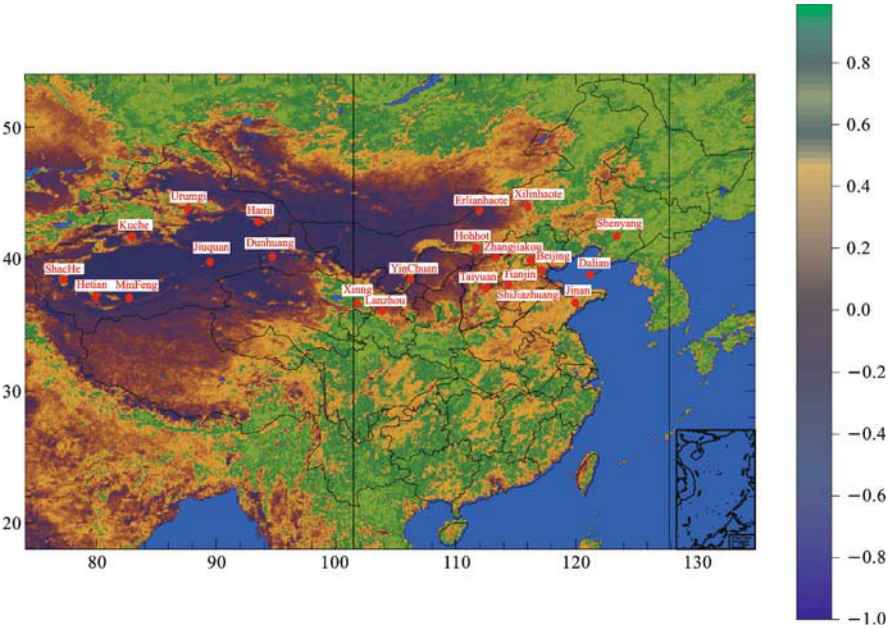

Fig. 2.18 The average vegetation index distribution in July,2001 (Gao et al., 2004, with permission from authors)

serious wind erosion.

Fig. 2.20 and Fig. 2.21 show the distribution of multi-year average precipi-

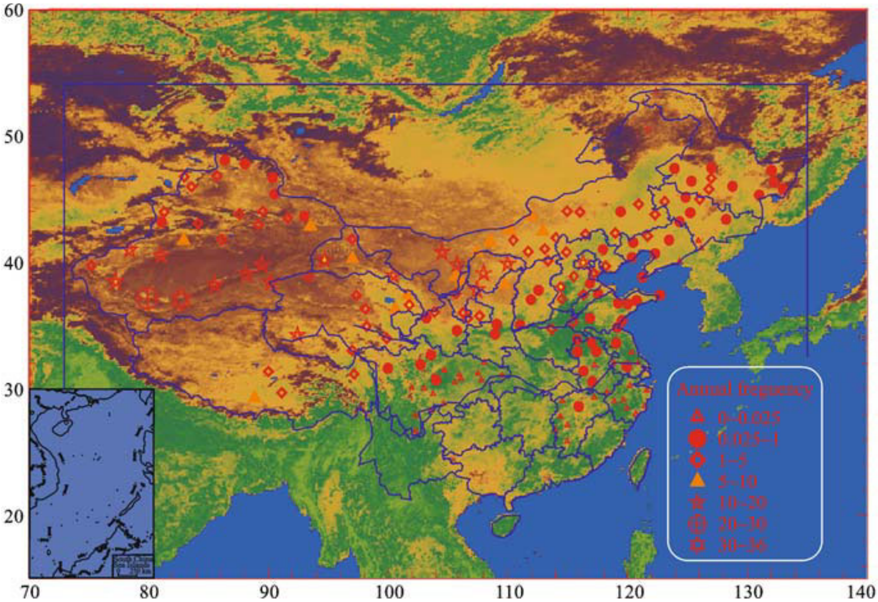

Fig. 2.19 The annual frequency of the average sand-dust storm occurrence between 1959–1998 in part of the meteorological observatories (Gao et al., 2004, with permission from authors)

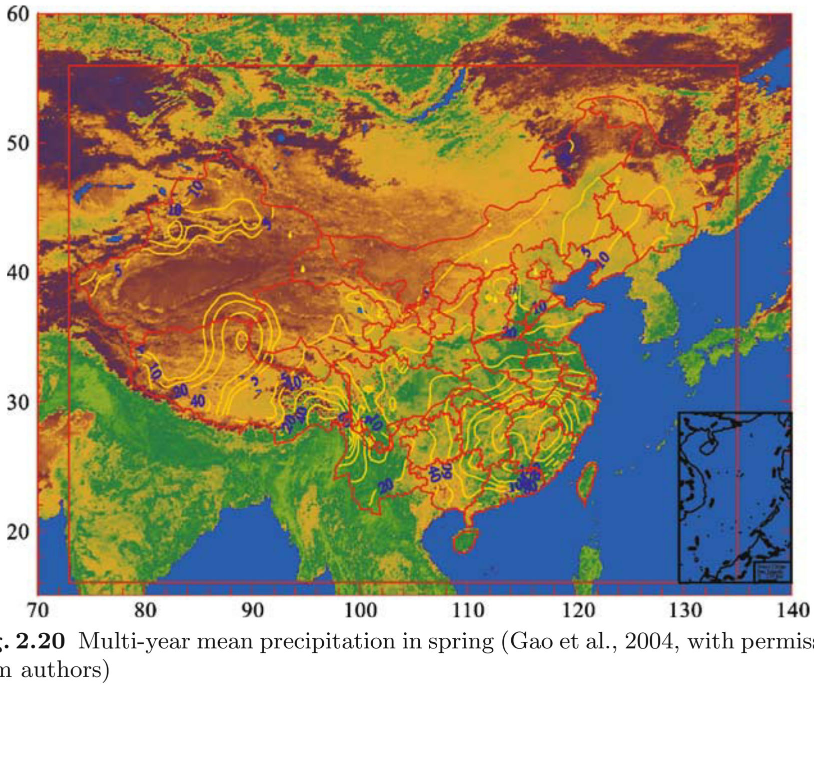

Fig. 2.20 Multi-year mean precipitation in spring (Gao et al., 2004, with permission from authors)

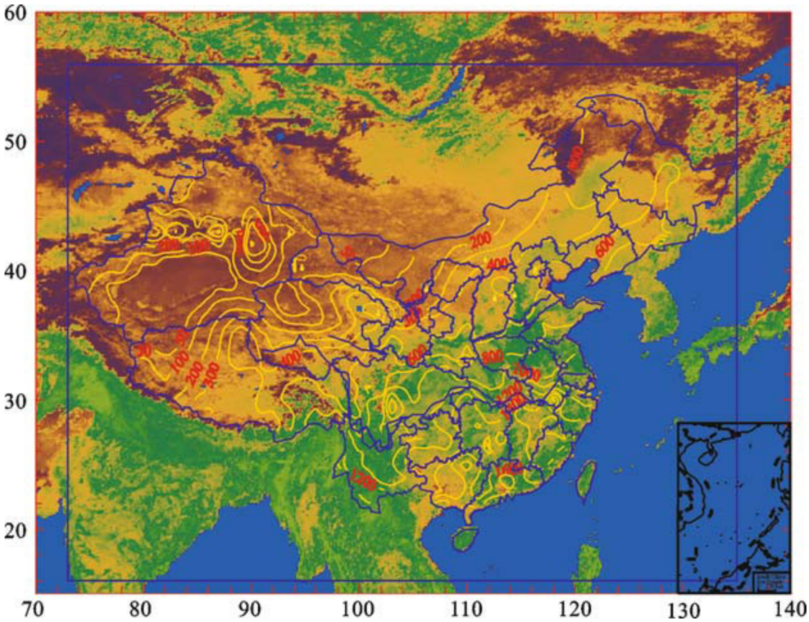

Fig. 2.21 Multi-year mean precipitation through the whole year (Gao et al., 2004, with permission from authors)

tation in spring and annually (the background is an NDVI map from March 2001). In the regions with frequent sand-dust storm occurrences, low precipitation and drought are the main natural factors that cause the high frequency of sand-dust storms.

It can be seen that the exposed ground surface and the loose soil in desertified areas provide sufficient source materials for the occurrence of sand-dust storms. Overlain with harsh climatic conditions such as frequent wind and drought, and inappropriate human activities, sand-dust storms have become the most serious disasters in desertified regions.

2.5.4 Sand-dust storms affecting Beijing

2.5.4.1 Historical evolution of sand-dust weather in Beijing

To develop a comprehensive understanding of sand-dust weather in Beijing, the weather records of the Beijing Weather Observatory, from 1954–2000, were collected and detailed analyse were undertaken. The frequency of occurrence of sand-dust storms, sand-raising and dust-floating weather in Beijing has tended to decrease over the period of time covered by the records. According to related research, Beijing is often affected by sand-dust storms during spring. The most recent serious sand-dust storms in Beijing occurred in March and

April 1995. The period between November 1965 and May 1966 was particularly active with sand-dust storms, with 22 recorded storms. Five sandstorms occurred within January 1966 alone. Another period with a high frequency of sand-dust storms was the mid-1950s. During the 1970s the frequency of sand-dust storms in the Beijing district decreased substantially (there have been no sand-dust storms sourced within the Beijing area recorded in recent years) (Fig. 2.22). The frequency of sand-raising weathers has decreased gradually over the period of the records. The active period for the sand-raising weathers occurred in the mid-1950s, and 1970s, and is currently at a low (Fig. 2.23). The long term variation in the frequency of the dust-floating weather is complex, mainly because the appearance of dust-floating weather is influenced by dust in the upper atmosphere. The main trend is a decrease in the frequency and variation of dust-floating events. During the 1990s, there was an increasing trend in the occurrence of dust-floating weather in Beijing (Fig. 2.24).

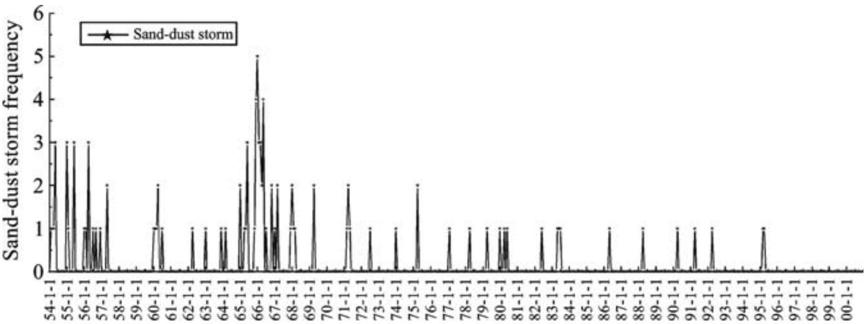

Fig. 2.22 Monthly sand-dust storm frequency from 1954 to 2000 in Beijing

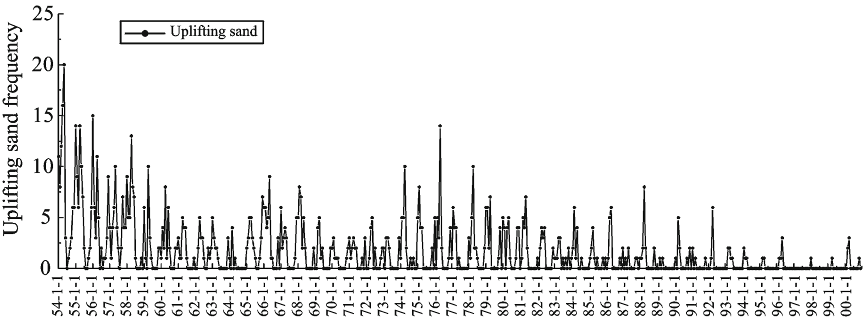

Fig. 2.23 Monthly sand-raising weather frequency from 1954 to 2000 in Beijing

To gain a comprehensive understanding of the sand-dust weather in Beijing, the three weather phenomenon, which are sand-dust storms, sand-raising weather storms and floating sand, have been carefully analyzed. It turns out that there is a recurrent cyclic frequency of sand-dust storm occurrence (Fig. 2.25). The sand-dust storm frequencies occurred in 1954, 1966, 1976 and 1998,

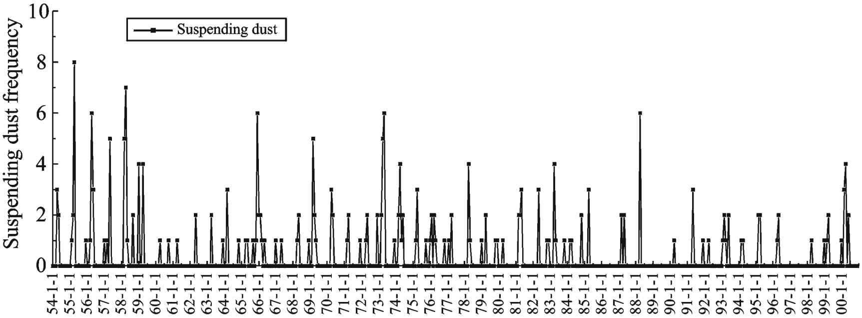

Fig. 2.24 Monthly dust-floating weather frequency from 1954 to 2000 in Beijing

less and less with the trough occurred in 1997 to the peak in 2000. The 46 years of analysis of the three types of sand-dust weather shows that in Beijing, sand-raising weather is the major type, and comprises 74.15% of the total sand-dust weather. Dust-floating weather is the next most common type of sand-dust weather (18.09%) and sand-dust storms are the least common (7.76%).

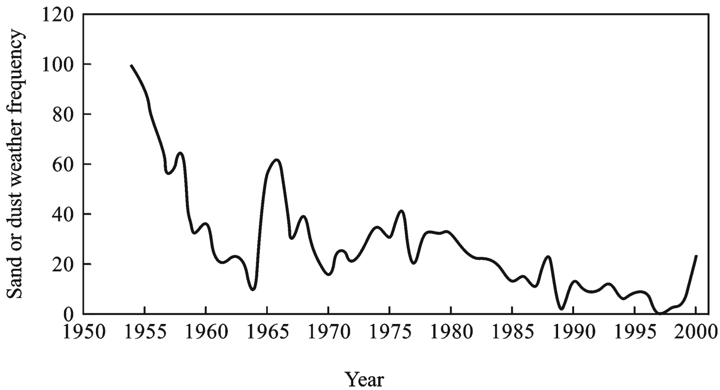

Fig. 2.25 Sand-dust weather frequency from 1954 to 2000 in Beijing (Gao et al., 2002, with permission from authors)

2.5.4.2 Contributions of external sand sources to sand-dust storm weather in Beijing

Beijing is located downwind of major sand-dust weather prone regions, and is influenced by sand-dust weather in the upper atmosphere. External sand source is a major contributing factor to the sand-dust weather which affects Beijing. Based on the daily observation records from the Beijing Weather Observatory in 1999 and 2000, detailed analysis of the path of sand-dust weather in Beijing has been determined.

Local Beijing sand-dust weather can be defined as sand-dust weather where there is a record of a sand-dust weather in Beijing but no sand-dust weather occurring in the surrounding area.

During 1999 and 2000, there were no local sand-dust storms recorded at the Beijing Weather Observatory, and in fact, no local sand-dust storms have been recorded there since 1996. Sand-raising weather occurred 18 times (i.e., days) during 1999 and 2000, with five of those instances (or 27.8% of the total) being local Beijing sand-raising weather phenomena. There are 13 recorded long distance sand-dust storms and the sand-raising storms in the surrounding regions, accounting for 72.2% of the total occurrences. One sand-dust storm that occurred from April 6th to 9th, 2000 is typical of a long distance sand-dust storm. The sand source for this sand-dust storm was the boundary between Mongolia and Inner Mongolia in China, and the climate systems that caused the sand-dust storm were the Mongolian cyclone and cold air. Dust-floating weather occurred 9 times during 1999 and 2000, 1 time in 1999, and 8 times in 2000. 2000 had the highest frequency of dust-floating weather in the recent 10 years period.

To summarize, there were 27 instances of sand-dust weather (over 22 days) during 1999 and 2000. In 2000, there were 17 days of sand-dust weather, which means that this year had the highest frequency of sand-dust weather in the 20th century, but this is still a much lower frequency than the average frequency of sand-dust weather between 1954 and 1989.

There are more than 20 weather observation stations in Beijing, with data from the Beijing Weather Observatory relating to the southern suburbs in this analysis. The China Meteorological Administration has identified that there were 18 occurrences of sand-dust weather in northern China between March 2nd and May 16th, 2001. These data show that the main effects come from Mongolian cyclones and cold air. Of the 18 occurrences of sand-dust weather in northern China, there were 3 strong sand-dust storms, 11 sand-dust storms and 4 sand-raising weather.

The first sand-dust storm in the 20th century occurred in western Inner Mongolia and at the China-Mongolia boundary on December 31st, 2000, and affected most parts of northern China moving in a southerly direction. On January 1st, 2001, a sand-raising and dust-floating weather occurred in Beijing. When the sand-dust crossed the boundary into the Beijing area, the measured concentration of respirable particulate matter reached 1,084.4 $\mu g \cdot m^{-3}$ in Beijing, and the concentration of total suspended particles (TSP) reached 1,000 $\mu g \cdot m^{-3}$. These concentrations are 7.2 times and 3.3 times higher, respectively, than the air quality standards specified in the Grade II national standards for air quality.

There were 19 occurrences of sand-dust weather (over 13 days) recorded at the Beijing Weather Observatory from January to May 2001. In those records there were six occurrences (over 4 days) of sand-raising weathers, and 13 occurrences of dust-floating weathers. The intensities of sand-dust weather in the Beijing district in 2001 were comparatively weaker than those in 2000. According to the records from more than 20 meteorology stations from

January to May 2001, there were 24 occurrences of sand-dust weather in the Yanqing County, Beijing (including six sand-raising events), 19 occurrences at the Beijing Observatory, and 16 occurrences at Miyun. The records of Pinggu, Daxing and Shunyi Districts all show less than five occurrences. Table 2.9 shows the frequency of occurrence of sand-dust weather recorded by the 18 meteorology stations in and around Beijing that have sand-dust weather records.

Table 2.9 Records of sand-dust days at 18 stations from January to May in 2001, Beijing

Station	Days	Station	Days	Station	Days	Station	Days
Yanqing	24	Badaling	6	Miyun	16	Pinggu	1
Haidian	5	Beijing Observatory	19	Shijingshan	3	Shangdianzi	1
Shunyi	4	Chaoyang	4	Tanghekou	4	Xizhaitang	10
Daxing	2	Fengtai	7	Tongxian	3	Changping	7
Foyeding	4	Gubeikou	4				

Table 2.9 shows the uneven spatial distribution of sand-dust days in the Beijing. The overall rate of occurrence decreases from the northwest to the southeast. This is consistent with the fact that one of the main routes that influence sand-dust weather in Beijing comes from the northwest. There are several areas where sand-dust weather is more frequent (Yanqing, Miyun, Xizhaitang and the Beijing Observatory). The locations of these sites with frequent sand-dust weather are influenced by the long distance sand-dust weather (sand-dust storms and sand-raising events), and also by local sand-raising events. For example, although 19 occurrences of sand-dust weather events were recorded at the Beijing Weather Observatory between January 1st and May 20th, 2001, the records of the surrounding counties are far lower than that in Beijing (7 occurrences in Changping, 5 occurrences in Haidian, 7 occurrences in Fengtai, 3 occurrences in Tongxian, 4 occurrences in Shunyi, and 3 occurrences in Shijingshan). This indicates that Beijing's sand-dust weather is not only influenced by external sand-dust weather, but the local sand sources also play an important role. When external sand-dust events, supplemented by local sand sources, come through under the influence of strong winds, sand-dust weather occurs more frequently in the center of Beijing than the surrounding areas. The local sand source in Miyun also contributes to the local sand-dust weather.

From the above analysis, we can divide the sand-dust weather events that affect Beijing into events caused by surrounding and long distance transmission of sand-dust, and local sand-raising events. The long distance impacts are mainly caused by sand-dust events that originate in Mongolia, central western Inner Mongolia in China and the western Hetao region. These events mainly influence northern and northwestern Beijing, and are caused by weather systems that move to the east. During 2001, two strong sand-dust storms were transmitted from the northwest and impacted northwest Beijing, occurring on 5th and 10th of April 2001. Sand-raising events influenced the northern part of Beijing from April 17th to 19th, 2001. Local sand-raising events refer to situations when there are sand-dust weather recordings at the Beijing Weather Observatory, but no similar recordings in the surrounding areas.

2.5.4.3 Effect of sand-dust weather on air quality in Beijing

The sand-dust weather in Beijing is closely related to the background weather conditions, the surrounding and surface ecological systems, development land and exposed land. The variation in the weather has a vital role in the occurrence of sand-dust weathers. The degradation of land ecosystems will increase the sand source, and with the expansion of building and development lands and the creation of more exposed land, a greater amount of local sand-raising events will be generated.

Sand-dust weather is one of the factors that influence air quality in Beijing. When sand-dust weathers occur, the concentration of sand-dust particles in the atmosphere increases sharply, causing turbidity and degradation of visibility, which causes inconvenience for residents and negatively affects their health by reducing air quality. On April 4th, 1999, during a sand-dust weather event in Beijing, the average concentration of TSP reached 1.282 mg·m^{-3} and 1.573 mg·m^{-3} at observatories in Dingling and the downtown, respectively. These concentrations are 4.27 times and 5.24 times the Grade II national standards for air quality (0.3 mg·m^{-3}). Additionally, concentrations of TSP were 1.182 mg·m^{-3} and 1.345 mg·m^{-3} in Dingling and the city center respectively during the sand weather event of April 8th, 2000.

By analyzing the relationship between dates with high levels of particulate pollution and sand-dust weather events in 1999 and 2000, we can understand the contribution of sand-dust weather to the particulate air pollution. During a two-year period, there were 43 days with a high pollution load, and 18 of those days were impacted by sand-dust weather. In other words, 41.87% of the high pollution days coincided with sand-dust weather. Twenty-five high pollution days (or 58.13%) were not caused by sand-dust weather. Between June 5th, 2000 and June 5th, 2001, there were 309 recorded days with high concentrations of respirable particulate matter (PM10). Of those, 183 days were heavily polluted days with concentrations exceeding the Grade II national standards for air quality, which accounts for 59.23% of the total number of days. During that period there were 12 days affected by sand-dust weather. It is obvious that the sand-dust weather contributes to the high levels of air pollution. However, the days that exceed the Grade II standards are not only influenced by sand-dust weather, but also by local pollutant emissions such as vehicle exhaust emissions and the secondary transference of other pollutants, in particular, sand-raising from local construction sites.

According to data provided by the Beijing Municipal Environmental Protection Bureau in 2000, there were 84 demolition sites in Beijing (excluding the Dongcheng District), involving 680,000 m^2 of land area, and 1,125 construction sites exceeding 31.14 million m^2. There were also 2.56 million m^2 of bare lands.

The urban area of Beijing began to increase gradually in 1987. Within 10 years, the area had increased by 26.07%, with the increase rate slowing after 1997. In that time, the length and the area of roadways, the number of bridges, and the number of vehicles and taxis on the road had increased dramatically. The expanding construction sites have provided a source for local sand-raising events during the strong winds that occur in the spring, have therefore affected the air quality and peoples' lifestyles in Beijing. The continually increasing number of vehicles is one of the other main factors that are intensifying the serious air pollution in Beijing.

2.5.4.4 Sources of Beijing's sand-dust weather and transmission routes

The main sand-dust weather prone regions are typically located in the Hexi Corridor, the Ningxia Yellow River irrigation district, southern Xinjiang, the Turpan region, the Qaidam Basin, the Yikezhao League in Inner Mongolia, Alxa Plateau, Hetao Plain, the Ordos Plateau, Yulin in northern Shaanxi, and the region along the Great Wall district. Sand-dust storms also often occur in the whole of Xinjiang, Gansu's Hexi Corridor, the central west of Inner Mongolia, the whole of Ningxia, northern Shaanxi, Huangshui District in Qinghai, and parts of Tibet. The sand-dust sent into the atmosphere from these areas can influence the east and southeast of China when cold strong air passes by with strong unstable vertical structures near the ground. This weather can cause sand-raising, dust-floating, slimy rain and sand-dust storms, all of which can seriously affect industrial and agricultural production, and cause harm to the environment.

According to a historical analysis of records of China's sand-dust weather, there is an obvious seasonal change. Spring is often popularly referred to as the dust season, and is the season with the most intense sand-dust storms, which have the widest impacts. This is because in the spring, the cold and warm air is extremely active, with frequent cyclone activities, scarce rainfall and drought conditions. The ice covering the ground melts and the weather becomes warmer. The exposed surface soil is loose, and the ground temperature is higher than the atmospheric temperature in areas with low altitudes so drought and unstable conditions are easily formed. Overall, this season is most likely to meet the three sand-dust storms formation conditions: abundant sand sources, strong winds, and strong vertical instability. In recent years, China has suffered from frequent sand-dust weather.

Below are the typical sand-dust weather processes that influenced the concentration of particulate matter in the atmosphere in 1998 and 2000. These data are based on the analytical results of the whole sand-dust weather process including the sand sources that influence the sand-dust weather in Beijing, and the methods of transmission. This could provide valuable information to help to control and improve China's air quality, and has provided scientific and technical support for scientists in Beijing.

By taking a detailed look at the processes of one strong sand-dust storm in 1998 and three sand-dust storms that impacted Beijing in 2003, we will find three main transmission routes as below:

(i) North route: The source area is south-eastern Mongolia, then → Wulanchabu League of Inner Mongolia → Erlianhaote, Abaga Qi at the western Xilinguole League → west Otindag Sandland → Zhurihe → Siziwang Qi → Zhangjiakou → Beijing;

(ii) Northwest route: The source area is the central and south of Mongolia, then → Alxa League of Inner Mongolia and the China-Mongolia border → Wulatezhong Qi and Wulatehou Qi → the Hexi Corridor → crossing the north and south sides of the Helan Mountains and across the Mu Us Sandland and Ulan Buh Desert → Hohhot → Zhangjiakou → Beijing;

(iii) West route: The source area is the edge of the Taklimakan Desert in Xinjiang Tarim Basin, then → Dunhuang → Jiuquan → Minqin → Yanchi → Etuoke Qi → Datong → Beijing.

The transmission routes of sand-dust storms that affect Beijing can be divided into two: one is initiated in southern Mongolia, then → Erlianhaote → the western edge of the Otindag Sandland → Siziwang Qi → Zhurihe → Zhangjiakou → Beijing. The other originates from central and southern Mongolia, then → Ejina Qi → Wulatehou Qi → Wulateqian Qi → northern Mu Us Sandland→ Yulin → Datong → Beijing.

The influence of this sand-dust weather can reach northern Jiangsu in the lower reaches of the Yangtze River.

Sand-dust storms can be divided into two categories, local and transmitting, according to their evolutionary processes and the route and scope of transmission.

Local sand-dust storms only move a small distance and their sand sources are mainly located in the Tarim Basin in Xinjiang, Qaidam Basin in Qinghai and parts of the desert area in Tibet. These sand-dust storms are mainly affected by local air circulation patterns and specific geographical environments and cannot easily form long distance sand-dust storms. Local sand-dust storms have a small area of influence and obvious changes occur on a daily basis. Occasionally, when a strong weather system passes by, these storms may form long distance transmitting sand-dust storms with large scale affects.

The domestic sand sources of the transmitting sand-dust storms are typically located in Hami, Xinjiang, Ejina and the Alxa Plateau in the central west of Inner Mongolia, the Hexi Corridor, the region west of Hetao, and central Inner Mongolia and the western edge of Otindag Sandland. The sand-dust storms initiated in these regions can affect northern and northeastern China, and extend as far as central China, as they travel with the weather system.

The distance of the transportation and the scale of influence of the transmitting sand-dust storms are largely determined by air circulation patterns.

The sand-dust storm weather in eastern China is mainly affected by the Mongolian low-pressure cyclonic system. Normally, after the formation of a Mongolian cyclone, the local dust will be raised up and will gradually move eastward and southward. In the process of moving, the convergence causing uplift in the air at the rear of the cyclone moves the dust with the air and transmits it downstream. Beijing is located in the downwind region, where the thick and deep cyclone often brings sand-dust storm weather.

Based on the comprehensive analysis of the daily weather map data from 1954–2000, some sand-dust storm processes in 1998 (Fig. 2.26) and 2000 (Fig. 2.27, Fig. 2.28, Fig. 2.29), and satellite remote sensing data for the whole year of sand-dust storm weather in 2001, we can speculate as to the main sources of sand-dust storm that affect the concentration of particulates in Beijing's air and the transmission routes of those storms. Transmitting sand-dust storm can be divided into a western route, a northern route and a northwestern route according to their transmission direction, initial sources and the transmission route.

The sand-dust storm sources that influence Beijing are:

(i) The initial external sources are located in the central, south and the southeastern regions of Mongolia, while the initial domestic sources are located at or near the China-Mongolia boundary.

(ii) The strengthening sources are located in the central and western parts of Inner Mongolia, the Hexi Corridor and the large area of reclaimed pastoral farming land(Fig. 2.30). The strengthening sources or the initial domestic sources of the northern transmission route are located at the Erlianhaote of central Inner Mongolia, Xilinhaote, Narenbaolige, east and west Wuzhumuqin Qi, Mandula, Zhurihe and Siziwang Qi and nearby areas. The strengthening regions and initial domestic sources of the northwestern route can be found in the Ejina Qi of western Inner Mongolia, Wulatezhong Qi, Wulatehou Qi, Etuoke Qi, Yanchi, Minqin and Guaizi Lake. The initial sources of the western route are the edge of the Taklimakan Desert of the Tarim Basin in Xinjiang and the Hami region in north Xinjiang.

Owing to its specific geographical location and environment, the sand-dust storm weather on the western route has a comparatively small impact on the concentration of particulates in Beijing. However, when meeting the strong weather system, the sand-dust storms can be transmitted long distances and potentially influence Beijing.

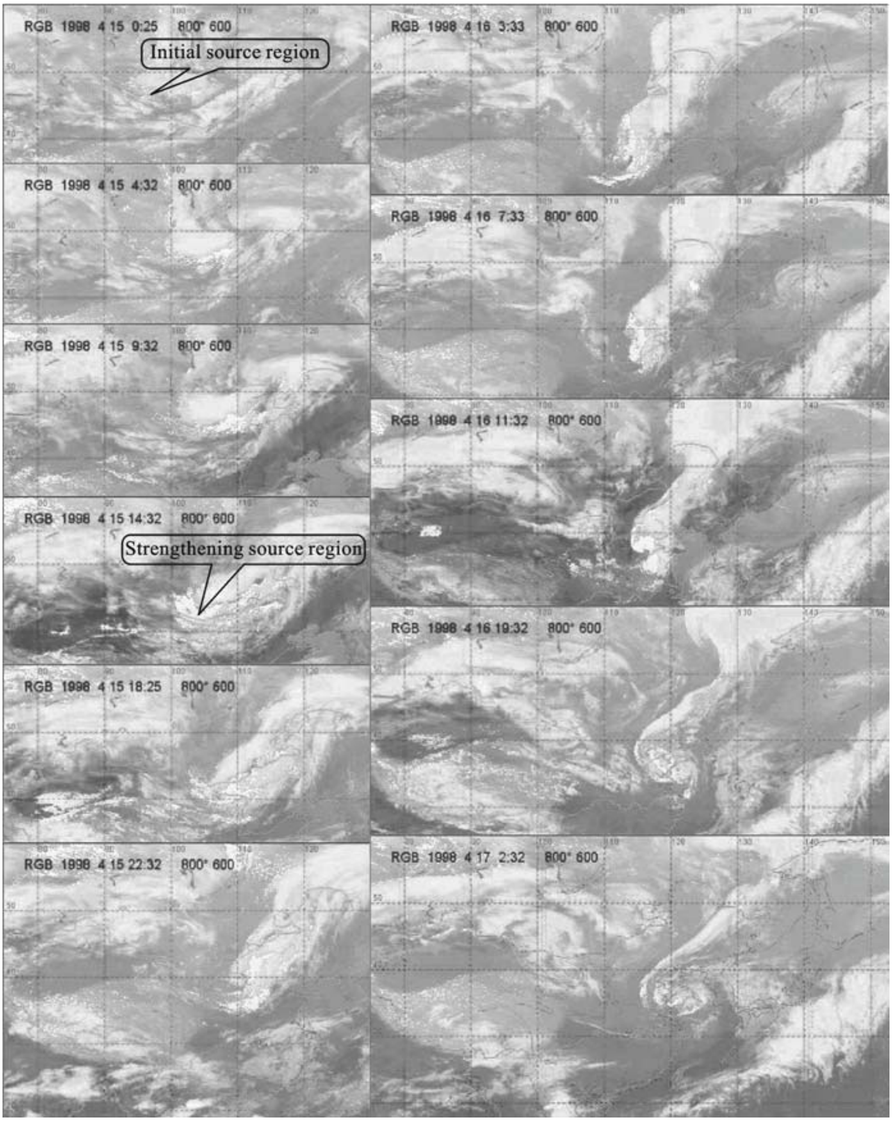

Fig. 2.26 The initiation, development and transmission of the sand-dust storm procedure from April 15th to 17th in 1998 (Gao et al., 2004, with permission from authors)

The sand-dust storm which occurred from April 15th to 17th, 1998 was a typical sand-dust storm which came from outside the country and was transported a long distance. The initial sand source was located in central and southern Mongolia, and the sand-dust storm was strengthened as it moved southeast through the Wulatezhong Qi and Wulatehou Qi in central Inner Mongolia, which means that a sand source within China also contributed to this sand-dust storm. The most serious effect of this sand-dust storm was to create a rare mud rain in Beijing. The influence of the storm extended to the southern part of the Yangtze River because of the northwest transmission path.

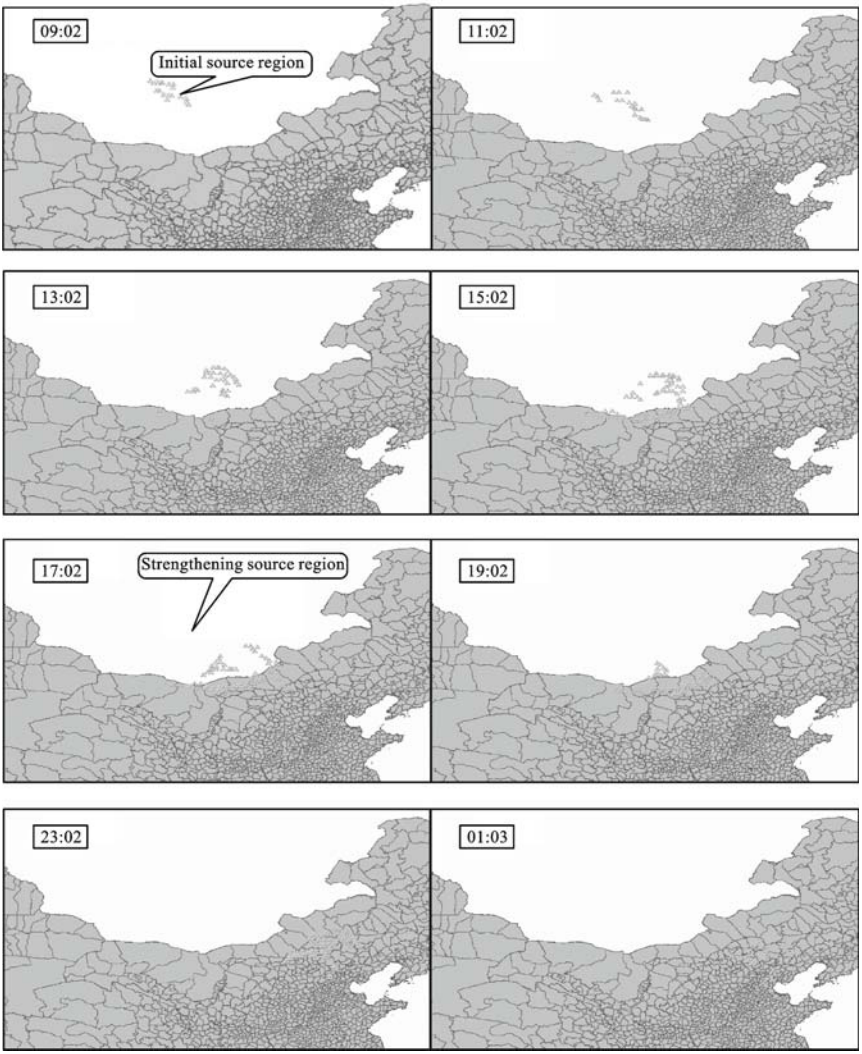

Fig. 2.27 The initiation, development and transmission of the sand-dust storm procedure from April 2nd to 3rd in 2000 (Gao et al., 2004, with permission from authors)

The original source of the sand-dust storm which occurred on April 2nd, 2000 was the south central area of Mongolia. As the sandstorm moved eastward, the Ejina Qi, Wulatezhong Qi and Wulatehou Qi of Inner Mongolia provided additional sand sources, intensifying the sand-dust weather. The regions of Inner Mongolia described above are the strengthening sources for storms that originate in south central Mongolia.

As sand-dust storms moved eastward via the Mongolian cyclonic system, they are intensified and further supplied with sand from the central and western part of Inner Mongolia. Sand-dust storms move in a southeasterly direction and influence most of the areas of north China, reducing the air quality in that region. The sand-dust storm route that influences Beijing sandstorms is the northwest route.

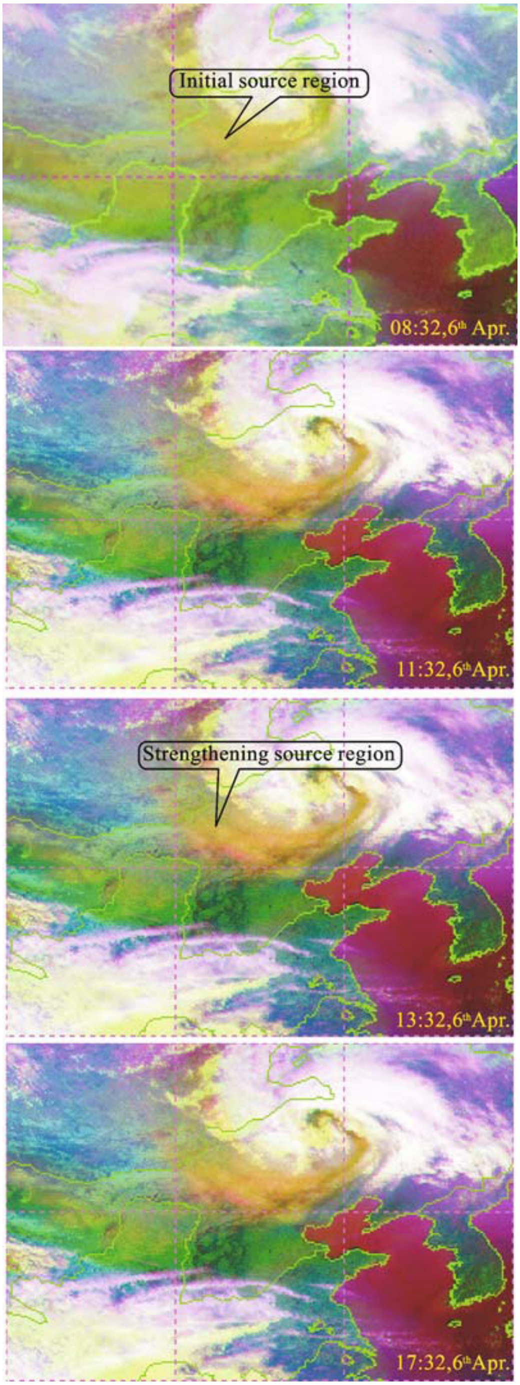

Fig. 2.28 The initiation, development and transmission of the sand-dust storm procedure in April 6th, 2000 (Gao et al., 2004, with permission from authors)

Influenced by the northeast eddy (April 6th, 2000), sand-dust storm originates from the boundary of central Inner Mongolia and Mongolia, and is intensified at the Erlianhaote, Wulatezhong Qi, Wulatehou Qi, and the Sunitezuo Qi at the western edge of Otindag Sandland in Inner Mongolia. As the northeast eddy transmitting to the southeast direction, it will influence Beijing and the northeast China.

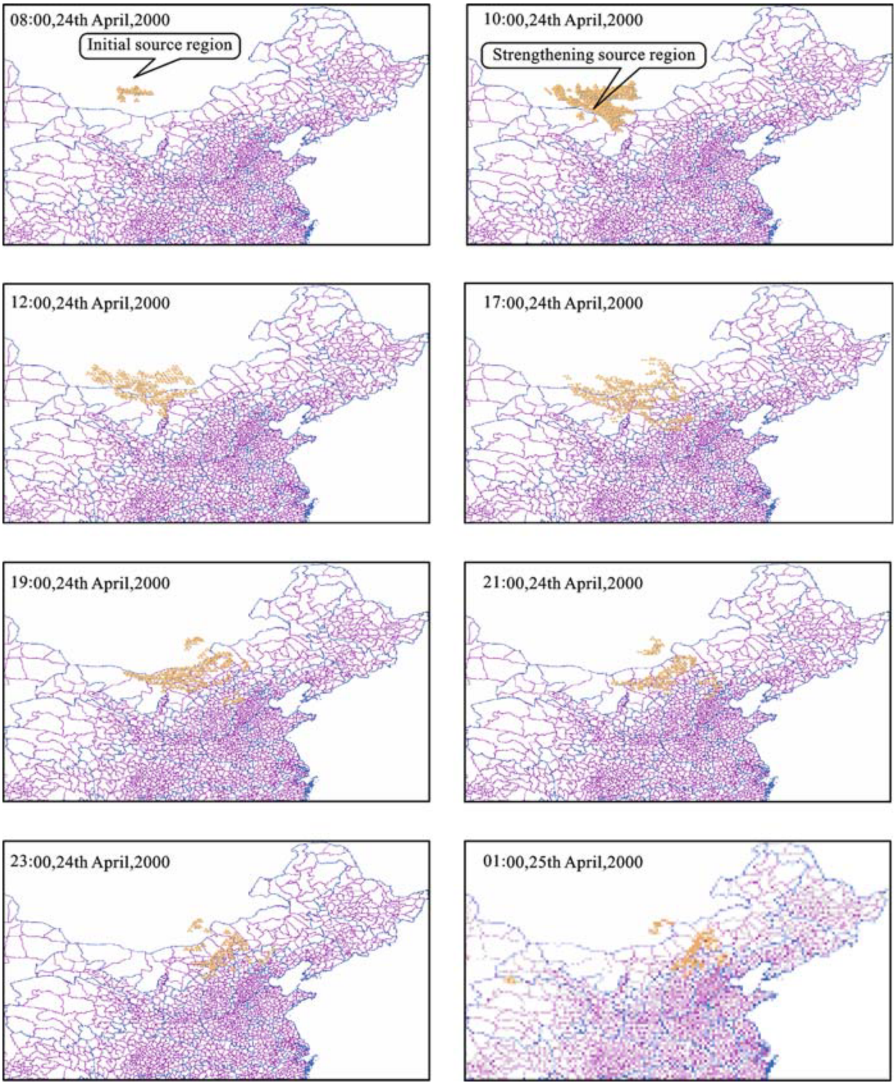

Fig. 2.29 The initial source and transmission path of the typical sand-dust storm procedure from April 24th to 26th, 2000 (Gao et al., 2004, with permission from authors)

The initial source of the sand-dust storm weather that affected Beijing between 24th and 26th April, 2000, was located in the central south of Mongolia, which is an external sand source. As the storm moved northward with the Mongolian cyclone system, domestic sand sources (Ejina Qi, Wulatezhong Qi and Wulatehou Qi in Inner Mongolia) continued supplementing and intensifying the storm, thus forming a large scale sandstorm.

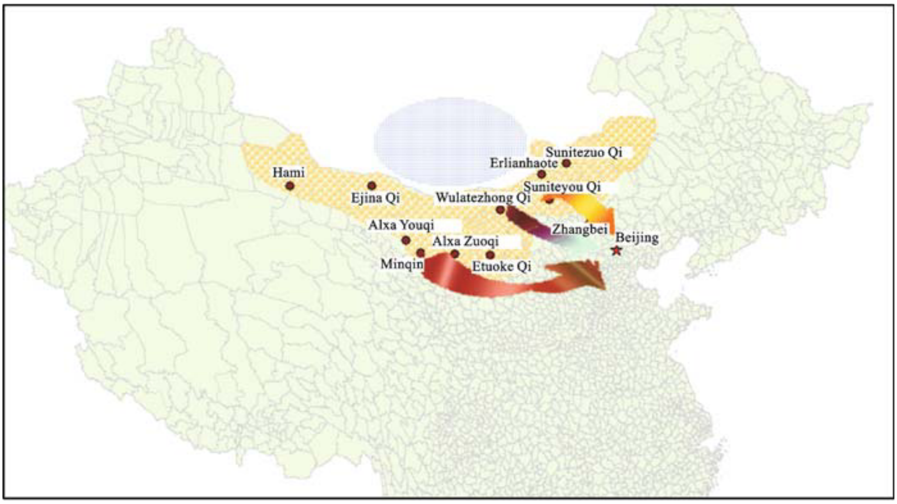

Fig. 2.30 The sand source that influences the particulate concentration of Beijing atmosphere and sand-dust transmitting route (Gao et al., 2004, with permission from authors)

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3 Natural Resources and their Utilization in the Drylands of China

Yuancun Shen

There are abundant natural resources in the drylands of China, wise utilization of these resources will be helpful to desertification control, poverty alleviation and social sustainable development in drylands. In this chpater, we give a summary description to these resources and utilization.

3.1 Climate resources and their potential capability

The drylands in China boasts its special climate resources, these resources include mainly solar radiation and photosynthetic production potential, temperature and the light-temperature production potential, and precipitation and light-temperature-water production potential. The study on climate resources and their potentials is aimed at using them more effectively.

3.1.1 Solar radiation and photosynthetic production potential

The drylands of China are exposed to high levels of solar radiation due to their relatively high altitude, droughts, low cloud presence, and long sunshine hours (Fig. 3.1). The total annual energy from solar radiation is between $544\ \mathrm{kJ} \cdot \mathrm{cm}^{-2} \cdot \mathrm{a}^{-1}$ and $670\ \mathrm{kJ} \cdot \mathrm{cm}^{-2} \cdot \mathrm{a}^{-1}$. Although these figures are lower than the annual solar radiation in high energy regions of the Qinghai-Tibetan Plateau ($> 670\ \mathrm{kJ} \cdot \mathrm{cm}^{-2} \cdot \mathrm{a}^{-1}$), they are much higher than the solar radiation recorded in the eastern coastal regions and southern China, and are nearly twice as high as the solar radiation in the western Sichuan Basin ($378\ \mathrm{kJ} \cdot \mathrm{cm}^{-2} \cdot \mathrm{a}^{-1}$). Thus, the drylands rank among the areas with the most abundant solar energy resources.

The assumption of the photosynthetic production potential is that envi-

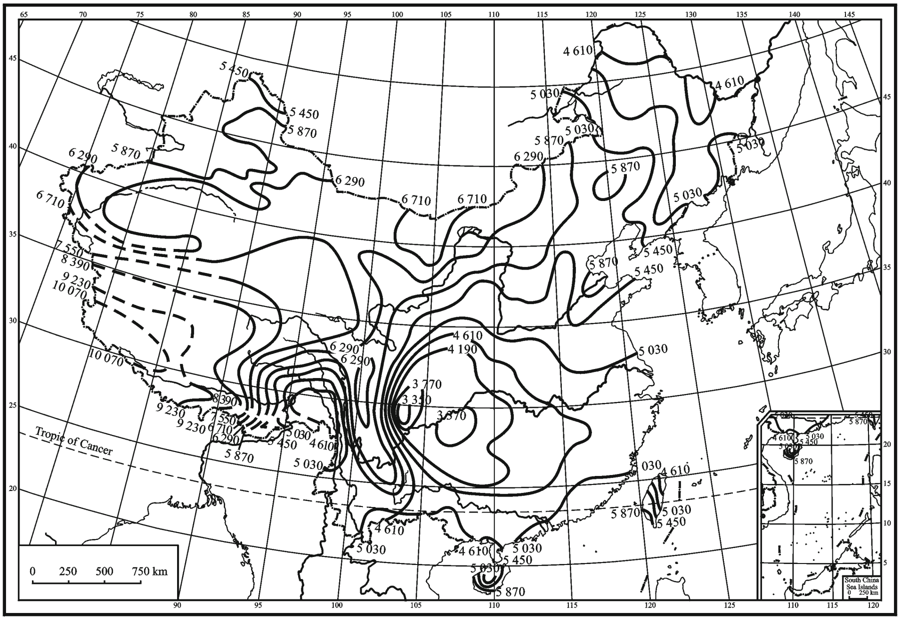

Fig. 3.1 Distribution of total solar radiation in China (Huang et al, 1986, with permission from authors)

ronmental factors such as temperature, moisture, carbon dioxide, and nutrient levels are optimized so that crops can achieve the highest possible yield through photosynthesis.

The photosynthetic production potential depends mainly on the level of solar radiation and utilization of the solar energy within the region by the crops. The photosynthetic production potential formula is as follows:

$$P_{\mathrm{f}} = [666.7 \times 10^4/(C \times 1\ 000)] \times F \times E \times Q \tag{3.1}$$

Where, P_{f} is the photosynthetic potential with units of kg/mu (1 mu = 1/15 ha). C is the conversion factor, namely, the chemical energy used by 1 g of dry matter. For most crops the average conversion factor is 17.8 kJ $\cdot \mathrm{g}^{-1}$. F is the solar energy utilization, and ranges from 2% (in the short-term) to 4% (in the long-term). E is the economic factor, which varies between crops. In most cases the E value of wheat (a C_3 crop) is 0.35, and the E value of maize (a C_4 crop) is 0.40. Finally, Q is the solar radiation, which has units of $\mathrm{kJ} \cdot \mathrm{cm}^{-2} \cdot \mathrm{a}^{-1}$.

After verifying the photosynthetic production formula, amending it and comparing a number of parameters, Bingwei Huang proposed a simpler calculation for photosynthetic production potential (Sun, 1988). The formula is:

$$P_{\mathrm{f}} = 0.0146Q \tag{3.2}$$

Where, P_{f} is the photosynthetic potential with the unit of $\mathrm{kg} \cdot \mathrm{mu}^{-1}$. Q is the solar radiation, with the unit of $kJ \cdot cm^{-2} \cdot a^{-1}$, and 0.014 6 is the coefficient of the conversion of total radiation into photosynthetic potential, also known as the Huang Bingwei Coefficient.

The photosynthetic production potential of the drylands in China, calculated according to the Huang Bingwei formula, ranges from 114,000 $kg \cdot ha^{-1}$ to 157,500 $kg \cdot ha^{-1}$ (Table 3.1, Fig. 3.2). The photosynthetic production potential is greater than 135,000 $kg \cdot ha^{-1}$ in the center of the Tarim Basin, the

Table 3.1 Comparison of photosynthetic production potential in typical locations in drylands and eastern plains of China

	Region	SR	PPP		Region	SR	PPP
	Manzhouli	522.1	114,525		Hami	638.3	140,010
	Chifeng	578.9	126,990		Shache	637.9	139,920
	Hohhot	601.9	132,030		Ruoqiang	635.8	139,455
	Yinchuan	601.5	131,940	Drylands	Urumqi	572.2	125,520
	Lanzhou	562.2	123,330		Lenghu	704.7	154,590
Drylands	Yulin	607.4	133,230		Ge'ermu	670.5	147,075
	Yan'an	530.0	116,265		Xining	612.8	134,415
	Minqin	652.9	143,220				
	Zhangye	645.0	141,480	Eastern	Shijiazhuang	550.5	120,750
	Jiuquan	630.3	138,270	plains	Beijing	543.8	119,295
	Dunhuang	654.6	143,595		Shenyang	512.9	112,500

SR: Solar radiation ($kJ \cdot cm^{-2} \cdot a^{-1}$), PPP: Photosynthetic production potential ($kg \cdot ha^{-1}$)

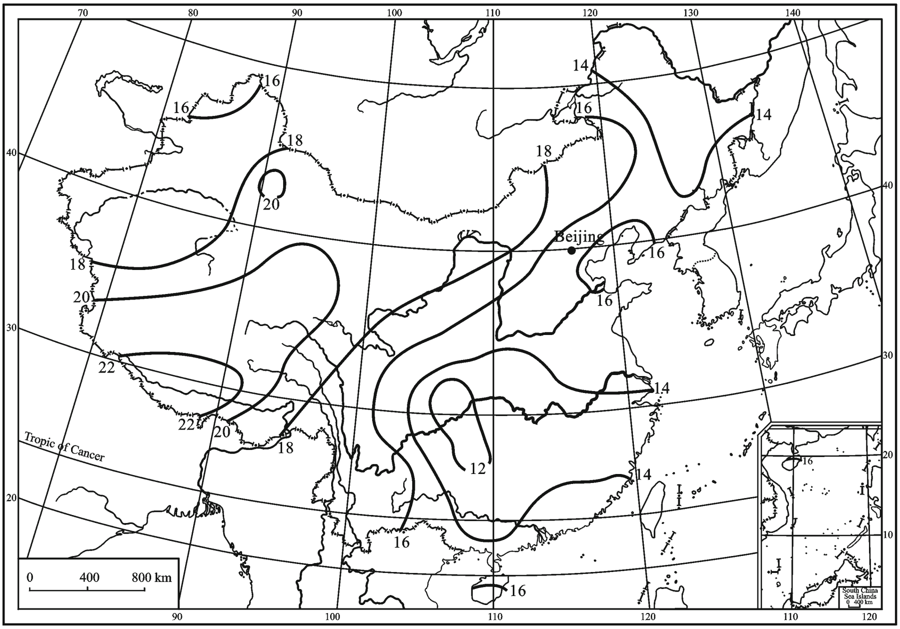

Fig. 3.2 Annual photosynthetic production potential in China (7,500 $kg \cdot ha^{-1}$) (Wang and Zhao, 1981, with permission from authors)

Qaidam Basin, and the Hexi Corridor. The value decreases gradually moving eastward and is at the lowest value of 114,000 kg·ha^{-1} in Manzhouli. Even in this area, the photosynthetic production potential is well above that of the southeast coast region and the Sichuan Basin, and ranks as one of the high value areas for China's photosynthetic production potential. Based on the current production status of the dryland, the utilization of solar energy is only 1.5–2.0% of the photosynthetic potential. Compared with an average of 4% utilization of solar energy in advanced countries, China's dryland agriculture still has considerable potential for the utilization of solar energy. In summary, there are significant prospects for the utilization of solar energy in drylands of China.

3.1.2 Temperature and the light-temperature production potential

There is a difference between the theoretical and actual temperature zones in the drylands of China. Considering their latitude, most of drylands should be warm temperate zones. However, due to the high elevations of 500 to 2,000 m above sea level, the temperature is lower than the expected, and hence most parts of the regions are temperate zones.

Table 3.2 shows that in the drylands of China, the Inner Mongolian Plateau and the Ordos Plateau, the eastern part of the Hexi Corridor, the northern part of the Qinghai-Tibetan Plateau and the Junggar Basin in Xinjiang are temperate climatic zones. Only the northern part of the Loess Plateau, the Tarim Basin and some small areas in the southeastern part of the Inner Mongolian Plateau are warm temperate zones.

Table 3.2 Comparison of temperature features in typical locations in drylands and eastern plains of China

	TF	D	CAT	AT	ELT	TZ
Drylands	Manzhouli	109.7	1,878.4	–23.8	–42.7	MTZ
	Chifeng	164.2	3,152.1	–11.7	–31.4	
	Hohhot	152.5	2,804.1	–13.1	–31.2	
	Yinchuan	172.0	3,298.1	–9.0	–30.6	
	Lanzhou	176.3	3,242.0	–6.7	–21.7	WTZ
	Yulin	167.8	3,217.6	–10.0	–30.9	MTZ
	Yan'an	173.0	3,270.8	–6.4	–25.4	WTZ
	Minqin	164.0	3,149.4	–9.6	–27.0	MTZ
	Zhangye	160.2	3,896.6	–10.2	–28.7	
	Jiuquan	159.8	2,954.4	–9.7	–28.6	
	Dunhuang	178.8	3,611.3	–9.3	–31.9	WTZ
	Hami	183.0	4,038.3	–12.2	–23.5	
	Shache	104.5	4,162.5	–6.6	–27.2	
	Ruoqiang	198.5	4,353.9	–8.5	–34.1	

Continued

	TF	D	CAT	AT	ELT	TZ
Drylands	Urumqi	154.3	3,063.3	–15.4	–34.3	MTZ
	Lenghu	112.1	1,728.3	–13.1	–33.6	
	Ge'ermu	130.2	2,009.8	–10.9	–24.9	
	Xining	133.6	2,037.3	–8.4	–26.5	
Eastern plains	Shijiazhuang	206.0	4,415.0	–2.9	–26.5	WTZ
	Beijing	199.4	4,118.1	–	–22.8	
	Shenyang	170.0	3,400.0	–12.0	–30.6	

TF: Temperature features; D: Days ⩾10 °C (d); CAT: The continuous accumulated temperature ⩾10 °C (°C); AT: Average temperature in the coldest month (°C); ELT: The extreme lowest temperature (°C); TZ: Temperate zone; MTZ: Moderate temperate zone; WTZ: Warm temperate zones

The heat resources in the drylands are characterized by:

(i) The temperature is lower than similar areas at the same latitude. For example, around the N 38° latitude line are areas including Yulin (N 38°14′, elevation 1,107.0 m), Yinchuan (N 38°29′, elevation 1,111.5 m), Zhangye (N 38°56′, elevation 1,482.7 m), and Lanzhou (N 36°06′, elevation 1,517.2 m). At each of these locations, the number of days with a temperature of ⩾ 10 °C is approximately 30 days less than that in Shijiazhuang (N 38°02′, elevation 80.5 m) on the North China Plain and the continuous accumulated temperature of ⩾ 10 °C is more than 800 °C less than that in Shijiazhuang. The reason is mainly that the elevation of drylands is 1,000 m higher than the North China Plain;

(ii) There are significant regional differences within the drylands and those differences are caused by the altitude, mountain structure and latitude. The southern region of the Loess Plateau and the Tarim Basin, which have lower elevations, are the regions with the best temperature conditions in the drylands, with over 180 days ⩾ 10 °C and the continuous accumulated temperature ⩾ 10 °C is above 3,600 °C;

(iii) The distribution of agricultural production is closely related to the regional differences in temperature. In the warm temperate regions, to ensure the efficient use of heat resources, crops which prefer this climate such as cotton, winter wheat, fruits, medicinal herbs, and other specialized crops should be grown, while the temperate regions are more suited to spring wheat, rapeseed, melons and other fruits, medicinal herbs, and other industries which prefer this kind of climate.

The temperature production potential, also known as light-temperature production potential, can be calculated based on the limited factor attenuation regulation in the drylands, i.e., the photosynthetic production potential (unrestricted), the light-temperature production potential (limited by temperature), the light-temperature-water production potential (limited by water restrictions), and the land production potential (limited by soil properties).

The temperature production potential in the drylands is calculated using the frost-free period. The formula is:

$$P_t = P_f \times f_{(t)} = P_f \times (n/365) \quad (3.3)$$

Where, P_t is the temperature production potential (light-temperature production potential), P_f is the photosynthetic production potential, $f_{(t)}$ is the light-temperature attenuation coefficient, and n is days in the frost-free period.

Calculated using the above formula, the light-temperature production potentials in the drylands are shown in Table 3.3 and Fig. 3.3.

Table 3.3 Comparison of light-temperature production potential in typical locations in drylands and eastern plains of China*

		FFP	LTPP
Drylands	Manzhouli	116	36405
	Chifeng	149	51840
	Hohhot	130	47115
	Yinchuan	169	61095
	Lanzhou	168	56760
	Yulin	156	56940
	Yan'an	180	57330
	Minqin	188	73770
	Zhangye	153	59310
	Jiuquan	161	60990
	Dunhuang	182	71595
	Hami	228	87465
	Shache	212	81270
	Ruoqiang	235	89790
	Urumqi	156	53640
	Lenghu	188	79620
	Ge'ermu	218	87840
	Xining	130	47880
Eastern plains	Shijiazhuang	195	64515
	Beijing	177	57855
	Shenyang	150	46230

FFP: Frost-free period (d); LTPP: The light-temperature production potential ($kg \cdot ha^{-1}$)

(*Source: China Meteorology Administration (CMA): China Regional Climate Information from 1951 to 1980 (internal) Volumes I, II, VI, Meteorological Press)

The data in Table 3.3 show that the production potential of the drylands is substantially restricted by temperature. The photosynthetic production potential in the Tarim Basin is greater than 138,000 $kg \cdot ha^{-1}$ but the light-temperature production potential is only 81,000–90,000 $kg \cdot ha^{-1}$. Similar situations exist in other dryland areas. For example, the photosynthetic production potential and light-temperature production potential are 142,500 $kg \cdot ha^{-1}$ and 60,000–75,000 $kg \cdot ha^{-1}$ respectively in the Hexi Corri-

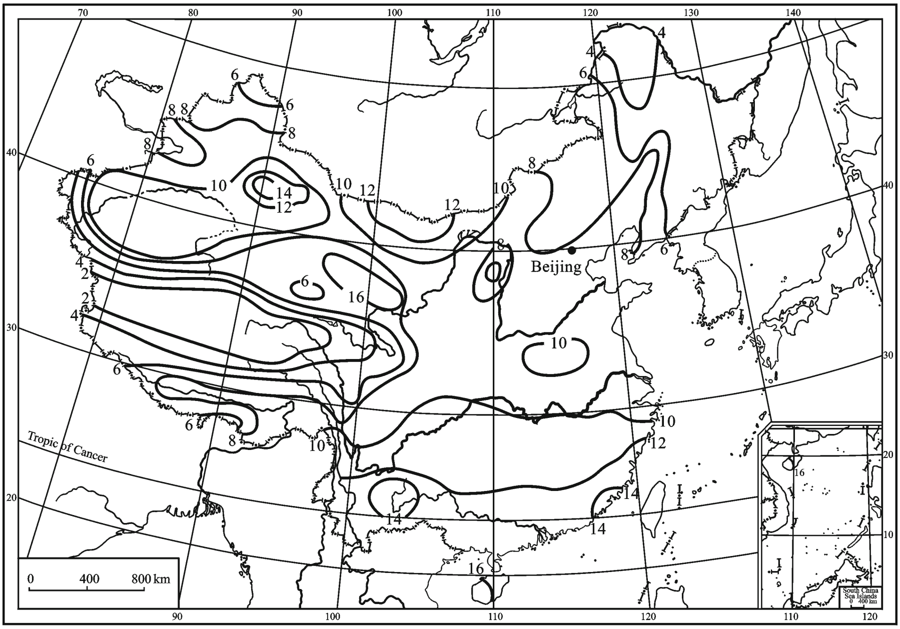

Fig. 3.3 Annual light-temperature production potential in China (7,500 kg·ha^{-1}) (Sun, 1988, with permission from author)

dor; 150,000 kg·ha^{-1} and 75,000–90,000 kg·ha^{-1} respectively in the Qaidam Basin; and 120,000 kg·ha^{-1} and 45,000–60,000 kg·ha^{-1} respectively in the Inner Mongolian Plateau. There are photosynthetic production potentials of 112,500–120,000 kg·ha^{-1} in the eastern North China Plain and the lower reaches of the Liaohe River Plain, lower than the drylands, but the light-temperature production potential is 52,500–67,500 kg·ha^{-1}. Clearly, increasing the temperature use efficiency and developing agricultural technologies that effectively use sunlight will play a positive role in enhancing the actual production potential of the drylands, and so should serve as an important part of the future agricultural technology system.

3.1.3 Precipitation and light-temperature-water production potential

The water vapor for precipitation comes from the ocean mainly. The major factors that influence the amount of precipitation are geographic location, atmospheric circulation and topography. China's drylands are located in the center of the Eurasian continent, a long way from the ocean, and there are mountains blocking the transport of water vapor, so there is little precipitation in the drylands. Coupled with little precipitation, the higher elevation, and higher evapotranspiration cause significant arid climate characteristics. Under a continental monsoon climate, dry and cold northwest winds prevail during the winter and spring seasons, and it is only in the summer that marine air masses can reach the drylands, bringing rainfall. Therefore, the precipitation in China's drylands has the following characteristics: First, precipitation is scarce, and the annual precipitation is generally below 400 mm. In terms of the average annual precipitation of China's four major sandlands and eight major deserts, this ranges from up to 400 mm in the Horqin Sandland in the east, to only 50 mm in the Taklimakan Desert in the west and about 60 mm in the western deserts of the Qaidam Basin (Table 3.4). Second, precipitation is unevenly distributed throughout the year. The precipitation in winter accounts for only 10% of the annual precipitation, while in summer, the rainy season, 70% to 80% of the annual precipitation will fall (Table 3.4). Third, the main types of precipitation are heavy rain and showers. The precipitation for a whole year is often concentrated in several heavy rainfall events, making it easy for floods to occur, yet during most of the year, there is no precipitation, causing prolonged drought. For instance, in the Taklimakan Desert, 70% to 80% of the annual precipitation can occur in a single day. Another example is Lanzhou, where a heavy rain, which only lasted for 5 hours in August 1978, delivered 90 mm of rain, which accounted for 27% of the precipitation in this year. Therefore, strategies of water resources use in the drylands include the use of runoff harvesting technologies to save rainfall water and the application of new water-saving technology.

Table 3.4 Precipitation in major sandlands and deserts of China (Geng, 1985)

Name	Precipitation ($mm \cdot a^{-1}$)	PIS ($mm \cdot a^{-1}$)	POP (%)
Hulun Buir Sandland	286	232	81
Horqin Sandland	402	358	87
Otindag Sandland	285	225	79
Mu Us Sandland	303	267	88
Qubqi Desert	241	200	83
Ulan Buh Desert	138	119	86
Tengger Desert	173	145	87
Badain Jaran Desert	62	54	84
Kumtag Desert	25	20	79
Gurban Tonggut Desert	142	75	53
Taklimakan Desert	48	39	81
Qaidam Basin Desert	60	39	65

PIS: Precipitation in summer; POP: Proportion of precipitation in rainy season (summer) compared to total precipitation (%).

The sections above, on the photosynthetic and the light-temperature production potentials, are based on the assumption that, except for the restrictions of light and temperature on agriculture, all other factors are ideal and fully coordinated to maximize production. However, such an idealized case cannot exist in the real world. Scarce rainfall and drought are characteristics of drylands, thus water shortage is a key constraint when water cannot meet the needs of crop growth. Therefore, the light-temperature-water production potential (also known as the climate production potential) is far lower than light-temperature production potential. Based on the agricultural production potential research system, the climate production potential is the light-temperature production potential multiplied by the effective water use coefficient.

Precipitation is the main source of water for plants, and other sources, such as groundwater, surface water, soil moisture, and ice/snow melt water are also derived from precipitation. However, in the evaluation of a region's water conditions, not only precipitation but evaporation should be taken into account. Owing to different evaporation rates, the same precipitation conditions have different effects on crops; therefore, the effective water use coefficient should also be considered. The calculation of the effective water use coefficient is mainly based on the balance of precipitation and evaporation caused by climatic processes. When the ratio of the mean of a region's precipitation and evaporation under average weather conditions is 1.00, it indicates a good balance between precipitation and evaporation, and that the synthesis rate of crop biomass is high. In contrast, when the precipitation is lower than the evaporation, the precipitation will not be able to meet the needs of plant growth, and then light-temperature-water potential will be less than the light-temperature potential. Because the precipitation in drylands is low, water is the major constraint factor for plant growth. Therefore, irrigation is an effective way to resolve the lack of balance in the moisture conditions, to develop production and increase land productivity.

The formula of the light-temperature-water potential is:

$$P_{\mathrm{w}} = P_{\mathrm{t}} \times f(w) \tag{3.4}$$

Where, P_{w} is light-temperature-water productivity; P_{t} is the light-temperature production potential; and $f(w)$ is the effective water use coefficient. Because evaporation depends on multiple factors, the calculation of $f(w)$ involves complicated factors. The commonly used formula is as follows:

$$f(w) = R/E_0 \tag{3.5}$$

Where $f(w)$ is the effective water use coefficient, R is precipitation, and E_0 is the evaporation. Using measured data, R (precipitation) can be easily calculated. E_0 (evaporation) is the maximum possible evaporation and is defined as the moisture content that can guarantee the maximum amount of evaporation assuming sufficient supply of water. There are many formulas for calculating evaporation, but the most recognized and accurate is the Penman formula:

$$E_0 = (\delta R_{\mathrm{n}}/L + rE_{\mathrm{a}})/(\delta + r) \tag{3.6}$$

Where: E_0 is the surface evaporation potential (mm); R_n is the daily solar radiation ($J \cdot cm^{-2} \cdot d^{-1}$); L is latent heat of water evaporation ($J \cdot cm^{-3}$); E_a is the air drying force ($mm \cdot d^{-1}$); δ is the slope of the curve of saturated vapor pressure against temperature; and r is the ventilated psychrometer constant. The unit of δ and r is hPa/°C. $\delta/(\delta+r)$ and $r/(\delta+r)$ are "weighting factors" when be converted into steam energy.

The calculation of this potential evaporation needs to be revised for altitude because the Penman formula is standard formula based at sea level. After revising the "weighting factors" and the radiation balance factor, the maximum surface evaporation potentials in the drylands and the light-temperature-water production potential under natural conditions have been calculated and shown in Fig. 3.4.

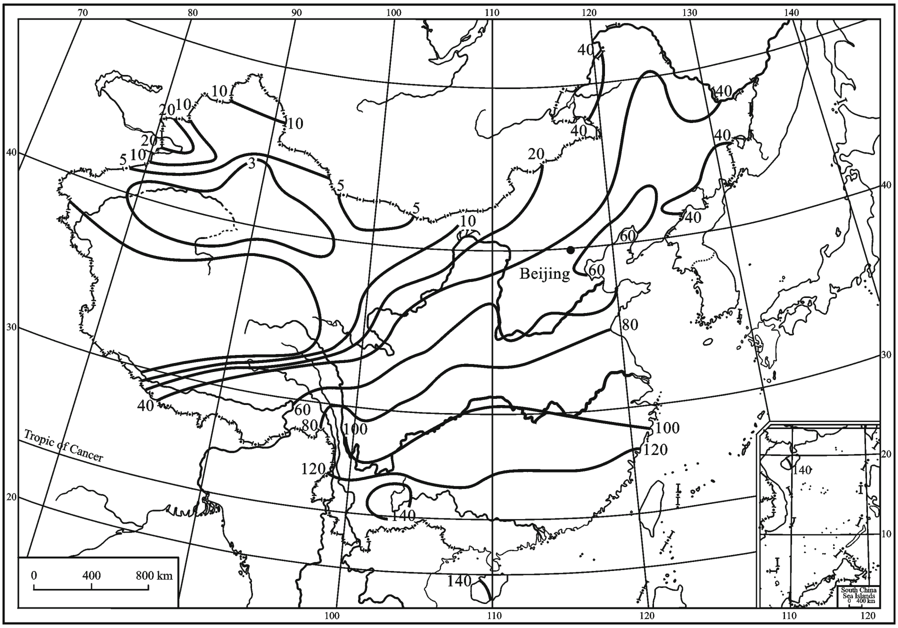

Fig. 3.4 Annual climate production potential in China (750 kg·ha^{-1}) (Sun, 1988, with permission from author)

Irrigation will greatly enhance the light-temperature-water production potential because the inadequate precipitation will be partially compensated by irrigation. The effective coefficient of the light-temperature-water production potential should be calculated from the combination of precipitation and supplementary irrigation. Hence, formula 3.5 should be amended to read:

$$f(w) = R/E_0 + f(i) \tag{3.7}$$

Where, $f(w)$, R and E_0 are the effective water use coefficient, the precipitation, and the evaporation respectively; and $f(i)$ is the effective coefficient for irrigation.

It can be seen from Fig. 3.4 that China's climate production potential decreases from east to west accompanying the reduction in precipitation. The climate production potential is up to 30,000 kg·ha^{-1} in the Horqin Sandland located in the eastern part of the drylands, and is reduced to 15,000 kg·ha^{-1} in the Hetao area of Inner Mongolia-Ningxia Plain. It drops to 7,500 kg·ha^{-1} in the Hexi Corridor and is less than 2,250 kg·ha^{-1} in the Taklimakan Desert.

The above analyses on the photosynthetic potential, the light-temperature production potential and the climate production potential show that although China's drylands have abundant solar radiation and high photosynthetic production potential of up to 150,000 kg·ha^{-1}, there is a significant temperature attenuation of photosynthetic potential due to the higher elevation and the cold winter. The light-temperature production potential is only about 75,000–105,000 kg·ha^{-1}. The climate production potential shows the most significant attenuation. Under conditions of scarce precipitation, drought and water shortage, the light-temperature-water production potential can be as high as 30,000 kg·ha^{-1} or as low as 2,250 kg·ha^{-1}. Consequently, precipitation is identified as the main climatic constraint to the production potential of the drylands. For example, in the Taklimakan Desert, the photosynthetic production potential is 135,000 kg·ha^{-1}, the light-temperature production potential is 75,000–90,000 kg·ha^{-1}, but the climate production potential is only about 2,250 kg·ha^{-1}. Clearly, moisture conditions are the most critical factors affecting the production potential. Considering that rainfall and plant growth are not always closely correlated due to the restrictions imposed by soil conditions, the actual production potential will be even lower in extremely arid situations. Therefore, in the development and utilization of climatic resources, the focus should be on the factors that are restricting production, especially the low precipitation. Searching for new technologies to enhance the use effectiveness of precipitation should be regarded as an important direction in the future research on climate resources of drylands.

3.2 Land resources and prospects for agricultural development

Drylands in China is characterized by serious land degradation and reduction of land productivity, and desertification control is to reverse land degradation and to increase land productivity. Hence, understanding land resources status in drylands will help us improve them more wisely.

3.2.1 Quality, quantity, and use status of land resources and existing problems

3.2.1.1 Quality, quantity and distribution of land resources

The development and utilization of land resources in China's drylands must be subordinate to the protection and improvement of the ecological environment. Therefore, the determination of land quality should be based not only on the suitability of land for agriculture, forestry and animal husbandry, but also on the ecological characteristics of restoration and management of vegetation. In other words, it is important to balance resource development and ecological improvement.

Among the past research on the quality and quantity of China's land resources, a representative output is "The map of China's land resources (1:1,000,000)" (Shi, 1991) which was prepared in the 1970s–1980s. The mapping process has divided the land within the country into eight categories according to classification indicators. Those categories are: land suitable for farming; land suitable for forestry and animal husbandry; land suitable for farming and forestry; land suitable for farming and animal husbandry; land suitable for forestry and animal husbandry; land suitable for forestry; land suitable for animal husbandry; and land not suitable for farming, forestry or animal husbandry. The categories can be further divided into three quality levels according to the extent of suitability and the level of productive potential. The quality levels are determined by the intensity of the restrictions on the land suitability. Ten types of restriction are classified, namely: no restrictions; water and drainage restrictions; soil salinization restrictions; effective soil thickness restrictions; soil texture restrictions; exposed bedrock restrictions; terrain slope restrictions; soil erosion restrictions; water restrictions; and temperature restrictions (Shi, 1991). However, the map only describes the potential areas at a provincial scale, and lacks a detailed scale. Also, the classification does not consider some ecological elements like shrubs, so it cannot be directly applied to the drylands.

Developing a classification system and related data on land resources for China's drylands was listed as the important outcome in "A comprehensive remote sensor survey of Three North Shelterbelt Areas" which was one of the State Sci & Tech key projects in "the Ninth National Five-Year Social and Economic Development Plan" from 1986–1990. The study regions of the project are basically the same as China's drylands. Therefore, the questions to be answered and countermeasures from the 1986–1990 survey have been identified as the main data sources for the analysis of land resources in this chapter. In addition, this chapter also includes some relevant data from "The rational utilization and exploitation of water resources and ecological environment protection in the Northwest China", which is another key subject of "the Ninth National Five-Year Social and Economic Development Plan".

(i) Land grading system and classification standards

To meet the needs of agriculture, forestry, and animal husbandry and to provide a scientific basis for protecting the ecological environment, the land resources have been divided into a series of land suitability categories, considering the land quality. These have been evaluated and mapped to a scale of 1:100,000 (Xu, 1994).

Land suitability categories reflect the ecological characteristics of the land and climate. Land suitability categories can be identified as warm temperate, moderate temperate, cold temperate, sub-cold temperate, and freezing temperate mainly on the basis of temperature and precipitation. The warm temperate, moderate temperate and cold temperate categories reflect a temperature range suitable for forestry and crop farming. The sub-cold temperate category has a temperature suitable for cold-tolerant shrubs, while crop farming is not suitable. The freezing temperate category is not appropriate for agriculture, forestry, or animal husbandry. The extent of humidity (or the drought index) is an indicator of moisture conditions. Trees can grow to form forests in humid and sub-humid conditions. Trees will not grow into forests in most areas with semi-arid conditions without irrigation. However, shrubs regenerate naturally in semi-arid and arid conditions. Only a few shrubs can be grown in arid and extremely arid conditions which are not appropriate for agriculture, forestry, or animal husbandry. According to the temperature and the water availability, the drylands can be divided into four categories based on their suitability for different land-use types: Type I has multiple suitability (suitable for agriculture, forestry, animal husbandry), Type II has dual suitability (suitable for forestry and animal husbandry), Type III has a single suitability (suitable for animal husbandry), and Type IV has no suitability (not suitable for agriculture, forestry or animal husbandry). Depending on the factors that restrict land use, the land categories can be further divided into nine levels. As the level increases from Level 1 to Level 9 the restrictions get more severe, the land quality declines, and the breadth of suitability gradually narrows. Levels 1 to 4 are sub-divisions of Type I, in terms of farming conditions, with Levels 1 to 3 suitable for permanent agriculture, while Level 4 is more suited to forest or grassland than farmland. Levels 5 to 7 are subdivisions of Type II, with Levels 5 and 6 considered suitable for planting trees, while Level 7 land is not appropriate for the normal growth of trees but is suitable for shrubs. Level 8 is consistent with Type III agriculture, and is only appropriate for the development of forage crops. Level 9 is not appropriate for agriculture, forestry, or animal husbandry (Xu, 1994). Among the nine levels, a separate level is used for land appropriate for shrubs (Level 7). Level 7 in this classification is an addition to the eight levels used in the United States and Europe and is not found in other classification systems in China. This classification system is more suitable for the ecological improvement of China's drylands and has a high application potential.

(ii) Land quality, quantity and distribution

Taking into account the vast area, and the obvious and very significant differences in the quality and quantity of land resources in different regions in the drylands, it is appropriate to evaluate land resources and identify typical administrative regions on the basis of physically geological zones. China's drylands can be divided into 13 natural zones. The various counties and cities found in each natural zone are shown in Table 3.5, while the quality and quantity of the land resources in each natural zone are shown in Table 3.6.

Table 3.6 shows that the quality and spatial distribution of China's drylands have the following characteristics: First, the overall land quality is low. The total area for Levels 1–4, accounts for only 22.5% of the total dryland area. The lands for Levels 1–3 amounts to only 14.8%, while the land for Level 9 accounts for 36.76%. Second, land quality is unevenly distributed among the different regions, with the east generally being of better than the west, and sub-humid areas being better than the semi-arid areas, and much better than the arid and extremely arid areas. For example, the proportions of land for Levels 1–3 are 62.61% in the forest-steppe region of the sub-humid Songnen Plain, 35.86 % in the forest-steppe region of the sub-humid southeast Loess Plateau, 14.60% in the steppe of the semi-arid central Inner Mongolian Plateau in Northwest China, 9.87% of the steppe of the semi-arid northwest Loess Plateau, 10.57% in desert of the arid Hexi Corridor and only 1.35% in desert regions of the hyper-arid Tarim Basin. Third, the proportion of the land inappropriate for agriculture, forestry or animal husbandry is large (36.76% of the total dryland area). The land types are the Gobi deserts, mobile sand dunes, heavy saline-alkali land, wind eroded residual hills and exposed hilly/gully areas. The proportions of land for Level 9 in the east are 8.61% in forest-steppe region of the sub-humid Songnen Plain, 2.25% in the Yanshan Mountains regions, 2.23% of the southeast Loess Plateau; 9.76% of the semi-arid Xiliao River regions; and 6.44% of central Inner Mongolia. In contrast, in the west, 26.50% in the Ordos Plateau, 46.46% in the Hexi Corridor, and 77.37% in the hyper-arid region of the Tarim Basin are categorized as Level 9. These data show a trend of desertification that becomes increasingly prominent and serious from east to west. Fourth, the land proportions suitable for trees and shrubs are 2.83% in the sub-humid Songnen Plain, 4.79% in the Yanshan Mountains regions, 2.35% in the southeast Loess Plateau; 1.61% in the semi-arid central Inner Mongolian Plateau, 1.61 % in the Ordos Plateau, 0.26% in the Hexi Corridor and 0.36% in the Tarim Basin. This reveals that when planting shelterbelts, trees are an appropriate choice in sub-humid areas while shrubs are more suitable in the semi-arid, arid and hyper-arid regions.

(iii) Factors restricting land use and their distribution

There are nine factors which restrict land use in China's drylands. In general, each category of land use often has only one or two dominant factors which have an impact on the production potential of the land resources. Good governance can improve the quality of land by overcoming the negative

Table 3.5 Natural zones and administrative areas of China's drylands

Natural zone number	Temperature and moisture type	Counties and cities	Size(10,000ha)	
			Subtotal	Total
1	Warm temperate,semi-humid	Beijing: Huairou, Yanqing, Changping, Miyun, Daxing, Fangshan, Fengtai	108.72	927.17
		Liaoning: Beipiao, Jianping, Jianchang, Lingyuan, Kazuoqi, Xihe District of Fuxin City, Qinghe District of Fuxin City, Fuxin, Shuangta District of Chaoyang City, Longcheng District of Chaoyang City, Chaoyang County	298.53	
		Hebei: Longhua, Luanping, Chengde, Fengning, Weichang, Pingquan, Wanquan, Huai' an, Chicheng, Chongli	445.59	
		Inner Mongolia: Ningcheng, Kalaqin	74.32	
2	Warm temperate, semi-humid	Shaanxi: Yichuan, Hancheng, Qianyang, Fengxiang, Linyou, Changwu, Binxian, Yongshou, Xunyi, Chunhua, Yaoxian, the suburbs of Tongchuan City, Baishui, Pucheng, Chengcheng, Heyang	213.46	299.28
		Shanxi: Daning, Xixian, Fenxi, Jixian, Puxian, Xiangning	85.81	
3	Warm temperate, hyper-arid	Xinjiang: Turpan, Hami, Kuche, Shache, Shule, Aksu, Hetian, Luopu, Qiemo	3,389.26	3,389.26
4	Temperate, semi-humid	Heilongjiang: Zhaodong, Zhaoyuan, Zhaozhou, Lanxi, Mingshui, Qinggang, Baiquan, Keshan, Kedong, Fuyu, Yi'an, Qiqihar, Tailai, Duerbote	493.73	1,102.04
		Jilin: Yushu, Dehui, Fuyu, Nong'an, Qian'an, Changling, Lishu, Gongzhuling	368.15	
		Liaoning: Xinmin, Liaozhong, Heishan, Yixian, Beizhen, Zhangwu, Changtu, Kangping, Faku	240.15	
5	Temperate, semi-arid	Inner Mongolia: Keyouzhongqi, Tuquan, Kezuozhongqi, Kezuohouqi, Kailu, Kulun, Naiman, the suburbs of Chifeng, Aohan, Wengniute, Balinyouqi	996.33	996.33
6	Temperate, semi-arid	Inner Mongolia: Taibus, Xianghuang, Siziwang, Zhuozi, Chayouzhongqi, Helingeer, Chayouqianqi, Qingshuihe, Xinghe, Fengzhen, Liangcheng, Tumote	701.86	840.67
		Hebei: Zhangbei, Guyuan, Shangyi, Kangbao	138.81	
7	Temperate, semi-arid	Inner Mongolia: Dalate, Junggar, Yijinhuoluo, Wushen	334.81	405.70
		Shaanxi: Yulin	70.89	

Continued

Natural zone number	Temperature and moisture type	Counties and cities	Size(10,000ha)	
			Subtotal	Total
8	Temperate, semi-arid	Shanxi: Tianzhen, Yanggao, Xinrong, Zuoyun, Youyu, Pinglu, Pianguan, Shenchi, Wuzhai, Jingle, Loufan, Xingxian, Lanxian, Shilou, Yonghe	253.65	1,154.97
		Shaanxi: Shenmu, Dingbian, Jingbian, Hengshan, Fugu, Qingjian, Jiaxian, Wuqi, Zhidan, Yan'an, Zichang, Ansai	470.89	
		Gansu: Dingxi, Huining, Jingning, Qin'an, Tianshui, Zhenyuan, Jingchuan, Lingtai, Qingyang, Ningxian, Zhengning	331.73	
		Ningxia: Yanchi, Xiji	98.71	
9	Temperate, arid	Ningxia: Helan, Yinchuan, Yongning, Qingtongxia, Zhongning, Zhongwei	121.81	224.59
		Inner Mongolia: Dengkou, Hangjinhouqi, Wulateqianqi	122.78	
10	Temperate and warm temperate, hyper-arid	Gansu: Dunhuang, Anxi, Yumen, Jinta, Jiayuguan, Jiuquan, Gaotai, Linze, Zhangye, Shandan, Minyue, Yongchang, Jinchang, Minqin, Wuwei, Gulang, Jingtai	1,422.60	1,422.60
11	Temperate, hyper-arid	Xinjiang: Fukang, Habahe, Wusu, Jinghe, Yining	506.90	506.90
12	Temperate, semi-arid	Qinghai: Huangyuan, Huangzhong, Datong, Xining, Huzhu	104.12	104.12
13	Temperate, arid and hyper-arid	Qinghai: Haixizhou and other counties, Yushuzhou: Zhiduo, Qumalai, Guoluo Prefecture, Maduo and other eight counties (cities)	2,468.64	2,468.64
Total		213 counties (cities)	13,862.26	

Natural zones: 1: Forest-steppe zone in Yanshan Mountains and Beijing Plain; 2: Forest-steppe zone in the southeast Loess Plateau; 3: Desert zone in the Tarim Basin; 4: Forest-steppe zone in the Songnen Plain; 5: Steppe zone in the Xiliao River Basin; 6: Steppe zone in central Inner Mongolian Plateau; 7: Steppe zone in the Ordos Plateau; 8: Grassland of the northwest Loess Plateau; 9: Desert-steppe zone of the Hetao Plain in Ningxia-Inner Mongolia; 10: Desert zone in the Hexi Corridor; 11: Desert zone in the Junggar Basin; 12: Steppe zone in the Haidong Mountains of the Qinghai Plateau; 13: Desert zone in the Qaidam Basin.

Table 3.6 Distribution of land use categories within natural zones in China's drylands (10,000 ha)

Natural zone number		Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8	Level 9	Total area
1		66.44	117.94	76.68	62.30	304.13	153.54	66.73	58.57	20.85	927.17
2		21.14	37.27	48.92	60.35	20.41	39.83	25.68	38.99	6.67	299.28
3		14.35	12.01	19.31	18.10	18.51	21.35	110.85	552.49	2,622.27	3,389.26
4		257.72	228.18	204.12	125.50	65.48	40.71	37.57	47.89	94.85	1,102.04
5		88.90	88.96	123.01	129.50	154.50	171.81	103.05	39.37	97.22	996.33
6		1.97	20.35	100.43	184.18	51.15	133.80	114.71	179.91	54.16	840.67
7		0.77	0.84	14.41	13.34	5.57	53.69	174.61	34.95	107.52	405.70
8		17.18	33.45	63.43	391.18	119.89	131.97	195.27	123.57	79.03	1,154.97
9		25.18	3.64	24.22	13.44	3.60	22.21	29.61	82.76	39.93	244.59
10		71.61	15.96	62.70	19.24	3.95	38.11	159.66	390.39	660.97	1,422.60
11		23.74	12.23	2.72	6.91	15.96	26.01	39.36	296.47	83.51	506.90
12		–	24.65	18.91	5.96	5.60	3.74	29.80	15.46	–	104.12
13		–	6.82	30.32	74.16	3.52	22.16	44.34	1,058.35	1,228.97	2,468.64
Total	Area	589.00	602.31	789.19	1,104.17	772.28	858.94	1,131.25	2,919.17	5,095.96	13,862.27
	%	4.25%	4.34%	5.69%	7.97%	5.57%	6.20%	8.16%	21.06%	36.76%	100%

Natural zones 1–13 are the same as in Table 3.5

impacts of the restrictive factors. The restrictive factors of China's drylands show significant differences in different regions. An investigation of regions such as the forest steppe zone in the southeastern Loess Plateau (a sub-humid area), the steppe zone in eastern and central Gansu (a semi-arid area), desert-steppe zone in Zhongwei-Yinchuan of Ningxia (an arid area), the desert zone of the Hexi Corridor (a hyper-arid area), and the high-cold desert zone of the Qaidam Basin (a hyper-arid area) reveals the main environmental issues for these different areas and identifies management options for the drylands.

Table 3.7 shows that different regions have different environmental problems and require different management solutions. The land area affected by water erosion accounts for 88.62% of the forest steppe zone in the southeast Loess Plateau, so the main environmental management direction in this area should be to control soil erosion by planting soil and water conservation forests. In the steppe zone in eastern and central Gansu Province, the land constraints mainly include poor water conditions (with a proportional area of 36.19%) and soil erosion (with a proportional area of 34.80%). With drought and soil erosion as the two major issues for this region, the management solutions involve soil and water conservation and the development of water-saving agriculture. In the desert steppe zone of Yinchuan-Zhongwei, the main restrictive factors are water (with a proportional area of 59.26%), soil texture (with a proportional area of 6.15%), salt restrictions (with a proportional area of 4.74%), and wind erosion (with a proportional area of 4.48%), so the regional management direction is mainly to develop water resources, combat desertification and control soil salinization. In the desert zone in the Hexi Corridor, the area restricted by soil texture accounts for 41.94%, the area restricted by water accounts for 20.08%, the area restricted by the thickness of fine soil is 9.88%, the area restricted by salinity is 8.69%, and the area restricted by wind erosion is 8.97%. This means that the main problems in the use of land resources are hazards associated with drought, such as the Gobi and desert (texture restrictions), water shortage and salinity, so the management direction will undoubtedly involve stabilizing the desert, controlling salinization, and developing water-saving oasis agriculture. In the alpine desert zone in the Qaidam Basin, the area restricted by water conditions is 24.50%; the area restricted by temperature is 21.35%; the area restricted by soil texture is 18.79%; the area restricted by salinity is 16.03%; and the area restricted by wind erosion is 11.97%. It can be seen that the factors restricting the land potential of the region are drought, low temperature, crude soil texture, salinity and sandstorms, etc. The best management would be to use water resources more wisely, to develop horticultural technology, to prevent sandstorms and to control salinization.

3.2.1.2 Land use status

In China there have been few studies on land use in drylands, and they have generally treated the dryland as a whole, and were conducted many years

Table 3.7 Composition of land restrictive factors in China's dryland (10,000 ha, %)

Regions	TA	AUL	ASE	AWR	ASTR	ASHR	ASR	AWER	AWLR	ASLR	ATR	UWA
Forest-steppe zone in the southeast Loess Plateau	299.28 (100)	21.15 (7.07)	265.22 (88.62)	11.98 (4.00)			0.58 (0.19)					0.35 (0.12)
Steppe zone in eastern and central Gansu	332.54 (100)	9.73 (2.93)	115.73 (34.80)	120.35 (36.19)	12.47 (3.75)	11.75 (3.53)	0.15 (0.05)			36.84 (11.08)	11.39 (3.42)	14.13 (4.25)
Desert-steppe zone in Yinchuan-Zhongwei, Ningxia	121.81 (100)	24.74 (20.31)		72.19 (59.26)	7.49 (6.15)		5.78 (4.74)	5.45 (4.48)	0.94 (0.78)	2.66 (2.18)	0.09 (0.07)	2.47 (2.03)
Desert zone in the Hexi Corridor	1,421.39 (100)	71.61 (5.04)		285.40 (20.08)	596.11 (41.94)	140.38 (9.88)	123.52 (8.69)	127.51 (8.97)	12.82 (0.90)	29.97 (2.11)	31.02 (2.18)	3.05 (0.21)
Alpine desert zone in the Qaidam Basin	2,468.98 (100)	5.75 (0.23)	3.17 (0.13)	604.93 (24.50)	463.90 (18.79)	153.65 (6.22)	395.73 (16.03)	295.50 (11.97)	1.97 (0.08)	1.90 (0.08)	527.10 (21.35)	15.38 (0.62)

TA: Total area; AUL: Area of unrestricted land; ASE: Area of soil erosion (water erosion); AWR: Area of water restrictions; ASTR: Area of soil texture restrictions; ASHR: Area of soil thickness restrictions; ASR: Area of salt restrictions; AWER: Area of wind erosion restrictions; AWLR: Area of waterlogging restrictions; ASLR: Area of slope restrictions; ATR: Area of temperature restrictions; UWA: Unexamined and waterbody area.

Note: Figures in parentheses are the percent of total regional area.

ago. Therefore, for the purpose of revealing the current land use situation in the drylands we have made reference to the integrated remote sensing survey of the "Three North Regions Shelterbelt Development Areas" in 1986–1990 and some relevant information and materials from the "Ninth Five-Year for National Social Economic Development Plan", State Research Programme in 1996–2000.

The land-use types and distribution within China's drylands are described below:

First, the rate of land use is not high. Unused or difficult-to-use land accounts for 40.96%, while cultivated land (including orchards and vegetable or cash crop farms) accounts for only 15.73%, rangeland, grassland and steppe cover 31.01%, and woodlands cover only 7.70%.

Second, land use is extremely variable in different regions. The land use intensity in the sub-humid areas in eastern China is higher than that in the semi-arid and arid areas of western China. Cultivated land accounts for 57.01% of the Songnen Plain, while unused land accounts for only 3.69%. Cultivated land accounts for 35.25% of the southeast Loess Plateau, while unused land accounts for 5.42%. The cultivated land is only 29.83% in the central Inner Mongolian Plateau, while the unused land is 3.86%. The cultivated land is only 7.58% and the unused land is a relatively high 9.70% in the Ordos Plateau. Although the cultivated lands account for 18.48% and 7.58% in the Hetao Plain in Ningxia-Inner Mongolia and in the Hexi Corridor, respectively, due to the irrigation water from the Yellow River and the inland rivers, the unused or difficult-to-use lands are 14% and 47%, respectively. Cultivated land is only 1.31% of the Tarim Basin, while the unused land is 77.81%. Cultivated land accounts only for 0.19% and unused land is as much as 71.54% of the Qaidam Basin. This shows that the development intensity of land use is high in the east and low in the west of China's drylands due to the regional differences such as rainfall and the constraints of the socio-economic development level. This situation is consistent with the suitability of land resources and geographical and environmental restrictions.

Third, as with vegetation distribution, the proportion of forest areas is higher in the east than that in the west, and higher in sub-humid areas than in semi-arid areas or arid areas. The Yanshan Mountains in North China and the Haidong Mountains in Qinghai both mainly consist of mountainous land, but the proportions of forest areas are 29.10% and 12.44 %, respectively. On the Loess Plateau, the proportions of the forest areas are 28.71% in the sub-humid southeastern part and 14.51% in the semi-arid northwestern part. The proportions of forest areas are 5.71%, 3.32%, 1.34% in the desert steppe in the Hetao Plain, the desert of the Hexi Corridor and the desert of the Tarim Basin, respectively. The proportion of forest areas shows a trend of decreasing from the east to the west. The proportion of rangeland is greater than 50% in the central part of the Inner Mongolian Plateau, the Hetao Plain, and the eastern part of the Ordos Plateau, all of which are located in the central part of the drylands. The proportion of rangeland decreases moving eastward to the Songnen Plain and the Xiliao River Plain, southward to the Loess Plateau, and westward to the Hexi Corridor, the Tarim Basin and the Qaidam Basin. This confirms that the core geographical region for animal husbandry in China's drylands is the central Inner Mongolian Plateau and the Ordos Plateau (Table 3.8).

3.2.1.3 Existing problems in land resources use

Considering the land use status and the goals of sustainable development and increasing land productivity, some existing problems associated with the land resources use are summarized as follows:

(i) Inappropriate exploitation of land resources, and severe land degradation

The livelihood and future development of mankind relies on the exploitation of land resources. However, such exploitation must be in harmony with the ecological resource attributes of the land so as to obtain both economic benefits and improvement of ecological efficiency. Unfortunately, past practices have sacrificed the ecological environment for quick results, and this problem is widespread due to limitations in earlier policies. For example, since 1949, to meet the need of food, China underwent three major stages of land exploitation (during the mid-1950s, early 1960s and early 1970s). Large areas of land unsuitable for farming, such as steppe, desert steppe, sandy grassland, and salinized grazing lands, were made available and cultivated. Overgrazing occurred in a quest to improve livelihoods, and resulted in serious degradation of the rangeland. To solve the problems of fuel supply, large areas of woodland and shrubland were cut down. In particular, the shrubs which stabilize the deserts were cut down and exploited in the semi-arid and arid areas. For short-term benefits, Chinese herbal medicines, such as *Glycyrrhiza uralensis* and *Ephedra* spp., were over-collected. The unthinking exploitation of land resources mentioned above eventually led to an increased spread of land degradation and has been the main cause of desertification in China in recent decades.

Desertification is having a tremendous negative effect on cultivated land, grassland and forest, and has brought about enormous losses to national and local economies. The degraded rangeland in China's drylands covers 1.05 million km^2, accounting for 56.6% of total rangeland. The area of degraded cultivated land is 77,300 km^2, accounting for 45.1% of the total area of cultivated land. The degraded woodland area is 10,000 km^2 (Shen et al., 2001).

(ii) Poor agricultural framework, inefficient productivity, and insufficient socio-economic development

The poor framework for land use in China's drylands can be seen in the use of a large proportion of land for agriculture and small proportion of land for forestry and animal husbandry. With agriculture, the proportion of food crops is high, while cash crops account for a comparatively small proportion. With

Table 3.8 Structure of land use in the drylands of China (10^4ha)

Natural zone number	Total	Cultivated land		Orchards and vegetable lands		Woodland		Rangeland	
		Area	%	Area	%	Area	%	Area	%
1	927.17	197.04	21.25	17.73	1.91	269.76	29.10	291.84	31.48
2	299.28	105.51	35.25	5.24	1.75	85.91	28.10	65.41	21.86
3	3,389.26	44.34	1.31	1.10	0.03	45.50	1.34	579.03	17.08
4	1,102.04	628.87	57.07	4.45	0.40	98.93	8.98	168.30	15.27
5	996.33	218.52	21.93	6.85	0.69	139.62	14.01	488.51	49.03
6	840.67	250.85	29.83	0.70	0.08	49.56	5.89	466.99	55.54
7	405.70	30.77	7.58	0.08	0.02	65.98	16.26	256.69	63.27
8	1,154.97	450.53	39.01	3.72	0.32	167.55	14.51	340.22	29.46
9	244.59	45.20	18.48	0.52	0.21	13.96	5.71	132.37	54.12
10	1,422.60	107.90	7.58	0.77	0.05	47.18	3.32	583.94	41.05
11	506.90	31.47	6.21	0.29	0.06	21.61	4.26	319.27	62.97
12	104.12	23.43	22.51	0.02	0.02	12.95	12.44	64.60	62.04
13	2,468.64	5.27	0.19	0.02	0.00	48.68	1.97	541.39	21.93
Total	13,862.27	2,139.71	15.43	41.50	0.30	1,067.19	7.70	4,298.56	31.01

Natural zone number	Land for residents, factories and mines		Land for transportation		Waterbody		Unused land	
	Area	%	Area	%	Area	%	Area	%
1	27.26	2.94	12.63	1.36	14.87	1.60	96.04	10.35
2	12.85	4.29	3.26	1.09	4.86	1.63	16.23	5.42
3	6.47	0.19	2.15	0.06	73.69	2.17	2,636.97	77.81
4	58.47	5.31	28.79	2.61	73.54	6.67	40.69	3.69
5	13.58	1.36	11.25	1.13	22.46	2.25	95.53	9.59
6	16.01	1.90	9.23	1.10	15.12	1.80	32.21	3.86
7	2.42	0.06	0.75	0.18	9.64	2.38	39.37	9.70
8	22.85	1.98	12.83	1.11	12.88	1.11	144.39	12.50
9	2.95	1.20	2.86	1.17	12.76	5.22	33.98	13.89
10	1.85	0.13	2.85	0.20	9.21	0.65	668.88	47.01
11	2.11	0.42	1.26	0.25	25.05	4.94	105.86	20.88
12	0.96	0.92	0.14	0.14	0.21	0.20	1.81	1.74
13	6.29	0.25	1.09	0.04	100.20	4.06	1,765.70	71.54
Total	174.06	1.26	89.09	0.64	374.50	2.70	5,677.66	40.96

Natural zones 1–13 are the same as in Table 3.5.

respect to forestry, trees are far more commonly planted than shrubs. Additionally, there is a lack of species diversity. With animal husbandry, rangeland is used only for grazing without any management practices. In addition, the proportion of artificial grasslands is small, as are the proportions of high quality grasslands and enclosed grazing lands.

It is generally accepted that the proportions of the population and land involved in agriculture are both large in China. This is especially obvious in the drylands of China. The land suitable for permanent farming accounts for 14.29% of the whole drylands, but the actual land use of farmland accounts for 15.73%. The over-cultivated rate is about 29.46% in the steppe zone of the northwest Loess Plateau; 15.31% in the steppe zone in the central Inner Mongolian Plateau; and 3.66% in the Ordos Plateau (Table 3.9). These zones are mostly agro-pastoral transitional zones and over-cultivation has worsened the spread of desertification. Therefore, marginal crop fields should be revegetated with artificial trees, shrubs or grasses as an essential element in the restoration of the drylands.

Table 3.9 Comparison between area of land suitable for agriculture and that of land used for agriculture in drylands (%)

Natural zones	Percentage of land suitable for permanent agriculture	Percentage of land actually used for agriculture	Percentage of land available for exploitation for agriculture
1	28.16	23.16	5.00
2	35.86	37.00	–1.14
3	1.35	1.34	0.01
4	62.61	57.47	5.14
5	30.20	22.62	7.58
6	14.60	29.91	–15.31
7	3.94	7.60	–3.66
8	9.87	39.33	–29.46
9	21.68	18.69	2.99
10	10.57	7.63	2.94
11	7.64	6.27	1.37
12	41.84	22.53	19.31
13	1.50	0.21	1.29
Total	14.29	15.73	–1.44

Natural zones 1–13 are the same as in Table 3.5.

An outstanding issue of dryland use is the imbalance between the output value of agriculture, forestry and animal husbandry and the structure of land use. Take Ningxia as an example: The total output value of agriculture, forestry, animal husbandry and fishery was 6.917 billion RMB in 1996, of which the crop production sector brought in 4.861 billion RMB (70.27%), forestry income was 138 million RMB (2.0%), animal husbandry was 1.798 billion RMB (26.0%), and fishing was 119 million RMB (1.72%). Another example is Inner Mongolia, where the total value of agriculture, forestry, animal husbandry and fishing was 46.533 billion RMB in 1996, of which the value of agriculture was 29.953 billion RMB (64.37%), forestry was 1.397 billion RMB (3.0%), the value of animal husbandry was 14.856 billion RMB (31.93%), and fishing was 327 million RMB (0.7%) (China Statistical Yearbook, 1997). Evidently, the low outputs from forestry and animal husbandry are one of the reasons causing unbalanced agricultural development between the three land uses. The future direction of the development of land resources should involve applying the latest scientific knowledge in forestry and animal husbandry operations to increase the output efficiency and the economic and social status.

(iii) Extensive land use and low technological levels

A key reason for the low productivity and serious land degradation is the extensive land use and low technological levels. Production still follows traditional farming methods, which use low technological inputs and are very labor intensive. The land area plowed by tractors is small, with only 17.9% in Gansu Province, 30% to 40% in the majority of provinces and autonomous regions, and less than 10% in mountainous areas. The application rate of fertilizers is low, with an average of 421.5 $kg \cdot ha^{-1}$, accounting for 35% of the national 1,203 $kg \cdot ha^{-1}$. The potential for coping with drought is low, with irrigated land accounting for 34.4% of all farmland and only 3.2% in Shaanxi Province. The traditional flood irrigation method is inappropriate at rates as high as 15,000 $m^3 \cdot ha^{-1}$, which not only seriously wastes water, but can also accelerate soil salinization. The multiple cropping index is as low as 113.7%. The promotion of advanced production technology and new breeds or species is weak, with the rate of transfer of scientific and technological knowledge only about 40%. The production chain is short, the processing system for agricultural produce is weak, the technology level is low, and the efficiency is also low. The crop yields are low, with the cereal production being 2,880 $kg \cdot ha^{-1}$ on average which is only 72% of the national average yield (Sun, 2001; Shen, 1997). The future use of land resources in the drylands will involve building knowledge-based structures of agriculture, forestry and animal husbandry.

3.2.2 Development potential of agriculture and measures to develop the land production potential

Although the current land productivity is low in drylands and many existing problems need solving, the drylands have a high light-temperature production potential. As long as modern science and technology is applied and the prevailing problems in land use are overcome, then the land resources in the drylands have good prospects. It is a challenge to recognize the development potential of land and search for effective measures to develop it.

3.2.2.1 Development potential for agriculture in drylands

(i) Development potential of photosynthetic, light and temperature productivity

The development potential of drylands for agriculture is enormous. A comparison with the North China Plain, which is located at the same latitude with well developed agriculture, reveals some useful information. Table 3.10 shows that the solar radiation value is over 543 kJ $\cdot$ cm$^{-2}\cdot$ a^{-1} in China's drylands, which is higher than the solar radiation value of 460–523 kJ $\cdot$ cm$^{-2}\cdot$ a^{-1} on the North China Plain. The light-temperature production potential is 53,000 to 73,000 kg $\cdot$ ha^{-1} in the drylands which is consistent with the North China Plain. This shows that the drylands are richer in solar energy resources than that in the North China Plain, so the development of industries that use these solar energy resources has great potential.

Table 3.10 Comparison of light-temperature production potential between typical regions in the drylands and the North China Plain (Shen et al, 2001)

Indices	Drylands				North China Plain	
	Yinchuan	Dunhuang	Hetian	Urumqi	Zhengzhou	Jinan
SR (kJ·cm^{-2}·a^{-1})	601.50	654.59	595.65	572.24	499.93	524.17
PPP (kg·ha^{-1})	131,940	143,595	130,650	125,520	109,650	114,975
FFP (d)	168	182	204.5	156	210.6	190.8
LTPP (kg·ha^{-1})	60,728.5	70,600.8	73,199.8	53,646.9	63,226.7	60,102.0

SR: Solar radiation; PPP: Photosynthetic production potential; FFP: Frost-free period; LTPP: Light-temperature production potential.

(ii) Yield potential

The most obvious limitation on production is the scarce rainfall in the drylands. Once the irrigation is solved, the production potential in the drylands will be higher than on the North China Plain with the same latitude. Comparing the irrigated oases in the Hetao Plain in Ningxia and in the Hexi Corridor with the North China Plain, note that with the same investment, the yield of the oases in the drylands was 16% higher than the yield on the North China Plain, and the yield of oil crops was 12% higher in above mentioned oases than in the North China Plain (Table 3.11). This means that with investment in agricultural development, the drylands can be more productive than the North China Plain and development of water-saving high-yield agriculture has great development prospects in the drylands.

The agricultural multiple cropping index is only 107.8% in the drylands, compared with 165.3% in the North China Plain (Shen et al., 2001). Therefore, an essential method for improving the yield per unit area is to raise the multiple cropping index. It is quite possible for the multiple cropping index to reach 150% with the measures such as an appropriate distribution of crop varieties and the use of cultivation techniques that increase temperature. An experiment in the Zhangye of the Hexi Corridor improved the multiple crop-

Table 3.11 Comparison of current productivity between different regions of northwest deserts and North China Plain (1993) (Shen et al., 2001)

Agricultural production and productivity level	NCP	IO
Area of farming land (km^2)	1,770.1	130.4
Area of land with effective irrigation (km^2)	1,145.4	110.2
Percentage of land with effective irrigation (%)	64.7	84.5
Mechanical power of cultivated land (W/ha)	4,497	4,371
Application of fertilizer (kg/ha)	255	300
Application of pesticide (kg/ha)	6.0	1.5
Yield of grain (kg/ha)	4,906.5	5,692.5
Yield of oil crops (kg/ha)	2,319.0	2,599.5
Average area of cultivated land for the rural population (ha)	22.5	43.5
Average area of mechanically cultivated land for the rural population (ha)	18.0	30.0
Per capita share of grain according to total rural population (kg)	443.5	511.1
Per capita share of oil crops according to total rural population (kg)	21.2	41.2
Per capita share of marketable grain according to total rural population (kg)	131.4	230.0
Per capita share of marketable oil according to total rural population (kg)	14.8	41.8

NCP: North China Plain; IO: The irrigated oases in the Hetao Plain in Ningxia-Inner Mongolia and in the Hexi Corridor.

ping index to 160% by adopting a sound planting structure of grain and cash crops. Through increasing the multiple cropping index the total grain production can be increased by about 40%, and the overall yield could increase by about 150 billion $kg \cdot a^{-1}$ in the drylands.

(iii) Overall potential of agricultural development in drylands

The discussion above illustrates that the drylands have an enormous potential for agricultural development. Under the same production conditions, the grain yield can be 16% higher and the oil crop yields can be 12% higher than those in the North China Plain. By developing water-saving systems and increasing the multiple cropping index, the grain yield could be increased from 37.5 billion kg in the mid-1990s to 75 billion kg, the oil crop yield could be increased from 2.2 million tons to 3.2 million tons, and cotton production could be increased from 0.8 million tons to 1.20 million tons.

3.2.2.2 Measures to increase land production potential

China's drylands have an enormous development potential for increasing land production. To achieve this potential, various approaches need to be adopted, and measures should be applied to establish a reasonable framework for land use for agriculture, forestry and animal husbandry, to adjust the planting structure of crops, to develop a modern agricultural system, and to develop knowledge-based industries in the drylands.

(i) Adjustment of land use structure and establishment of an optimum land use framework

The main problem that constrains the effectiveness and sustainable development of drylands is land use structure; therefore, the key to solving the problem is to establish an optimum land use framework. The suitability and restrictions of land resources need to be fully recognized, so that an optimum framework for land use protection and planning will allow the balanced development of both economy and ecology. The relationship between agriculture, industry, transportation and house building should be properly managed, and with sustainable land management and associated regulations, the ratio of land use to productive yields should be increased. In addition, land use programs should be adjusted depending on the stage of socio-economic development. An information system for land management should also be established.

(ii) Adjustment of cropping composition and development of a diversified agricultural economy

Crop farming is the main economic activity in the drylands. Therefore, it is important to establish a reasonable crop composition which aims to develop a diversified agricultural economy so that economic benefits and ecological efficiencies are achieved. The main crops currently planted in the drylands are food crops which account for 70% to 75% of the cropping land, and bring in about 60% of the total agricultural income. The land used for cash crops (oil seeds, cotton, melons and other fruits, Chinese herbal medicine and raw materials for sugar production) is about 25% to 30% of the cropping land, but accounts for about 40% of the total output value. The focus on food crops leads to a low rate of return from the land use, and is a common phenomenon in agricultural areas from less developed counties/cities where the development of cash crops would improve income. Given the rich solar and thermal resources, and dry climate, the agriculture in the drylands should compress the area of food crops, and develop a diversified economy with specialized industries to achieve an economic and environmental sustainability.

(iii) Establishment of a water-saving agricultural system

Drylands are characterized by frequent droughts and water shortage, and the water resources is a key restriction on economic development and ecological improvement. At present, the water resources used for agriculture account for 70% to 80%, and can be as much as 90% of the total volume of water resources in China's drylands. The available ecological water outside agricultural areas has been squeezed. Due to the low levels of technology in agricultural operations, the use of flood irrigation has resulted in a serious waste of water resources and caused salinization in some regions and aridization of broad areas. The establishment of a water-saving agricultural system is a key initiative to ensure both agricultural development and the promotion of regional ecological improvement. One of the main directions of agricultural development is to introduce new technology and decrease the water volume used for crop irrigation from 15,000–22,500 $m^3 \cdot ha^{-1}$ to the 5,300–7,500 $m^3 \cdot ha^{-1}$ required by crops. The basic ways for establishing water-saving agriculture system are: to develop an anti-seepage and leak-proof water canal system with the introduction of new technologies; to improve the efficiency of water supplied to crops by irrigation; to implement the technologies of sprinkler irrigation and drip irrigation which will minimize evaporation and preserve soil moisture; and other technologies. The implementation of a water-saving agricultural system will provide a good foundation for the sustainable development of the drylands.

(iv) Development of knowledge-based industries and implementation of sustainable development of economy and ecology in the drylands

The Gobi and deserts are widely distributed in China's drylands, covering a total area of 1.56 million km^2, and accounting for about 31% of China's drylands (China Statistical Yearbook, 1993). For a long time, the Gobi and deserts were both theoretically and practically regarded as barren lands, the "seas of death", and the source of disasters. With the trends towards improved technology, new materials and new techniques, Xuesen Qian, a famous scientist in China regarded the abundant light and heat conditions in deserts as resources and advocated the development of "agricultural, knowledge-based, sand development industries" in the drylands. The basic premise for drylands development is based on "new technology, more light, less water and high efficiency". After nearly 20 years of practice, particularly in large areas of Zhangye region, Gansu Province, this approach has shown significant success and proved to be the correct choice for implementing a knowledge-based economy in China's drylands.

The abundant light and temperature resources are the exclusive natural advantages of the drylands. However, these advantages are restricted by drought and water shortages. If water-saving agricultural technologies are applied, such as drip irrigation, pipe irrigation, micro-irrigation, and other advanced methods, and water reduction projects are applied in factories, the problems imposed drought may be managed and the capability for the integrated use of light, temperature and water will be enhanced. The introduction of advanced technologies includes not only the use of water-saving technology, but also the application of biotechnology, new materials and new technologies. In Zhangye region, the implementation of a five-year plan for developing a sand development industry was initiated in 1995. The plan focused on the use of sunlight, adopting the technology of water-saving drip irrigation, promoting new varieties, and implementing mulching cultivation and biological microalgae production. By 1999, the output value of typical plots (on a per hectare basis) was about 450,000 RMB, the per capita income grew from 15,600 RMB to more than 42,000 RMB, and the average annual growth of GDP was more than 13%. Adoption of technology has proven that China's drylands have tremendous potential for agricultural development. The implementation of a knowledge-based system could possibly raise the agricultural output value of the drylands in Northwest China from around 25 billion RMB in the 1990s to 100 billion RMB. This will eventually realize the goal of a stable foundation of agricultural development in balance with the ecological environment protection.

3.3 Water resources and ecological water use

Water is the most important element in drylands. The drylands of China are one of the birthplaces of the Chinese civilization with a 6,000–7,000 year history. The cultures which have developed in the drylands, from the Silk Road culture to modern culture, have all developed around the oases which are rich in water resources. Ninety percent of the population and 95% of the industrial and agricultural output in drylands occur in and around oases. The oases are, of course, totally dependent on the availability of water resources. Therefore, studying the water resources and the ecological water use is important to combat desertification and to maintain the sustainable development of the drylands.

3.3.1 Type, quantity and distribution of water resources in drylands

Drylands in China are distant from the sea, and the water supply is almost dependent on precipitation. Therefore, the amount of precipitation and its temporal and spatial distribution, are the basic measurement of the abundance of water resources. Due to solar radiation, temperature, topography, vegetation and other factors, the evaporation and transpiration rates (collectively known as evapotranspiration) will vary between regions. This means that given the same amount of precipitation, the amount of water available would be different because of the different evapotranspiration rates. Therefore, to study the availability of water resources, we need to determine: first, the available precipitation; second, the total volume of water, including surface water and groundwater; and third, the amount of water available in glaciers and lakes. With the above data, we can develop a thorough understanding of the water resources in the drylands.

3.3.1.1 Total water balance in drylands

Precipitation is the only water source in the drylands and therefore the precipitation could be defined as the total water resource amount. After precipitation, some of the water will evaporate from the ground surface and will not be usable, while some of the water will infiltrate into soil and become soil water that can be used for various ecological purposes. The remaining will produce surface runoff, feeding rivers and lakes. To summarize, precipitation can be divided into evaporative water (ineffective), infiltration water (effective) and runoff water. A total water balance has been calculated for inland drylands in Northwest China (Table 3.12).

Table 3.12 Generalized water balance in the inland drylands in Northwest China

Provinces or regions		Area	Precipitation	Evaporation		Infiltration		Runoff	
		10^4 km^2	10^8 m^3	10^8 m^3	%	10^8 m^3	%	10^8 m^3	%
Xinjiang	Northern Xinjiang	39.5	1,047.4	151.3	14.4	466.1	44.5	430.0	41.1
	Southern Xinjiang	104.9	1,327.4	499.8	37.7	428.0	32.2	399.6	30.1
	Eastern Xinjiang	21.0	140.9	54.7	38.8	58.8	41.7	27.4	19.5
	Whole Xinjiang	165.4	2,515.7	705.8	28.1	952.9	37.9	857.0	34.1
Hexi Corridor	Shule River	17.0	163.7	69.5	42.5	71.4	43.6	22.8	13.9
	Heihe River	12.8	164.3	45.8	27.9	76.9	46.8	41.6	25.3
	Shiyang River	4.1	89.9	16.9	18.8	55.5	61.7	17.5	19.5
	Whole Hexi Corridor	33.9	417.9	132.2	31.6	203.8	48.8	81.9	19.6
Qaidam Basin		25.8	296.4	110.4	37.2	139.2	47.0	46.8	15.8
Sum		225.1	3,230	948.3	29.4	1,296.0	40.1	985.7	30.5

(Resource: "The Ninth National Social and Economic Development Five-Year Plan", Key Project (96–912) the Rational Utilization of Water Resources and Ecological Environment Protection in Northwest China-Overall Strategy Research on the Sustainable Utilization of the Water Resources, 2001).

Table 3.12 shows:

(i) In the inland drylands, the ratio of evaporation to infiltration to runoff is about 3:4:3, which means that only 30% of the precipitation feeds surface water resources such as rivers and lakes. The surface runoff modulus is about 43,789 $m^3 \cdot km^{-2}$ and is viewed as a low rate of runoff.

(ii) The distribution of total water resources varies between regions. Regions that have a high evaporation typically have a relatively low runoff. For instance, considering the precipitation, the proportion of evaporation in northern Xinjiang is low at 14.4 %, while the proportion of runoff is high at 41.1%; the evaporation in the Shule River in the Hexi Corridor is 42.5%, while the runoff is low at 13.9%; the evaporation at the Shiyang River in the Hexi Corridor is 18.8%, while the runoff is 19.5%, and in the Qaidam Basin, the evaporation is 37.2%, and the runoff is only 15.8 %. The highest evaporation and lowest runoff occurs at the center of the Shule River, and the evaporation decreases and runoff increases moving out from there.

(iii) The distribution of evaporation rates matches with the drought index patterns. In the inland drylands, the Shule River basin has the highest drought index and the figure declines gradually, going northwest to the Wulungu River and the Altai (northern Xinjiang), east to the Shiyang River watershed, and south to the Qaidam Basin. This is consistent with the evaporation rate, which is 42.5% along the Shule River watershed, declining slightly to 38.8%

in eastern Xinjiang, 37.7% in southern Xinjiang and only 14.4% in northern Xinjiang, while to the east in the Heihe River watershed the proportion of evaporation is 27.9%, in the Shiyang River watershed it is 18.8% and to the south of the Qaidam Basin it is 37.2%.

3.3.1.2 Regional distribution of precipitation, surface water, and groundwater

After falling, precipitation changes into evaporated water, soil water, surface water and groundwater. In terms of water use, evaporation water is ineffective and unusable; infiltrated soil water, used by plants, is called effective water; and groundwater and surface water are often referred as the water resources. The precipitation, surface runoff water and groundwater in the drylands of China can be seen in Table 3.13.

(i) Precipitation

Precipitation is the only new supply of water in China's drylands because they are located at the center of the Eurasian continent, distant from the sea. Additionally, affected by prevailing weather conditions and by the uplift of the Qinghai-Tibetan Plateau, precipitation is scarce. According to the statistics around the watersheds in Xinjiang, Gansu, Qinghai, Ningxia and Inner Mongolia, a total of 891.71 billion m^3 of precipitation occurs over a total area of 3.875 million km^2 (Table 3.13). That equates to a precipitation rate of 230,100 $m^3 \cdot km^{-2}$, which means that this is an area of lower precipitation.

The center of the low precipitation area is the Shule River, southern Xinjiang and the western part of the Qaidam Basin, which has a precipitation of less than 50 $mm \cdot a^{-1}$. Moving eastward to the Horqin Sandland, precipitation gradually increases to 400 $mm \cdot a^{-1}$, while moving westward and northwestward to Yining and Altai in Xinjiang the precipitation increases to 200–250 $mm \cdot a^{-1}$.

The drylands in each province have different precipitation amounts because of spatial variations in precipitation and the area of the watersheds (Table 3.13). There is approximately 251.57 billion m^3 of precipitation in the drylands of Xinjiang; 106.42 billion m^3 of precipitation in the drylands of Gansu; 318.3 billion m^3 of precipitation in the drylands of Inner Mongolia; 129.37 billion m^3 of precipitation in the drylands of Qinghai; 15.12 billion m^3 of precipitation in the drylands of Ningxia; and 70.93 billion m^3 of precipitation in the drylands of Shaanxi.

(ii) Surface runoff water

Most runoff water in the drylands comes from precipitation in the mountains. Because the altitude is low and the temperature is high in inland basins, the precipitation in the inland basins is low while the evaporation rate is relatively high, but in the mountains, the precipitation is higher and the evaporation rate is lower. Therefore, the surface water in the drylands is typically produced in the mountains and caught in the basins. Generally speaking, there are three sources of surface runoff water which come from the moun-

Table 3.13 Distribution of runoff water in the deserts of China

Provinces and corresponding watersheds			Area (10^4km^2)	Precipitation (10^8m^3)	SRW (10^8m^3)	GW (10^8m^3)	RC	RM (10^4m^3 ·km^{-2})
Xinjiang		Northern Xinjiang	39.5	1,047.4	403.7	149.0	0.39	10.9
		Southern Xinjiang	104.9	1,327.4	370.2	212.9	0.28	3.8
		Eastern Xinjiang	21.0	140.9	20.5	21.0	0.15	1.3
		Total	165.4	2,515.7	794.4	383.0	0.34	5.2
Gansu		Inland rivers	21.5	354.4	58.4	56.9	0.18	3.0
		Yellow River	14.3	709.8	134.3	64.9	0.20	9.9
		Total	35.8	1,064.2	192.7	121.8	0.19	5.78
Qinghai		Inland rivers	37.4	652.2	128.3	69.8	0.21	3.6
		Yellow River	15.3	641.5	210.3	89.2	0.30	13.8
		Total	52.7	1,293.7	338.5	159.0	0.27	6.52
Sha'anxi		Yellow River	13.3	709.3	106.6	80.2	0.18	9.3
Ningxia		Yellow River	5.2	151.2	9.7	29.8	0.08	2.3
Inner Mongolia	West	Yellow River	14.4	247.3	14.7	24.3	0.14	2.3
	West	Inland rivers	21.7	241.4	0.4	18.8	0.07	0.8
	West	Western part	36.1	488.7	15.1	43.1	0.10	1.41
	East	Exorheic region	79	2,694.3	355.9	257	0.17	5.91
	Total		115.1	3,183.0	371.0	300.2	0.16	4.40
Total			387.5	8,917.1	1,812.9	1,074.0	0.23	5.32

SRW: Surface runoff water; GW: Groundwater; RC: Runoff coefficient; RM: Runoff modulus (Resource: "Ninth National Social and Economic Development Five-Year Plan", Key Project (96–912) on the Rational Utilization of Water Resources and Ecological Environment Protection in Northwest China-Overall Strategy Research on the Sustainable Utilization of the Water Resources, 2001; Department of Hydrology, Ministry of Water Conservancy and Electronic Power, 1987).

tains: runoff from rainfall, which accounts for 40–45% of the surface runoff water; glacier melt water, which accounts for 10–15% of the surface runoff water; and underground water supply in the mountains, which provides about 40% of the surface runoff water. The quantity of surface runoff water (totaling 181.29 billion m^3) is shown in Table 3.13. The surface runoff water is distributed with 79.44 billion m^3 in the drylands of Xinjiang; 19.27 billion m^3 in the drylands of Gansu; 33.85 billion m^3 in the drylands of Qinghai; 10.66 billion m^3 in the drylands of Shaanxi; 970 million m^3 in the drylands of Ningxia; and 37.1 billion m^3 in the drylands of Inner Mongolia.

(iii) Groundwater

The groundwater in China's drylands mainly originates from the infiltration of surface water. Particularly in inland river basins, when the runoff flows through the diluvial plains, water infiltrates into the ground to become groundwater. The groundwater can then be released from the ground in the form of springs and can become surface water again, often at the piedmont alluvial plains. The transformation between surface water and groundwater can occur as many as three or four times over the path of a river and is an important part of the hydrological cycle in the drylands.

The groundwater resources in China's drylands are variably influenced by runoff water. Normally, the more runoff water there is, the greater the amount of groundwater, and the greater the number of transformations between surface water and groundwater. The volume of groundwater in the drylands of China is shown in Table 3.13. There is a total volume of 107.4 billion m^3, with 38.3 billion m^3 in the drylands of Xinjiang, 12.18 billion m^3 in the drylands of Gansu, 15.9 billion m^3 in the drylands of Qinghai, 8.02 billion m^3 in the drylands of Shaanxi, 2.98 billion m^3 in the drylands of Ningxia and 30.02 billion m^3 in the drylands of Inner Mongolia.

3.3.1.3 Glaciers and lakes

(i) Glaciers

There are series of mountain ranges in the drylands of China and they are source areas of water resources. The main mountain ranges are the Altai, Tianshan, Kunlun, Qilian, Helan, Yanshan, and Da Xing'anling mountains (Fig. 3.5). Among these, the mountain ranges in the western part of the Helan Mountains have huge glaciers. Glaciers in arid and extremely arid regions are a solid water reservoir and the melt water from glaciers is an important water source in arid regions. Therefore, the sizes of the glaciers and consequently the volume of melting water that runs off the glaciers can significantly impact the water supply and affect the balance of water resources.

Fig. 3.5 Distribution of mountains in drylands of China(Shen et al.,2001, with permission from authors)

Table 3.14 shows the location and quantity of glaciers in the drylands of China. There are 24,061 glaciers in the drylands of China, accounting for 51.9% of the total number of glaciers in China. These glaciers cover an area

Table 3.14 Glaciers in the drylands of China (Cheng et al., 2001a)

Watersheds	Number		Area		Volume	
	Number	%	km^2	%	km^3	%
Irtysh River	403	1.67	289.29	0.81	16.395 3	0.30
Junggar inland river	3,412	14.18	2,254.10	6.31	137.443 2	2.52
Central Asian inland river	2,385	9.91	2,048.16	5.73	143.710 6	2.64
Tarim Basin	11,711	48.67	19,888.81	55.68	2,313.301 6	42.49
Turpan-Hami inland river	446	1.85	252.73	0.71	12.633 0	0.23
Hexi Corridor inland river	2,194	9.12	1,334.75	3.74	61.549 4	1.13
Qaidam inland river	1,581	6.57	1,865.05	5.22	128.528 0	2.36
Datong River	108	0.50	40.97	0.11	1.250 1	0.02
Qiangtang Plateau *	1,821	7.57	7,746.00	21.69	263.000 0	48.30
Total in drylands	24,061	100.00	35,719.97	100.00	3,077.811 2	100.00
Total in China	46,298	100.00	59,406.00	100.00	5,590.000 0	100.00
Proportion in drylands (%)	51.97		60.13		55.06	

Watersheds	AAG (km^2/number)	GMWR ($10^8 m^3$)	MOR ($10^8 m^3$)	RGMWTWA (%)
Irtysh River	0.72	3.62	100.00	3.60
Junggar inland river	0.66	16.89	125.00	13.50
Central Asian inland river	0.86	26.41	193.00	13.70
Tarim Basin	1.70	133.42	347.00	38.50
Turpan-Hami inland river	0.57	1.90		
Hexi Corridor inland river	0.61	9.99	72.40	13.80
Qaidam inland river	1.18	6.31	47.60	13.30
Datong River	0.38	0.12	3.20	3.80
Qiangtang Plateau *	0.03	16.03	246.00	6.52
Total in drylands	0.13	214.69	1,034.20	20.76
Total in China	1.28	604.65	3,241.86	18.65
Proportion in drylands (%)	10.16	35.51	31.90	

AAG: Average area of glaciers; GMWR: Glacier melt water runoff volume; MOR: Mountain outlet runoff; RGMWTWA: Ratio of glacier melt water to total water amount. (*Sources: Department of Hydrology, Ministry of Water Conservation and Electricity, 1987) of 35,719.97 km^2, accounting for 60.13% of the total area of glaciers in China, and the water storage in the glaciers is 3,077.81 km^3, accounting for 55.06% of the total storage of glaciers in China. The amount of melt water from glaciers in drylands is 21.469 billion m^3, which is 20.76% of the total water volume (103.42 billion m^3) that flows from the mountain outlets, 2.11% higher than the average glacier melt water in China (18.65%).

There are significant differences between the various glacier areas in drylands. The hyper-arid Tarim Basin is surrounded by the Kunlun Mountains in the south and the Tianshan Mountains in the north, which are mostly covered by well developed glaciers. There are 11,711 glaciers, covering 19,888.81 km^2, with a total volume of 2,313 km^3 in these two mountain ranges, and the average area covered by each glacier is 1.70 km^2. This region is the most developed glacier area which is consistent with the number, scale and volumes of the glaciers. Considering water resource production, this is also the region with the maximum volume of melt water (13.342 billion m^3) in the desert, and the region where glacier melt water supplies the highest proportion of the water resources (38.5%). Because of these glaciers, the Tarim River is the biggest inland river in China with the largest water volume. In other hyper-arid desert regions, such as the Turpan-Hami Basin, the glacier volume is only 12.6 km^3 and average size of each glacier is only 0.57 km^2. Melt water from glaciers in this region contributes only 190 million m^3. In other desert regions including the Junggar Basin, Central Asia, the Hexi Corridor, and the Qaidam Basin, the glacier melt water accounts for 13% to 14% of total water resource amount. In the Datong River watershed areas, the Qiangtang Plateau and the Irtysh River watershed area, the glacier melt water contributes less than 7% and as little as 4% to the total water resource amount (Table 3.14).

(ii) Lakes

There are many lakes in the drylands of China and most of them are geographically endorheic lakes. There is a clear geographical border along the western foothills of the Da Xing'anling Mountains, the southern edge of the Inner Mongolian Plateau, the Yinshan, Helan, Qilian, Riyue and Bayanhar mountains, and the Nianqing Tanggula Mountains. To the west of this border the lakes are endorheic lakes, while to the east of this border the lakes are normally exorheic lakes. Depending on their geographical location, the lakes in the desert regions of China are classified as being in either the Qinghai-Tibet lakes region or the Inner Mongolia-Xinjiang lakes region (Table 3.15).

Published information (Lang, 1983; CTERA, 1986; Wang et al., 1988) indicates that there are a total of 1,377 lakes which are equal to, or larger than 1 km^2 in size in the drylands. Of these lakes, 90.5% are endorheic lakes, and 9.5% are exorheic lakes. The total area covered by the lakes is 43,329 km^2. The total area of the astatic lakes is 40,874 km^2 (or 94.3% of the total lake area). In terms of water storage, the total volume of the endorheic lakes is 493.8 billion m^3 which accounts for 94.1% of the total lake storage volume of 524.6 billion m^3, while the exorheic lakes account for only 5.9% of the volume.

Table 3.15 Lakes in the drylands of China

Lake distribution		Number of lakes			Area of lakes (km^2)		
Lake regions	Province (Region)	AL	EL	Sum	AL	EL	Sum
Inner Mongolia-Xinjiang lakes region	Xinjiang	135	2	137	5,018	54	5,072
	Inner Mongolia	258		258	4,244		4,244
Qinghai-Tibet lakes region	Qinghai	109	132	241	9,377	2,401	11,778
	North Tibet	675		675	22,235		22,235
Total		1,177	134	1,311	40,874	2,455	43,329

Lake distribution		Storage (100 million m^3)						
Lake regions	Province (Region)	AL		EL		AEL		Total
		FW	SW	FW	SW	FW	SW	
Inner Mongolia-Xinjiang lakes region	Xinjiang	15	497	8		23	497	520
	Inner Mongolia	0.5	173.5			0.5	173.5	174
Qinghai-Tibet lakes region	Qinghai	140	1,270	31	269	171	1,539	1,710
	North Tibet	300	2,542			300	2,542	2,842
Total		455.5	4,482.5	39	269	494.5	4,751.5	5,246

AL: Astatic lake; EL: Exorheic lake; AEL: Astatic- Exorheic lake; FW: Fresh water; SW: Saline water (Note: Statistics for all lakes with area >1 km^2)

In terms of mineralization, the storage volume of saline lakes is 475.15 billion m^3, or 90.6% of the total storage. In summary, almost all the lakes in drylands of China are endorheic saline lakes, and the number and water storage volumes of both exorhetic and freshwater lakes are only small percentage of the total.

The Qinghai-Tibet lakes region refers to lakes in Qinghai Province and the northern part of the Tibetan Plateau. Most lakes in this region are geological texture lakes and glacial lakes with altitudes higher than 4,000 m above sea level. These lakes can be described as frigid lakes on a cold plateau. The number of lakes in this region comprises 69.9% of the total number of dryland lakes, accounting for 78.5 % of the total lake area and 86.8% of the total water storage. In this region, the majority of the lakes are saline lakes, although the water storage includes up to 455.2 billion m^3, the fresh water is only 17 billion m^3. All of the large endorheic lakes at high altitudes can be found in this region. Namucuo Lake, located in the northern part of the Tibetan Plateau, is 4,718 m above sea level and is the highest saline lake in the world. Qinghai Lake is the largest inland lake in China, and has an area of 4,200 km^2 and storage of more than 74 billion m^3. Eling Lake and Zhaling Lake, located upstream of the Yellow River source region and commonly known as the twin-sister lakes of the Yellow River, are both more than 4,200 m above sea level. The total area of the twin-sister lakes is 1,300 km^2, with water storage of 15.47 billion m^3. These lakes serve as a stable water supply resource for the Yellow River. The numerous saline lakes in the Qaidam Basin and on the northern Tibetan Plateau contain a large amount of salt minerals, including mirabilite, lithium, boron and non-metallic minerals. In summary, the lakes of the Qinghai-Tibetan Plateau are rich in water and mineral resources and have high development potential.

The Inner Mongolia-Xinjiang lakes region includes all of the lakes located from Inner Mongolia and Xinjiang to the northwest part of Hebei Province. The total area of the lakes in this region is 9,316 km^2, which is 21.5% of the total area of dryland lakes in China, and the water storage (69.4 billion m^3) accounts for 13.2% of the total water storage in dryland lakes. The Heihe River is a dividing line that separates the lakes in the west which are the geological texture (tectonic) lakes and in the east which are aeolian (deflation) lakes. The majority of lakes in this region are brackish or saline with 67.05 billion m^3 water storage. Therefore, this region has the second largest deposits of salt minerals in China. Because of the scarce rainfall and high evaporation rates in the region, the water volumes in these lakes have been significantly impacted by human activities. Many of the lakes in this region are showing a trend of retreat and reduction in size and storage. The Taitema Lake and Lop Nor Lake downstream of the Tarim River; the Juyanhai Lake downstream of the Heihe River; and the Yezhu Lake downstream of the Shiyang River have all dried up and disappeared. Many large lakes such as Hulun Lake (2,315 km^2), Bositeng Lake (1,019 km^2), Buir Lake (located on the China-Mongolia Border), Ulungur Lake (745 km^2), and Ebinur Lake (1,070 km^2) are being threatened by retreat and reduction. The careful and sustainable use of water resources, including planning for water consumption at upper, middle and lower reaches of rivers, the operation of water-saving systems and the improved efficiency of water use are the fundamental solutions in realizing the sustainable development of these lakes.

3.3.2 Water resources use status and existing problems

3.3.2.1 Water resources use status

The water resources use in the drylands of China varies between agricultural, industrial and domestic use due to the natural environment, development intensity, population, and differences in traditional livelihoods and production methods. The water consumption information for each dryland province, except Shaanxi Province where there is no data on water consumption (Table 3.16), shows that the overall ratio of water use can be as high as 40.53%, particularly in Gansu where the water use ratio is 56.33% and in Xinjiang where it is 51.74%. With the exclusion of water quantity in non human settlement areas and cross-territory water volumes, the exploitation and utilization rate of water resources in main economic development zones of Xinjiang can be as high as 70%. The rate of water use in the Urumqi River area is 153% and the

Table 3.16 Water consumption and water use patterns in the main dryland provinces in China

Provinces (Region)	TWS ($10^8 m^3$)	TWC ($10^8 m^3$)	WRDUR (%)	ACW ($10^8 m^3$)		
				FI	FHF	Total
Xinjiang	857.0	443.4	51.74	350.5	77.3	427.8
Ningxia	11.7	89.0		73.6	8.5	82.1
Qinghai	344.0	26.9	7.82	20.2	1.8	22.0
Inner Mongolia*	518.0	109.4	21.02	99.2	3.1	102.3
Gansu**	206.8	116.5	56.33			92.9
Total	1,937.5	785.2	40.53			727.1

Provinces (Region)	IWD ($10^8 m^3$)	DCW ($10^8 m^3$)		
		Urban areas	Rural areas	Total
Xinjiang	9.7	3.47	2.5	5.9
Ningxia	5.7	0.8	0.4	1.2
Qinghai	3.1	0.6	1.2	1.8
Inner Mongolia*	5.7			1.4
Gansu**	17.8			5.8
Total	42.0			16.1

TWS: Total water storage; TWC: Total water consumption; WRDUR: Water resources development and utilization rate; ACW: Agricultural consumption of water; IWD: Industrial water demand; DCW: Domestic consumption of water; FI: Farm irrigation; FHF: Forestry, husbandry and fishing. *Data are sourced from *Inner Mongolia in* 2000 Inner Mongolia People's Publish House, 1988 (statistics from 1985); ** Data are sourced from Ma, 2001; Other data are from "the Ninth National Five-Year Plan for Social and Economic Development of China", State Key Project: "The Rational Utilization of Water Resources and Environment Protection in Northwest China".

basic needs for water consumption can be met only by exploitation of groundwater. The water resource development and utilization levels of the Shiyang River and the Heihe River watersheds are almost 100%①. The development of water resources varies between regions. The water resource exploitation rate in arid regions can be as low as 7.82%. This is mainly because the land conditions do not allow for agricultural development. Although the overall water resource exploitation ratio is only 21% in Inner Mongolia due to the significant geographic differences from east to west, the exploitation ratio of water resources in the arid Alxa Prefecture is as high as 100%. The water throughout the drylands is mainly used for agriculture, which requires 92.6% of the total water usage. Within that, the majority is used for cultivation and crop irrigation (90%), so that the pattern of water use is highly irrational.

3.3.2.2 Existing problems in water use

By analyzing the water resources use in the drylands from the viewpoint of sustainable development, and water-saving and efficient development and

① State key project of "the Ninth Five-Year Plan for Social and Economic Development: Overall Strategic Studies on Water Resources Utilization in Northwest China"; Chinese Academy of Hydrology and Electricity Research, 2001.

utilization of water resources, several key problems facing the drylands have been identified.

(i) Over-exploitation of water resources in some areas reduces available ecological water and causes spread of desertification

In some drylands of China, such as the middle section of the northern slopes of the Tianshan Mountains, eastern Xinjiang, the Shiyang River of the Hexi Corridor, the Heihe River watershed, and the headwaters, upper and middle reaches of the Tarim River, water use exceeds its carrying capacity. The excessive use of water resources, over-exploitation of groundwater resources, and the lack of consideration of ecological water, have caused the shrinking of oases, the drying of lakes, increasing salinity, desert expansion and sand movement and the spread of desertification.

(ii) Serious waste of water resources and low water use efficiency

The area of cultivated land in the drylands is 22 million ha, most of which is irrigated with flood irrigation. Therefore the water use per hectare can be as high as 15,000 $m^3 \cdot a^{-1}$. This causes secondary soil salinization in lower patches, along with the low water use efficiency. For example, the water use coefficient of irrigated canal systems in the new reclamation area of the Tarim River basin is 0.25–0.30, in the Qaidam Basin it is 0.35, and the water use coefficient in the field plots is only 20% to 30%.

(iii) Serious water use conflicts between upper and lower reaches

Water in the drylands usually originates from the mountains and flows through the plains. A large amount of water is channeled away for irrigation uses at the piedmont plain, which decreases the available water for the oases in the lower reaches. This creates a situation where a small part of the region profits from the channeled water while the majority of the region's environment deteriorates. For instance, massive land reclamation in upper reaches of the Tarim River in the 1990s resulted in a reduction in the amount of water in the middle and lower reaches by 45%. This has caused severe land degradation with impacts such as dune movement and shifting sands, and the drying up of Taitema Lake.

The Shiyang River is another example. The water volume of the whole watershed is approximately 1.6 billion m^3. Because of the excessive use of water resources in the middle reaches of the river at Wuwei Oasis, the water supply to Minqin Oasis in the lower reaches was reduced from 500–600 million m^3 in the 1950s–1960s to less than 200 million m^3 in the 1990s. To maintain the livelihoods of those who lived at the oasis, groundwater was over-exploited and as a result the water table at Minqin Oasis was lowered from 0.5–1 m in the 1950s to 8–10 m in 1990s. This lowering of the water table further salinized a large area of cultivated land, sickened or killed a large number of trees, shrubs and bushes, and rapidly enlarged the desert area. The Minqin Oasis is now under serious threat of desertification. Consequently, the ecological and economic viability of the Shiyang River watershed is threatened.

(iv) Poor water resources management systems

To improve the water resources use, sound management practices and targets for the responsible use of water resources are the key solutions for sustainable management. At present, the lack of coordination between various agencies for water resources management and inter-watershed use, between water use and water price and between water conservation and water taxes, has lead to poor management of water use and protection. These situations demand a sound management system to realize the responsible utilization of water resources and promote sustainable ecological and economic development.

3.3.2.3 Ecological water usage in drylands

Ecological water usage, or the ecological water requirement, refers to the volume of water required for the maintenance of the ecosystem, including both natural and artificial ecosystems. The natural ecological water requirement is the minimum volume of water required to maintain the stability of the natural ecosystem while developing and utilizing water resources. The artificial ecological water requirement is the water supply volume necessary to sustain artificial plantings (forest and grassland) and provide the normal role of ecological service.

The typical landform system in the drylands of China is mountain-basin (plain) system. There is more precipitation in the mountains, which are the headwaters of the rivers, and in these areas the ecological water requirements can be met. It is only the basins (plains), due to their location with less precipitation, where serious water shortages and the fragility of eco-environment cause a sharp conflict over the ecological water requirements. Accordingly, the research on ecological water requirements in the drylands should be mainly focused on basins (plains).

Research on ecological water requirements was initiated in the late 1990s. The State Project on Rational Development and Utilization of Water Resources and the Protection of Ecological Environment in Northwest China is one of the key projects of the National Ninth Five-Year Scientific and Technical Development Plan (1996–2000). The project prioritized systematic research on the ecological water requirements of the inland river watershed areas in the drylands of China, which cover a total area of 12.23 million km^2. The theory is based on the water balance, that the sum of runoff (R) from mountain outlets and the precipitation (P) onto plains are considered as the total volume of water resources in the plains. The ecological water requirement is determined from the equilibrium between the effective evapotranspiration (E_0, the ecological water consumption), the changing volume of the groundwater storage in plains (ΔG), the changing volume of reservoir water storage in plains (ΔW) and the evaporation (E_{n}) from salinized and alkalized lands, deserts and the Gobi in the plains. The equilibrium equation is as follows:

$$R + P = E_0 + \Delta G + \Delta W + E_{\mathrm{n}} \tag{3.8}$$

Through combining calculations of the evapotranspiration value of various vegetation types (Table 3.17), the intensity of water consumption in four ecosystems (deserts, artificial oases, natural oases, and the transitional zone of desert and oasis) (Table 3.18), the area of the four ecosystems (Table 3.19), and the present status of ecological water requirement in typical drylands of China (Table 3.20) can be calculated.

Table 3.17 Average evapotranspiration rates of various vegetation types in drylands of China (mm/a)

Region	Woodlands		
	Woodland	Bushland	Sparse woodland
Northern Xinjiang	490	340	285
Eastern Xinjiang	540	340	270
Southern Xinjiang	520	340	280
Shule River	540	340	270
Heihe River	510	340	280
Shiyang River	440	330	285
Qaidam Basin	540	340	270

Region	Grasslands			Water evaporation of rivers and lakes
	High coverage	Middle coverage	Low coverage	
Northern Xinjiang	470	190	115	1,000
Eastern Xinjiang	580	185	70	1,200
Southern Xinjiang	530	188	90	1,150
Shule River		180	65	1,200
Heihe River	520	185	74	1,100
Shiyang River	430	188	114	900
Qaidam Basin	580	180	60	1,200

The estimated ecological water requirement of the drylands is 108.4 billion m^3, which is totally reliant on the effective precipitation. Northern and southern Xinjiang have the highest ecological water requirements.

The total ecological water requirement in the inland plains is 57.92 billion m^3, of which, 38.54 billion m^3 is originated from runoff (66.5%) and 19.38 billion m^3 is from precipitation (33.5%). This means that the majority of the ecological water requirements on the plains is provided by runoff, with precipitation a secondary source.

In the three ecosystems excepting deserts, natural oases have the highest ecological water requirement, accounting for 57.1% (33.06 billion m^3) of the total ecological water requirement, the transitional zone requires 33.2% (or 19.21 billion m^3)of the total, and the artificial oases require 9.7% (5.64 billion m^3) of the total ecological water. For the source of the ecological water, some of the ecosystems are more dependent on runoff and others on precipitation. For example, natural oases rely more on runoff (27.65 billion m^3, 83.6%), than on precipitation (5.41 billion m^3, 16.4%) while the artificial oases rely even less on precipitation with only 9.4% (530 million m^3) of ecological water

Table 3.18 Amount of water consumption in drylands of China ($mm \cdot a^{-1}$)

Region	Total water consumption			
	Desert	Transitional zone between desert and oasis	Natural oasis	Artificial oasis
Xinjiang	34	111	453	666
Northern Xinjiang	61	136	637	523
Eastern Xinjiang	21	70	555	766
Southern Xinjiang	28	90	376	822
Hexi Corridor	29	80	605	659
Shule River	20	65	662	803
Heihe River	28	74	534	633
Shiyang River	65	119	787	649
Qaidam Basin	25	60	190	760
Average of inland areas	32	102	401	666

Region	Runoff consumption		
	Transitional zone between desert and oasis	Natural oasis	Artificial oasis
Xinjiang	35	377	590
Northern Xinjiang	22	523	409
Eastern Xinjiang	34	519	730
Southern Xinjiang	44	329	776
Hexi Corridor	12	537	591
Shule River	30	628	769
Heihe River	14	474	573
Shiyang River	5	673	535
Qaidam Basin	30	160	730
Average of inland areas	32	331	596

(Source: "the National Ninth Five-Year Plan for Scientific and Technology Development", State Key Research and Technical Project on Rational Allocation and Holding Capacity of Water Resources in Northwest China, Chinese Academy of Hydrology and Electricity, December 2000).

Table 3.19 Area of ecosystem types in the drylands of China (100 km^2)

Regions	Total area (%)	Desert (%)	Transitional zone(%)	Oasis (artificial + natural) (%)
Xinjiang	9,338 (100%)	6,648 (71%)	1,456 (16%)	1,235 (13%)
Northern Xinjiang	2,603 (100%)	1,426 (55%)	683 (26%)	494 (19%)
Eastern Xinjiang	1,539 (100%)	1,436 (93%)	66 (4%)	37 (2%)
Southern Xinjiang	5,196 (100%)	3,786 (73%)	706 (14%)	704 (14%)
Hexi Corridor	1,870 (100%)	1,474 (79%)	245 (13%)	151 (8%)
Shule River	707 (100%)	611 (86%)	76 (11%)	20 (3%)
Heihe River	896 (100%)	700 (78%)	120 (13%)	76 (9%)
Shiyang River	267 (100%)	164 (61%)	49 (18%)	54 (20%)
Qaidam Basin	1,020 (100%)	639 (63%)	189 (19%)	193 (19%)
Total	12,228 (100%)	8,760 (72%)	1,889 (15%)	1,579 (13%)

Table 3.20 Ecological water requirement in the drylands of China (10^8 m^3)

Regions	EPM	EWRP			EWRTZ		
		Total	Runoff	Precipitation	Total	Runoff	Precipitation
Xinjiang	779.4	483.4	318.0	165.4	161.1	48.0	113.1
Northern Xinjiang	331.8	212.2	105.6	106.6	92.9	15.0	77.9
Western Xinjiang	55.1	14.0	10.9	3.1	4.6	2.2	2.4
Southern Xinjiang	392.5	257.1	201.5	55.6	63.6	30.8	32.8
Hexi Corridor	176.9	48.4	28.8	20.0	19.6	4.2	15.4
Shule River	68.1	11.0	8.0	3.0	4.9	2.3	2.6
Heihe River	65.1	24.9	15.5	9.4	8.9	1.7	7.2
Shiyang River	43.7	12.5	4.9	7.6	5.8	0.2	5.6
Qaidam Basin	127.6	47.3	39.0	8.3	11.3	5.6	5.7
Total inland areas	1,084.0	579.2	385.4	193.8	192.1	57.9	134.2

Regions	EWRNO			EWRAO		
	Total	Runoff	Precipitation	Total	Runoff	Precipitation
Xinjiang	272.7	225.0	47.7	49.6	45.0	4.6
Northern Xinjiang	106.8	80.8	26.0	12.5	9.8	2.7
Western Xinjiang	8.0	7.3	0.7	1.4	1.4	0.0
Southern Xinjiang	157.9	136.9	21.0	35.6	33.8	1.8
Hexi Corridor	22.8	18.9	3.9	6.0	5.3	0.7
Shule River	5.0	4.7	0.3	1.0	1.0	0.0
Heihe River	12.5	10.5	2.0	3.6	3.3	0.3
Shiyang River	5.3	3.7	1.6	1.4	1.0	0.4
Qaidam Basin	35.2	32.6	2.6	0.8	0.8	0.0
Total inland areas	330.6	276.5	54.1	56.4	51.1	5.3

EPM: Effective precipitation in mountain; EWRP: Ecological water requirement in plains; EWRTZ: Ecological water requirement in transitional zone; EWRNO: Ecological water requirement in natural oases; EWRAO: Ecological water requirement in artificial oases.

supplied from this source, and the majority from runoff. The transitional zone, however, mainly relies on precipitation, which supplies 69.9% (13.42 billion m^3), while runoff supplies only 30.1% (5.79 billion m^3) of the ecological water requirements.

3.3.3 Strategies for water resources development and managing water utilization

China is a country facing the problem of shortage of water resources. The total volume of water resources in China is about 2,634.1 billion m^3, which means that it has the 6^{th} largest water resources in the world. However, on a per capita basis, the water resource in China is only a quarter of the world's average, ranking the 88^{th} in the world. The water shortage is more serious in the drylands of China and is the key challenge for sustainable development. It is an emergent priority to create practical development strategies and to mobilize solutions to manage water utilization.

3.3.3.1 Strategies of water resources development in the drylands

From a regional perspective it is necessary to both protect the environment and use resources efficiently to achieve the objective of sustainable socio-economic development. This requires a water resource strategy for the drylands that is planned and designed in line with the above objectives. The water resource strategy should be focused on: The establishment of a social development system for saving water; ensuring the supply of ecological water while realizing sustainable development; the establishment of a market access mechanism; and the establishment of high-tech water harvesting development systems.

(i) Establishment of a water-saving social development system

The drylands are short of water. Although the water shortage problem could be alleviated by pumping water and importing water from outside regions, the water conflict can be fundamentally solved by the establishment of a water-saving public water supply system. Water is a sparse resource in the drylands. Therefore, a public water-saving campaign to raise awareness of the issues and increase public participation are key bases for establishing public system that saves water and reduces water consumption in the drylands.

Agricultural water-saving is the most important challenge in the drylands. Agricultural water consumption accounts for about 90% of the total water consumption, but much of this is due to traditional irrigation methods that waste a great deal of water, so that more than 15,000 m^3 of water may be used to irrigate one hectare of cropland. If advanced water management techniques were adopted, such as anti-infiltration techniques, small patch irrigation and timely sowing and resowing skills, then high yield crops could be harvested which have only consumed 9,000–10,500 m^3 per hectare cropland. With water-saving techniques, like sprinkler and drip irrigations with subsoil pipes, and greenhouse techniques, water consumption could be reduced to 6,000–7,500 m^3 per hectare. This has been shown in many demonstration sites and pilot projects in Zhangye region, Gansu. In summary, reducing water use in agricultural sector through improved technology is the most effective means to reduce water shortages in desert regions.

There is also significant water-saving potential in the industrial sector. Although industrial water consumption accounts only for 6–7% of the total water usage of the drylands, this does not mean water-saving in the industrial sector is unimportant. First, water-saving in the industrial sector is an important component of social water-saving; second, water-saving in the industrial sector is important for improving industrial efficiency. Currently, for every 10,000 RMB of product from the industrial sector in the drylands in Northwest China has consumed approximately 147 m^3 of water (compared with the international advanced water quota of 10 m^3/10,000 RMB). This equates to more than 1.5 times of the national average water use. The future of industry in the drylands should be focused towards low water consumption and high output value.

Domestic water-saving in both urban and rural areas should also not be ignored. Currently, domestic water consumption accounts for only 3–3.5% of the total water consumption in urban and rural areas, but, along with the rapid urbanization and improvements in livelihood and living standards, water consumption is expected to increase sharply. The water conflicts between agricultural, industrial and domestic sectors will become increasingly acute. Therefore, the establishment of a water-saving system in urban and rural areas should be prioritized as a key component of social water-saving.

(ii) Guarantee of sufficient ecological water supply

People worldwide are coming to the understanding that ecological security will help ensure the security of natural resources and socio-economic stability. The basic need for achieving ecological security is the stability of ecological cycling. The provision of the ecological water requirement is a prerequisite for a healthy ecosystem succession. Therefore, the necessary ecological water requirement must be incorporated into any strategy to manage water resources.

Traditional water consumption for agricultural and industrial purposes has diverted some of the required ecological water and this practice is continuing. Consequently, there is continuing deterioration of the eco-environment and a reduction in areas suitable for human habitation. The disappearance of the ancient Loulan Oasis and the spread of desertification downstream of the Tarim River; the deterioration of the Minqin Oasis downstream of the Shiyang River; the disappearance of the Juyan Lake downstream of the Heihe River; the transformation of Qinghai Lake from freshwater to saline lake; and the expansion and dune movements of desert along the Great Wall of the Ming Dynasty in Ningxia-Inner Mongolia from the northwest to the southeast, are good examples of environmental deterioration and desertification that illustrate the consequences of excessive development and mis-management of water resources.

The total volume of water resources in the drylands is comparatively low, and consequently, as more water is used in the agricultural and industrial sectors, there will be less ecological water left. If water storage cannot meet the requirements for ecological water consumption, it will result in the acceleration of occurrences and development of dust and sandstorms, enlargement of shifting sand dunes, expansion of desertification in oases, rapid soil salinization, degradation of vegetation, infertility of crop soil, and the reduction of land productive potential. Therefore, ensuring that there is sufficient ecological water is the basis of the concept of renewable resources, and sustainable socio-economic development.

The change and improvement of traditional practices of water use, and the reduction of water consumption in agricultural and industrial sectors and domestic water use by practicing water-saving techniques, should be prioritized as targets for changing the pattern of water consumption in the future.

(iii) Introduction of market mechanisms and perfect management of water resources

According to traditional economics, water resources become a valuable product only when they are integrated into agricultural and industrial production. Water resources have commonly been viewed as valueless, and therefore something which could be wasted. This concept is the root cause of over-exploitation of water resources which can cause ecological destruction.

Water resources perform functions of both ecological service and economic production and are of value, although that value is manifested in different forms. The product of ecological servicing is the improvement the eco-environment and human is a direct beneficiary of this. When used for economic production, agricultural produce and industrial goods are the end products and the beneficiaries of this are the producers and makers of commodities. Therefore, both the ecological product and the productive goods should reflect the value rule, including the price of water. The introduction of market mechanisms to the management of water resources, so that water use can be regulated through water price, has significant potential benefits for the restoration of the value of water resources, and also has an important role in the establishment of water-saving systems in both the agricultural and industrial sectors.

The effective management of water resources is an important solution to realize the value of water resources. The design of any management framework for water resources must be compatible with the "Water Law" of the PRC, the total volume of regional water resources and the integrated development of regional ecology and economy. Any such management framework must address the following: First, the implicit value of water must be considered in the optimum allocation of water resources; second, water efficiency and water reduction have key benefits for ecological servicing and economic development, and the adoption of new technology should be a key target; and third, a market mechanism should be implemented to develop a water pricing structure and therefore assign value to water resources.

A policy of "pay more for high water consumption and pay less for low water consumption" should be administered. The current policy, which charges for water used for agriculture on per person or per ha basis, should be replaced by a new policy on charging for agricultural water on the basis of water consumption (m^3). Water resources should be a state-owned asset and all water consumers, either state, collective or even private stakeholders, must get permission and authorization from a governmental authority in advance to exploit groundwater or pump surface water, and then they should pay water fees on the basis of the volume of water exploited or pumped. The over-exploitation and mis-management of water resources should be minimized. The total volume of water resource should be used to determine how much can be exploited, and the price of water should be determined based on the overall availability of the resource.

(iv) Increasing of water use efficiency with advanced scientific techniques

Insufficient water, from all sources, is reality in the drylands of China. The keys to solving the problem of water resource shortages for ecological improvement and economic development are scientific advances in water resource management and new technologies for efficient use of water.

The awareness and recognition of temporal and spatial transformations of precipitation to surface water to soil water, and the development of fundamental theories related to water resources will help humans adapt to these transformations and develop a balanced relationship with nature.

The improved ability to control water resources, through the adoption of new technologies and new methods, will help implement water transfers and water conservation. It could also help resolve the issues of imbalances of water resources between regions, excessive consumption of water resources within different sectors and increase awareness about the management of water resources. In addition, the development of new water resources and alternative water resources are also important solutions to water shortage.

It is possible to increase the utilization rate of water resources by applying modern theories related to water resources, and science and technology in the drylands. Improved water-saving in agricultural and industrial sectors using variety of products and technological processes, would mean that the water resources in drylands can meet the regional development needs. A positive outlook is required when considering the new water sources and new potential to exploit water resources in future in drylands.

3.3.3.2 Strategies for the utilization of water resources in the drylands

The strategies for the utilization of water resources are a series of interactive measures and solutions developed to deal with the existing problems, under the guideline of a developmental strategy of water resources, with the aim of solving the issues caused by water conflicts.

(i) Sound watershed planning considering differences in water use between upper and lower reaches

In the drylands of China, mountains and basins are interspersed in a varied landscape. In the mountains, snow and rainfall are comparatively abundant and these are water production areas. The basins, with low precipitation, are water consumption areas. Mountains and basins are connected through rivers, which direct water resources from the mountains to the basins. Therefore, there are differences in water use between the upper and lower reaches in a watershed. The planning and management of water resources at watershed scale is an urgent problem in the current management of water resources in the drylands.

The water use in the Shiyang River watershed in the Hexi Corridor is representative of this issue. The Shiyang River originates from the eastern Qilian Mountains in the southern part of the Hexi Corridor. It can be divided geographically into headwater conservation forest areas in the upper reaches, agricultural oases on alluvial-diluvial plains in the middle reaches and salinized-alkalized and desertified oases on diluvial-lacustrine plains in the lower reaches. The total volume of the water resources in the river watershed is 1.6995 billion m^3. If the minimum ecological water consumption is considered as 30%, the maximum water available for use is less than 1.2 billion m^3 (or approximately 70% of the total). At the end of 1950s, with a small population and only small-scale agricultural development, there were no significant water conflicts between the Wuwei Oasis in the middle reaches and the Minqin Oasis in the lower reaches. Approximately 500 million m^3 of surface water were supplied from the middle reach to the Minqin Oasis and its water table was less than 1 m with a salinity of 2 $g \cdot L^{-1}$, with which nearly 67,000 ha of cropland were irrigated. During the 1970s and 1980s, the Wuwei Oasis was rapidly developed. The farmlands were enlarged quickly and the intensity of the water usage also increased sharply. The water which flowed downstream was consequently reduced and the water volume into the Minqin Oasis decreased to only 200 million m^3. To maintain the existence of the oasis, large volumes of groundwater were pumped up. By the end of 1980s, the water table had dropped to 8–9 m and the water mineralization increased to more than 3 $g \cdot L^{-1}$. Soil salinization/alkalization was accelerated and area of farmland was reduced to 40,000 ha from previous 67,000 ha. A large area of protective forest withered and died, the oasis became completely degraded and serious blown-sand events occurred which affected an area reaching to the Wuwei Oasis (Shen, 1991). Similar situations have also occurred along the Heihe and Tarim River watersheds in the drylands. This shows that a well constructed, watershed-based water utilization plan is required for the appropriate control and management of water resources. This must include a fair distribution of water between the upper, middle and lower reaches to combat desertification, protect oases and practice overall sustainable development.

(ii) Improvement of water-saving technology and establishment of a highly efficient water-saving system

The efficiency of water utilization is low in the drylands of China. The use index for runoff water resources is only about 0.4. There is a lot of waste in the utilization process, and therefore there is a great water-saving potential. The current tasks are to promote water-saving technologies and to establish a water-saving system for the agricultural and industrial sectors and domestic water consumption in urban and rural areas. According to various case studies and demonstration sites, the water-saving techniques that could be popularized and extended on large-scale include anti-leakage techniques or mulching of canals which is mainly applied to irrigation channels, the use of advanced irrigation techniques, and the use of mulching to reduce evaporation from the land.

Using materials such as concrete and cement tiles or vertical cement barriers in irrigation channel construction, the loss of water to infiltration can be reduced from 50–60% to 30–35%. Low pressure pipe techniques use cement concrete pipes or plastic pipes under the topsoil to raise the water use efficiency by more than 0.9 in the irrigation canals, and raise the land use efficiency by 0.2.

Sprinkler irrigation techniques can reduce the water amount used for irrigation by 30–50%, and increase the yield by 20–30%. Micro-irrigation techniques can reduce the water use by 50–70% and increase yield by more than 20–30%. Plastic mulching can significantly reduce the field evaporation, increase the ground soil temperature, reduce irrigation water use by 10–15% and increase the yield by 30% (Xiao and Li, 1999).

Through the application of the water-saving techniques described above, the water conflicts in dryland could be reduced. Accordingly, these techniques should be an important part of the solutions to the water utilization problem.

(iii) Establishment of water market mechanism and improvement of water resources management

The current management mechanism of water resources in China was established during the period of the planned economy era. One of its characteristics is that water resources were considered to be valueless or low-cost. This resulted in wasted water, which caused a serious ecological crisis, shortage of water resources and conflicts between social development and economic growth. Therefore, a change in the process of water consumption and the establishment of a water market system are necessary and inevitable. The development of water resources economy is a fundamental method for solving the problems of water resource allocation.

The basic premise of the water market is to determine a reasonable price based on the value of the water resources and insist on the principle of user-pays. Therefore, a reasonable water price should be enacted and implemented as early as possible.

A standard rate of water usage for different sectors and groups should be determined. Following from this, a double price system can be developed, where there is an additional charge for over-use water.

The quality and quantity of water resources in different regions are completely different. It is necessary to establish a reasonable system for determining water price, which must reflect the carrying capacity of the water resources. The specific method for determining water price should be developed as soon as possible.

The use of economic principles to manage water resources will regulate the development of industry and agriculture and will help restrict the development of sectors with low efficiency, water wastage and water pollution, and enhance the productive value of water resources per unit volume.

(iv) Improvement of integrated water management systems

Integrated water management involves the understanding of the principles of socio-economics, resource management and the environment which are integrated to ensure the sound operation of these processes. The solutions to current problems in the drylands, and the measures to develop new water sources and to save current water resources for the future are inseparable from the science and technology management. The integrated management of these issues is the only way to achieve effective and responsible use of water resources.

The main measures to be implemented are: effective regulation of water use at watershed, regional and sectoral scales, the establishment and strengthening of a coordinating body such as a water management authority and monitoring organization to provide leadership on water resources development; the formulation of regional water resource management regulations according to the "Water Law"; establishment of water use monitoring systems to allow for timely adjustment of the plans and help with the effective management and integrated water planning; and the establishment of research and observation systems related to water resources and the promotion of the effective utilization of water resources.

3.4 Protection and utilization of biological resources

Biological resources include plant resources and animal resources, in which plant resources are the primary resources for human being. In spite of lower biological production in drylands, special utilization values of these resources play the important roles in sustainable development of drylands.

3.4.1 Biological resources and their current status of utilization

3.4.1.1 Botanical resources

(i) Living forms

The living form of botanical resources is closely connected to human production and livelihood. The living form of the botanical resources can be divided into categories of trees, shrubs and grasses. Each category can be divided into lower levels. It is necessary to understand the features of the seed plants, such as trees, shrubs and grasses and their families, genus and species.

i) Living form of botanical families in the drylands

In China's drylands, there are a total of 83 families of seed plants, among which there are ten families of trees (Cypress, Pinaceae, Tamaricaceae, Rosaceae, Salicaceae, Ulmaceae, Lonicera, Bignoniaceae, Rhamnaceae and Moraceae families), three families of shrubs (Leguminosae, Ephedraceae and Polygonaceae) and 70 families of grasses. The families of trees, shrubs and grasses account for 10.97%, 3.66% and 85.37% of the total number of botanical families respectively (Pan et al., 2001).

ii) Genus composition of plants in the drylands

There are a total of 484 genera of plants in drylands, of which there are 44 genera that belong to the woody plants comprising 9.09% of the total, many of which exist only in the drylands and have important roles in ecological restoration. The remaining 440 genera are grasses, accounting for 90.91% of the total. The vast majority of plant genera in the drylands are grasses.

iii) Species composition of plants in the drylands

In the drylands of Northwest China, there are a total of 1,704 species of plants, including 1,409 species of grasses, which account for 82.68% of the total number. Among them, 484 species are annuals (or 28.04% of the total); 33 species are biennials (1.94%), 892 species are perennials (52.34%). There are also 35 species of trees (2.05%), and 260 species of shrubs (15.26%) (Table 3.21).

Table 3.21 Statistics of plant's living form in drylands of Northwest China (Pan et al., 2001)

	Trees	Shrubs				
		Shrubs	Semi-shrubs	Small shrubs	Small semi-shrubs	Sub-total
No.of species	35	127	78	39	16	260
(%)	2.05	7.45	4.58	2.29	0.93	15.25

	Grasses			
	Annuals	Biennials	Perennials	Sub-total
No.of species	484	33	892	1,409
(%)	28.40	1.94	52.92	82.68

iv) Summary of forest resources and utilization status

Forests have a prominent role in the national economic reconstruction and in the maintenance of a sound ecological environment. Forests are indispensable to human production, and are also an important element in the improvement of the ecological environment. They have an irreplaceable role in human livelihood and production. There have been quite a few researches and statistical studies on forest resources in drylands in the past, but until now there has been insufficient standardized data. However, during the last five decades, the forestry departments of all provinces and autonomous regions have been continuously carrying out work on forest inventories, management and administration. The use of this detailed forest information from provinces and autonomous regions is a solid base for conducting research on the forest resources and their sustainable development.

Forests in the drylands of China are mainly located in Xinjiang, Gansu, Ningxia, Qinghai and Inner Mongolia (provinces and autonomous regions), as well as Shaanxi, Shanxi and the northern parts of Hebei. The overall status of the forests in these provinces and autonomous regions can be seen in Table 3.22.

Table 3.22 Forest resource in the drylands of China

Province (region)	Land for forestry use (10^4ha)	%	Existing forest area (10^4ha)	Forest coverage rate (%)	Total land area (10^4ha)
Xinjiang	408.85	2.5	130.56	0.79	16,631.20
Inner Mongolia*			392.82	0.46	8,490.33
Ningxia	102.73	15.5	10.20	1.54	518.00
Gansu	727.03	16.2	198.86	4.33	4,544.02
Qinghai	287.54	4.0	25.01	0.35	7,211.89
Sub-total	–	–	757.45	2.02	37,395.44
Entire country	2,688.85	27.4	1,370.35	13.92	96,051.36

(* Source: EC-MRIMAR, 1991. The area of Inner Mongolia excludes the Da Xing'anling Mountains; Other information in the above table is cited from Sun, 2001).

Table 3.22 shows that there are about 7.5745 million ha of forest in the drylands of China, with a forest coverage rate of only 2.02%. The distribution of forests is uneven. In the arid and extremely arid drylands of central and western Inner Mongolia and Xinjiang, the forest coverage rate is 0.45–0.80%. With a high latitude and cold temperature, the forest coverage rate in Qinghai is even lower with forests occupying only 0.35% of the total land area of the province. The second characteristic of the forest distribution is that natural forests and secondary natural forests are mainly located in the middle areas of the mountains in the drylands. In the basin areas of the drylands, precipitation is scarce but the upper and middle areas of the mountains have abundant precipitation. For example, in the upper and middle parts of the Tianshan Mountains in Xinjiang, the precipitation is as high as 400–600 mm$\cdot$a^{-1}, and the precipitation in the upper and middle parts of the Qilian Mountains is 300–400 mm$\cdot$a^{-1}, which means that these areas of the mountains are forest islands in the drylands. The Altai, Tianshan, Kunlun, Qilian, Maxian, Liupan, Guanshan, Helan, Ziwuling, Luoshan and Yinshan mountains are the main locations of mountainous forest in the drylands of China.

The artificial forests include farmland shelterbelts, windbreaks, sandbreaks and community forests. The area of these artificial forests is small, but they play an important role in improving the eco-environment.

The development of forest resources has experienced different stages. During the period from the 1950s to 1970s, as a consequence of logging, natural forests were severely destroyed and the mountainous forest line retreated rapidly. Since that time, regeneration has occurred, and most of the forests have been turned into secondary natural forests where the quality of the timber is worse and the ecological environment is deteriorating. The desert shrublands in the plains were cut for fuelwood or reclaimed into croplands and uncontrolled collection of fuelwood is still occurring. The xerophilous shrubs and trees are disappearing and the forest coverage in the drylands is declining year by year. Since the 1980s, especially after the formulation of the "State Forest Law", a series of national reforestation or replantation projects, such as the National Natural Forest Protection Project have been developed. The National "Three North Regions Shelterbelt Development Project", the National Farmland Shelterbelt Project, and the on-going Grain for Green Project, are all focused on restoring the forests and their ecological services. The excessive cutting of fuelwood, destruction of vegetation, deforestation and over-reclamation for croplands are gradually being controlled and the reforestation, replantation and revegetation are being rapidly accelerated. The development and protection of forest are positive signs for sustainable management.

v) Rangeland and its status

Rangeland plays an important role in economic development and the improvement of eco-environment in the drylands. The understanding and comprehension of the quality, quantity and carrying capacity of rangeland are the basic requirement for making full use of it. The rangelands in the drylands of China are mainly located in Xinjiang, Inner Mongolia, Ningxia, Gansu, Qinghai and the northern part of Shaanxi, with a total area of approximately 199 million ha, accounting for 51.33% of the total land in those provinces and autonomous regions. In Inner Mongolia, the area of rangeland is the largest in all the dryland provinces and autonomous regions and covers 79.1529 million ha (39.8% of the total rangeland area of China); second is Xinjiang which has 57.2588 million ha of rangeland accounting for 28.8% of the total in China; and in Qinghai, the rangeland covers approximately 36.3697 million ha, representing 18.3% of the total rangeland in China. The areas of rangeland in the other dryland provinces are small, making up the remaining 13.1% of the total rangeland in China (Table 3.23).

There are 163 million ha of usable rangeland, accounting for 81.7% of the total area of rangeland in the drylands. The proportions of usable rangeland to the total rangeland area are 89.7% in Gansu Province, 87.1% in

Ningxia, 86.7% in Qinghai, 83.8% in Xinjiang, 83.5% in Shaanxi, and 75.8% in Inner Mongolia (Table 3.23). There are 137 species of plants in the rangeland, which provide good fodder for animals. Among the fodder species there are nine species are *Salsola* spp., six species of *Artemisia* spp., five species of *Potamogeton* spp., four species of *Atriplex* spp., three species of *Agriophyllum* spp., two species of *Populus* spp., *Anabasis* spp., *Glycyrrhiza* spp., *Ceratoidess* spp., *Elaeagnus* spp., *Stipa* spp., *Kalidium* spp., *Rosa* spp., *Astragalus* spp., *Caragana* spp., *Oxytropis* spp., *Bassia* spp., *Haloxylon* spp., *Ceratoidess* spp., *Potentilla* spp., *Agropyron* spp., *Calamagrostis* spp., *Cleistogenes* spp., one species of *Ephedra sinica*, *Aellenia* spp., *Halogeton* spp., *Sympegma* spp., *Shepherdspurse* spp., *Soongorica* spp., *Tamarix* spp., *Plantago* spp., *Artemisia* spp. and *Achnatherum* spp. (Pan et al., 2001).

Table 3.23 Types and locations of rangeland in China

Province (region)	TRA (10^4 ha)	RRT (%)	URA (10^4ha)	RURT (%)	TCA (10^4sheep/a)	CC (sheep/ha)
Xinjiang	5,725.88	34.88	4,800.68	83.8	3,224.9	0.67
Inner Mongolia*	7,915.29	68.40	5,998.43	75.8	5,924.2	0.99
Ningxia	301.41	58.19	262.56	87.1	147.1	0.57
Gansu	1,790.42	42.07	1,607.17	89.7	1,104.1	0.69
Qinghai	3,636.97	51.36	3,153.07	86.7	2,900.4	0.92
Shaanxi	521.62	25.32	434.92	83.5	903.0	2.08
Total	19,890.59	51.33	16,256.83	81.7	14,203.7	0.87**

TRA: Total rangeland area; RRT: Proportion of rangeland to total land area; URA: Usable rangeland area; RURT: Proportion of usable rangeland to the total land area; TCA: Theoretical carrying amount of rangeland; CC: Carrying capacity of rangeland; (EC-MRIMAR, 1991; other information is cited from Sun, 2001). **Average of actual carrying capacity of rangeland

Due to the relatively poor quality of rangelands in the drylands of China, the carrying capacity is relatively low, with an average of 0.87 sheep $\cdot$ha^{-1}. Shaanxi Province has a relatively high carrying capacity of 2.08 sheep $\cdot$ha^{-1}, followed by Inner Mongolia, Qinghai, Gansu, Xinjiang, and Ningxia (Table 3.23). The total carrying amount of rangeland in dryland of China is 142.037 million sheep, which is mainly distributed between Inner Mongolia (59.242 million sheep) and Xinjiang (32.249 million sheep), while Qinghai, Gansu, Shaanxi and Ningxia have lower carrying amount.

There is a long history of animal husbandry in the drylands of China with rangeland mainly used for grazing. The summer and autumn grazing lands are mainly located in the mountainous and remote regions, where summer is cool and winter is cold. The winter and spring grazing lands are located in valleys, basins and settlements in low lying areas. At present, the main problems of the rangeland utilization are that most of the rangeland is used for free-grazing with few enclosed areas for rotational grazing and winter and spring grazing land, which covers a smaller area than summer and autumn grazing land, is severely degraded due to overgrazing. Prior to 2000, the rate of degraded rangeland was as high as 49–52% of the total rangeland area

(Sun, 2001). Livestock are generally raised following a cycle of "strong in the summer, fat in the autumn, tired in the winter and dying in the spring", with the commercialization of sheep farming at only 13%.

The excessive collection of fuelwood and medicinal herbs is also destructive to local rangeland, decreasing the productive potential. Due to the shortage of fuelwoods, large quantities of desert plants were cut down for fuel for heating and cooking. Some valuable medicinal desert plants, such as licorice roots, *Codonopsis pilosula* and Chinese *Ephedra*, have also been over-harvested.

Currently, the area of degraded rangeland is approximately 1.05 million km^2. It is estimated that 50 million head of sheep are lost each year. Since the early 1950s, about 23,500 km^2 of rangeland has developed into shifting sand areas or been occupied by dunes and mobile sands, and the average annual loss of rangeland is 520 km^2 (Lu, 2000). Sound management of rangeland needs to be promoted, with measures including the prevention of further rangeland degradation, increasing the rate of artificial forage farms and grazing lands, improving the carrying capacity of rangeland, installation of fundamental facilities in the rangeland to increase the ability to resist disasters and protect livestock from damage, and identification of the optimum livestock components to establish the number of head of livestock for sale and the commodity rate. These urgent problems and crucial challenges in rangeland management are priority issues that need to be solved.

(ii) Ecotypes and their status

The ecotype of a plant refers to the adaptation of the physiological features of the plant to the environment. Considering characteristic responses of the plant to moisture and humidity, plants can be classified into xerophytes, mesophytes, hygrophytes and hydrophytes. Within the 1,704 species of plant in the drylands of Northwest China, 958 species are xerophytes, accounting for 56.6% of the total plant species; 436 species are mesophytes, accounting for 25.6% of the total; 135 species are hygrophytes representing 7.9%; and 35 species are hydrophytes, representing 2.1% of the total number of species. In addition, there are 11 species of parasitic plants (or 0.7%) and 129 species of ephemeral plants, accounting for 7.6% of the total plant species. It is clear that a majority of the dryland plants are xerophytes (Table 3.24).

Table 3.24 Ecotypes of plants in the drylands of Northwest China (Pan et al., 2001)

Total	EX	X	PX	XM	M	H	H	PP	EP
1,704	34	566	89	274	436	135	35	11	129
% of the total	2.0	33.2	5.2	16.1	25.6	7.9	2.1	0.7	7.6

EX: Extreme xerophytes; X: Xerophytes; PX: Psammophytes-xerophytes; XM: Xerophytes-mesophytes; M: Mesophytes; H: Hygrophytes; PP: Parasitic plants; EP: Ephemeral plants.

In terms of classification of the ecological characteristics of the living form, the plants in drylands can be classified into the following types (Pan et al., 2001):

i) There is only one species of xerophilous evergreen tree, *Sabina chinensis*, and this is also a native species in China located in the Qaidam Basin, mountainous areas of the Hexi Corridor and the middle part of the Longshou Mountains at the southern periphery of the Alxa Plateau.

ii) Xerophilous and mesophilous deciduous trees include species such as *Populus euphratica*, *Populus* spp. *Salix* spp. and various species of *Ulmus* spp.

iii) Xerophilous dwarf trees such as *Haloxylon ammodendron.*

iv) Xerophilous evergreen shrubs mainly include *Ammopiptanthus mongolicus*, *Ammopiptanthus mongolicus*, and *Ephedra junceum.*

v) Xerophilous shrubs are shrub species that are characterized by xerophilous physiological features and xerophilous morphology such as leaf degradation, bearing thorns and the carnification or lignification of leaves and branches. Plants bearing thorns include *Caragana centraliasiaticus*, *Caragana intermedia*, *Caragana calcaratum*, *Caragana austromongolica*, *Canagana korshinskii*, *Potaninia mongolica*, *Brachanthemum pulvinatum*, *Brachanthemum gobicum*, *Helianthemum songaricum*, and *Convolvulus tragacanthoides.* Shrubs that exhibit leaf carnification include *Zygophyllum xanthoxylon*, *Tetraena mongolica*, *Nitraria sphaerocarpa*, and *Nitraria tangutorum*, and shrubs that have degraded leaves and lignificated branches include *Ephedra* spp.

vi) Halophilous shrubs and semi-shrubs are plant species that have adapted to salinized soils. These plants include *Nitraria sibirica*, *Halostachys caspica*, *Kalidium foliatum*, *Tamarix ramosissima*, *Tamarix elongata*, *Tamarix hispida*, *Tamarix leptostachys*, *Tamarix chinensis*, *Reaumuria soongarica*, *Salsola collina*, and *Sympegma regelii.*

vii) Xerophilous semi-shrubs refer to semi-shrubs associated with the arid deserts, sandlands or gravel deserts. The leaves of these shrubs have deep cracks and floss. The main species are *Peganum harmala*, *Hippolytia trifida*, *Ceratoidess latens*, *Ajania fruticulosa*, *Oxytropis aciphylla*, *Oxytorpis aciphylla*, *Artemisia sphaerocephala*, *Artemisia ordosica*, *Artemisia wudanensis* and *Ceratoidess tibetica.*

viii) Xerophilous perennial herbs are drought tolerant, and mainly of the fascicular gramineous type, such as *Achnatherum splendens*, *Puccinellia distans* and *Stipa* spp., Cyperaceae, Liliaceae, *Astragalus* spp., *Oxytropis* spp., *Cinquefoil* spp. and *Artemisia* spp.

ix) Parasitic plants are plants that rely on nutrient materials taken from hosting plants, and include *Cuscuta chinensis*, *Cynomorium songaricum*, *Orobanche coerulescens*, and *Cistanche deserticola.*

x) Annuals are plants that complete their life-cycle within a year, and are also known as short lived plants. Of these, the cruciferous plants are the major component of the plant community and are widely distributed. Common species are *Lepidium apetalum*, *Alyssum desertorum*, *Chorispora tenella*, *Tetracme quadricornis*, *Leptaleum filifolium*, *Tulipa gesneriana*, *Trigonella foenum-graecum*, *Eremostachys moluccelloides*, *Eremopyrum triticeum*, and *Bromus japonicus*.

xi) The hydrophytes grow mainly in swamp areas, and include only a few species, such as *Potamogeton octandrus*, *Triglochin palustre*, *Butomus umbellatus*, *Vallisneria natans*, and *Phragmites australis*.

3.4.1.2 Fauna and their utilization

Fauna is an important component of biological resources, and is closely related to the livelihood and development of humans. Although studies on fauna in China can be traced back for 2,500 years to the "*Yugong* Chapter" (Classic Work of Chinese Geography completed in the Warring States Period, 475 BC–221 BC) and in *Shangshu* (Collection of Ancient Texts), there has been very little systematic research into the faunal classification, species and geographic distribution.

In the 1950s, Zheng (1950), a zoogeographer, conducted studies on birds, Shou (1955) carried out studies and observations on fur animals, Zhang (1954) completed research on freshwater fish, and Zheng and Zhang (1956) conducted research on the regional distribution of birds and mammals. These studies provided the background for research on the modern fauna and their distribution (Zhang, 1999b). Faunal research is still weak due to a lack of research foundations, so basic information and theories on faunal sciences should be promoted and improved.

(i) Fauna divisions

The fauna in the drylands of China is found in the Inner Mongolia-Xinjiang (IM-XJ) and the Qinghai-Tibet (QH-TB) zones. Rongzu Zhang divided the modern animals of the IM-XJ and QH-TB zones into five sub-zones according to their geographical and species distribution. Table 3.25 shows the results of fauna division.

Table 3.25 Regional division of fauna in the drylands of China

zones	Sub-zones	Climatic zones
1. Inner Mongolia-Xinjiang	1.1 Eastern steppe	Semi-arid
	1.2 Western desert	Arid
	1.3 Tianshan Mountains	Semi-arid, sub-humid
2. Qinghai-Tibet	2.1 Qiangtang Plateau	Arid, semi-arid
	2.2 Qinghai-southern Tibet	Sub-humid, semi-arid

(ii) Distribution of faunal species

In terms of terrestrial vertebrates, there are 167 families, 744 genera and 2,470 species in China, accounting for about 10.9% of the total terrestrial vertebrates worldwide. Within which there are 1,186 species of birds or 13.5% of the total worldwide, 500 species of animals or 11.5% of the total worldwide, 435 species of amphibian or 6.8% of the total number worldwide, and 352 species of reptiles or 6.7% of the total worldwide (Zhang, 1999b).

There are many disparities in the distribution of the main species of vertebrates in the IM-XJ and QH-TB zones (Table 3.26). The species can mainly be classified as the Northern type (mainly in eastern steppe sub-zone) and the Central Asian type (mainly in western desert sub-zone and the Tianshan mountain sub-zone). In terms of the number of species, there are 489 species classified as the Northern type and 264 species classified as the Central Asian type. In addition, the Dongyang-Upland type also includes a considerable proportion of the terrestrial vertebrates (263 species). The regional distribution of different species is uneven. In IM-XJ zone, there are more amphibians, resident birds, breeding birds, and migratory birds of the Northern type than the Central Asian type, while in terms of reptiles and animals, the Central Asian type accounts for a higher percentage than the Northern type. In the QH-TB zone, there are more Northern type vertebrates of all kinds than Central Asian type.

Table 3.26 Species and distribution of terrestrial vertebrates in the Inner Mongolia-Xinjiang and Qinghai-Tibet zones (Zhang, 1999b)

Species	North type			Central Asian type			Dongyang-Upland type		
	IM-XJ	QH-TB	Total	IM-XJ	QH-TB	Total	IM-XJ	QH-TB	Total
A	4	2	6	3	0	3	0	10	10
R	8	2	10	24	1	25	0	8	8
RB	43	0	43	35	0	35	3	0	3
BB	202	91	293	92	14	106	21	128	149
MB	40	10	50	1	0	1	7	2	9
B	66	21	87	78	16	94	6	78	84
Total	363	126	489	233	31	264	37	226	263

A: Amphibians; R: Reptiles; RB: Resident birds; BB: Breeding birds; MB: Migratory birds; B: Beasts; IM-XJ: Inner Mongolia-Xinjiang; QH-TB: Qinghai-Tibet.

(iii) Management of faunal resources

In terms of quantity and use, the fauna in the drylands can be divided into resource animals, rare animals and aquatic animals (mainly fish).

Resource animals: Humans have many uses for animals and animals can be classified according to use types, including:

Meat animal resources: including wild goat, wild hare, *Muntiacus reevesi*, roe deer, *Phasianus colchicus*, and antelope.

Fur and leather animal resources: including wild poephagus grunniens, marmot, grass rabbit, petaurista leucogenys, foxes, squirrels, wild sheep, mink, badger, wolf, roe deer, tufted deer, wild boar, lynx and polecats.

Resource animals with medical uses: including forest musk deer, red deer, white lip deer, Tibetan antelope, badger, leopard, civet, bear and flying squirrel.

Rare animal resources: Rare animals include the Mongolian mustang, wild Bactrian camel, high-nose reindeer, white lip deer, red deer, takin, Ling jets geese, wild donkey, wild yak, Tibetan antelope, argali, golden cat, snow leopard, steppe cat, desert cat, Vulpes corsac, black badger, Chinese autumn sand ducks, white-tailed sea eagles, white shouldered carving, lanma hen, green tailed red pheasant, red ventral horned pheasant, black necked crane, golden eagle, vulture, and swan.

The Chinese government pays attention to the protection of rare animals and has improved hunting bans through formulation of state laws to protect rare animals. Even so, the poaching and hunting of many of these animals is still prevalent. In the future, more efforts should be made to raise awareness of animal protection, improve animal management, strengthen legalization and conduct studies on the artificial feeding of rare animals.

Fish resources: There are many lakes, reservoirs and rivers in the drylands of China and these are inhabited by over 200 fish species. The high economic value native fish species includes the Qinghai yellow croaker and others. Exotic fishes include triangular bream, bream, silver grass carp, rainbow sturgeon and *Tilapia mossambica.*

3.4.2 Specific biological resources and their industrial development

Under the unique environmental conditions in the drylands of China, including aridity, strong solar radiation, huge geological structural change and alpine coldness, specific biological resources with particular characteristics are formed. These biological resources can provide a basis for commercial development of biological resources based on the unique species.

3.4.2.1 Medicinal plant resources and their commercial development

(i) Medicinal plant resources

There are hundreds of plant species with unique medical effects and broad prospects for development. All the species contain special chemicals which have physiological roles that can be used in the medical treatment of various illnesses. Among them, Dicotyledons are the most common plants from families such as Leguminosae, Ranunculaceae, Rosaceae, Polygalaceae, Umbelliferae, Solanaceae, Euphorbiaceae, Araliaceae, Gentianaceae, Asclepiadaceae and Campanula. Monocotyledons, such as Liliaceae and Araceae species are other common medicinal plants. There are some species of Gymnosperm, including the *Ephedra* spp., Pinaceae and *Cypress* spp., *Lycopodium* spp., Selaginellaceae and Equisetaceae which also have medicinal applications.

There are a variety of antitussive and expectorant medicinal plants, including *Glycyrrhiza uralensis*, *Polygala tenuifolia*, *Polygala sibirica*, *Prunus sibirica*, *Anemarrhena asphodeloides*, *Lilium pumilum*, *Platycodon grandiflorus*, *Codonopsis pilosula*, *Adenophora stricta*, *Euphorbia fischeriana*, *Thy-*

mus mongolicus and *Plantago asiatica*, with developing prospects.

There are also numerous medicinal plants which, in Chinese medicine, are considered to have a warming effect. The plants that are widely distributed include: *Aconitum kusnezoffii*, *Bupleurum scorzonerifolium*, *Saposhnikovia divaricata*, *Mentha haplocalyx*, *Scutellaria baicalensis*, *Thymus mongolicus* and *Artemisia capillari*.

There are several varieties of aphrodisiac plants, including *Cistanche deserticola*, *Haloxylon ammodendron*, *Cistanche sinensis*, *Astragalus membranaceus*, *Taraxacum mongolicum*, *Polygonatum odoratum*, *Polygonatum sibiricum*, *Codonopsis pilosula* and *Lycium chinense*.

Species that can be used for diuretic purposes include *Phragmites australis*, *Alisma plantago-aquatica*, *Lilium pumilum*, *Polygonum aviculare*, *Plantago asiatica* and *Casuarina equisetifolia*.

There are a variety of species that can be used for the purpose of reducing body temperature or relieving fever and diminishing inflammation, such as *Cirsium setosum*, *Cirsium maackii*, *Euphorbia fischeriana*, *Euphorbia humifusa*, *Polygonum hydropiper*, *Kochia scoparia*, *Ranunculus japonicus*, *Corydalis bungeana*, *Scutellaria baicalensis* and *Scrophularia ningpoensis*.

There is a wide distribution of plant species that can be used for analgesia, sedation, and to relieve uneasiness of body and mind, such as *Datura stramonium*, *Saposhnikovia divaricata*, *Papaver nudicaule*, *Ziziphus jujuba* var. *spinosa*, *Platycladus orientalis*, *Paeonia Lactiflora*, *Scutellaria baicalensis*, *Xanthium sibiricum*, and *Arisaema erubescens*.

Other medicinal plants have uses in hemostasis such as *Selaginella tamariscina*, *Equisetum arvense*, *Equisetum Hyemale*, *Sophora flavescens*, *Sophola japanica*, *Artemisia annua*, *Pyrola calliantha* and *Imperata cylindrica*.

Table 3.27 shows different parts of some medicinal plants and their uses.

(ii) Commercial development of medicinal plants

Commercial development of medicinal plant resources includes the direct use of raw materials, the refinement of a series of extracted medicines and research and development into new and medical products. From the view of sustainable development, the commercialization of the medical plant industry should consider the following:

Responsible development of natural medicinal plant resources should be implemented. Medicinal plant resources are widely spread in the natural environment and are completely dependent on natural light, temperature, water, soil and nutrients and they have a comparatively low natural productive potential. Therefore, commercial development of these medicinal plants must be dependent on natural productivity. In the past, as a consequence of favoring short term interests, medicinal plants have been collected without sound management and on an uncontrolled scale. The over-exploitation of licorice and *Ephedra* is so widespread that it has already led to rangeland degradation. The scale of commercial development of medicinal plants should be determined according to the growth rate and productivity of the medicinal plants,

Table 3.27 Effects of some medicinal plants in drylands of China (Pan et al., 2001)

Plant	Medical parts	Effects
Casuarina equisetifolia	Stem and leaf	Induce perspiration, control asthma, diuresis
Populus nigra	Leaf bud	Skin inflammation, burn
Polygonum amphibium	Whole plant	Relieve fever and diuresis
Polygonum aviculare	Whole plant	Diuresis, inseicidal, antipruritic
Lycium chinense	Fruit, leaf, root and hull	Tonic, treating Yin deficiency by reinforcing body fluid and nourishing blood, promote the secretion of saliva
Cistanche deserticola	Fruit	Tonic, cure erectile disfunction, cure metrorrhagia
Cynomorium songaricum	Whole plant	Tonic, cure erectile disfunction, cure metrorrhagia
Nymphaea tetragona	Flower	Alleviate fever and reduce phlegm
Glycyrrhiza uralensis	Root and rhizoma	Tonic, stomach tonic, moisten heart and lung
Astragalus membranaceus	Root	Aeipathia is infirm, notify primordial qi
Sophora alopecuroides	Root and seed	Antipruritic, insect repellent, detoxify
Limonium aureum	Whole plant	Regulating menstruation, promoting blood, stop aching
Limonium gmelinii	Root	Stop bleeding
Plant	Medical parts	Effects
Artemisia annua	Upper part above ground	Clear heat, stop blooding, get rid of summer heat and refreshing
Alisma plantago-aquatica	Bulb	Diuresis, alleviate fever and noxious dampness
Apocynum venetum	Leaf	Calming liver, soothe the nerves, cure high blood pressure
Isatis indigotica	Root	Relieve internal heat or fever, cure hepatitis
Taraxacum mongolicum	Whole plant	Relieve internal heat or fever, acute severe hepatitis
Tulipa L.	Bulb	Clear heat, relieve coughing
Fritillaria karelinii	Whole plant	Relieve coughing and reduce phlegm, alleviate fever and depression
Salsola collina	Whole plant	Reduce blood pressure
Capseua bursa-pastoris	Whole plant	Staunch bleeding
Nitraria sibirica	Fruit	Stomach tonic, Tonic, aphrodisiac
Elaeagnus angustifolia	Fruit	Reduce phlegm
Zygophyllum xanthoxylon	Root	Circulate the Qi

emphasizing both protection and responsible use of medicinal plants.

Artificial plantations of medicinal plants should be established. The conflict between the supply and demand of medicinal plants has meant that natural medicinal plant resources have been over-exploited. Artificial cultivation measures should be adopted to establish production bases for medicinal plant which would allow intensive production, and this should be of the key focus for commercial development of medicinal plants. In farms growing licorice roots in Xinjiang, Inner Mongolia and Ningxia autonomous regions, the yield of artificially cultivated four year seedlings is 2.28–9.67 $t{\cdot}ha^{-1}$. This means the productivity of cultivated licorice root is 4.5–16.2 times the productivity in the wild (Pan, et al., 2001). The introduction of *Ephedra* and the establishment of production farms are also popular. There are also demonstration farms for *Radix isatidis* and *Rhodiola* plantations. These cultivated medicinal plant farms provide experience and demonstrations of successful operations to encourage future development.

Refining and developing the raw herbs into medicines is an important direction for the future development of medicinal plant resources. Refined drugs, such as *Rhodiola* liquid, refined licorice essence, *Bupleurum* injections, *Radix isatidis* instant herbal mixture, and Ephedrine can be produced from herbs using advanced technology. The exploitation of medicinal plant resources through commercial development processes is of great potential and could be an important development in medicine plant use in future.

3.4.2.2 Edible plant resources and their commercial development

Edible plant resources are plants that contain ingredients which could be used as raw materials of food, such as starch, protein, fats, carbohydrates, vitamins and other nutrients. Edible plant resources are abundant in drylands of China. Based on their nutritional content, the plants can be divided into starch plants such as *Elaeagnus angustifolia* (fruit), *Melilotus suaveolens* (seeds), *Iris lactea* var. *chinensis* (seeds), *Phragmites australis* (rhizomes), *Scirpus yagara* (root), *Sagittaria sagittifolia* (corm), *Gymnadenia conopsea* (rhizomes); protein plants such as *Atriplex* spp. (seeds), *Atriplex patens* (seeds), *Salsola collina* (leaf), *Melilotus suaveolens* (leaf); oil plants including *Salicornia europaea* (seeds), *Suaeda glauca* (seeds), *Halocnemum strobilaceum* (seeds), *Kochia scoparia* (seeds), *Hippophae rhamnoides* (seeds), *Elaeagnus angustifolia* (seeds), *Nitraria sibirica* (seeds), *Lycium chinense* (seeds), and *Chambers mustard* (seeds) and vitamin-rich plants such as *Hippophae rhamnoides* (fruit), *Elaeagnus angustifolia* (fruit), *Cirsium setosum* (seedling), *Nitraria sibirica* (fruit), *Lycium chinense* (fruit), *Suaeda glauca* (seeds), and *Salsola collina* (soft leaves).

In addition to basic exploitation methods such as direct collection and raw material provision, the edible plant resources should be commercially developed into value-added products through further manufacturing according to their nutrient composition. The plants could be processed into drinks including plants such as *Nitraria* spp., *Elaeagnus angustifolia* and *Hippophae rhamnoides*. *Sagittaria sagittifolia* is suitable for refinement as a quality herb food, and other species can be developed into condiments.

3.4.2.3 Processable or aromatic plant resources and their commercial development

Processable plants are species that contain elements which can be used for making light industrial products, such as those that contain alkali or ingredients for cosmetics. Aromatic plants are species that contain processable aromatic ingredients. There are many varieties of processable plants. Those with rich of potential development include *Populus euphratica*, *Kalidium foliatum*, *Halostachys caspica*, *Halocnemum strobilaceum*, *Salicornia europaea*, and *Populus nigra*. The most potentially useful aromatic plants include *Chenopodium botrys*, *Salsola junatovii*, *Glycyrrhiza glabra*, *Elaeagnus angustifolia*, *Elaeagnus oxycarpa*, *Glechoma longituba*, *Mentha haplocalyx*, *Schizonepeta annua*, *Artemisia annua* and *Artemisia mongolica*. The plants which could be used for the weaving industry include *Poacynum pictum*, *Typha orientalis*, *Phragmites australis* and *Achnatherum splendens*.

To date there has been little development of processable or aromatic plant resources, and the processing technology is still under-developed. The strategy for future development is to adopt advanced technology to make refined herb products. The development of aromatic plants in particular is potentially one of the most lucrative commercial processing and manufacturing industries for the future.

3.4.2.4 Plant resources for urban landscaping and their commercial development

Towns or cities are the center of socio-economic development in drylands of China. The improvement of the urban ecological environment will become more and more important with increasing urbanization in future. Selecting the right plants for greening towns or cities can help improve environment, reduce pollution, minimize dust and control noise, and in addition, can also help create a good living environment and offer comfortable living and working spaces for citizens and employees.

The selection of appropriate native plants for landscaping towns or cities in the drylands of China will help improve the survival rate of plants within the cities. Appropriate woody species include *Ulmus pumila*, *Sabina przewalskii*, *Sabina vulgaris*, *Tamarix* spp., *Caragana* spp., *Hippophae rhamnoides*, *Lycium chinense*, *Amygdalus mongolica*, *Rosa* spp. and *Spiraea hypericifolia*. There are more potentially suitable species of herb plants, including *Limonium* spp., *Lagochilus grandiflorus*, *Hyssopus officinalis*, *Verbascum thapsi*, *Lythrum salicaria*, *Linaria bungei*, *Veronica ferganica*, *Saussurea superba*, *Carex duriuscula*, *Tulipa gesneriana*, *Iris tectorum*, *Cypripedilum calceolus*, *Orchis latifolia*, and *Thymus mongolicus*.

It is difficult to provide the required plants for urban greening and development by simply collecting plants from natural areas. The establishment of cultivation centers for native plants and the promotion of commercial nursery cultivation are important for future development and urban landscaping. The first task of commercial nursery cultivation is to introduce native species and enlarge the market of local seedlings to meet the needs of urban greening and landscaping; the second task is to promote research and experiments on the introduction of new species to meet the needs of urban development; and the third task is to import and introduce exotic species from other regions or countries.

3.5 Mineral resources and their development and utilization prospects

Drylands in China boasts its rich mineral resources, wise exploitation of theses mineral resources will accelerate the regional economic development and strength the desertification control.

3.5.1 Metal mineral resources

Metal ores are important fundamental resources for the national economy, national defense, and most sophisticated technologies and high-tech industries. According to the properties and reserves of the minerals, the metal resources can be divided into black metal ores, non-ferrous metal ores, precious metals and rare earth metals. Almost every type of metal ore can be found in the drylands of China (Table 3.28).

Table 3.28 Distribution of mineral resources in the drylands of China

Type of ore	Varieties of ores	Metals
Black metals	5	Iron, manganese, titanium, vanadium, chromium
Non-ferrous metals	13	Copper, lead, zinc, aluminum, nickel, cobalt, molybdenum, mercury, tungsten, magnesium, tin, bismuth, antimony
Precious metal minerals	8	Gold, silver, ruthenium, rhodium, palladium, osmium, iridium, platinum
Rare metals	7	Niobium, tantalum, ytterbium, beryllium, strontium, rubidium, cesium
Rare earth metals	17	Lanthanum, cerium, yttrium, ytterbium, and other lanthanides
Rare dispersed metals (Semi-conductors)	7	Gallium, indium, thallium, germanium, selenium, tellurium, rhenium

3.5.1.1 Black metal resources

As shown in Table 3.29, the resource deposits of most black metal ores found in drylands are not rich, with the exception of chromium ores. Chromium reserves in the drylands, on the other hand, are abundant and account for 55.66% of the reserves of the whole country, at 5.306 million tons. Inner Mongolia (IM), Xinjiang (XJ) and Gansu (GS) provinces and autonomous regions are rich in chromium ore reserves.

Table 3.29 Black metal resources in drylands of China

Ore	Unit	National total (a)	Desert area (b)	b/a (%)	XJ	GS	IM	NX	QH	SHX
Iron	Ore (10^4t)	458.9	44.06	9.6	7.07	8.73	20.16	0.01	2.25	5.84
Manganese	Ore (10^4t)	5.4	0.24	4.45	Small	Small			Small	0.24
Titanium	Ore (10^4t)		161.9	0.46						
Chrome	Ore (10^4t)	1,027	530.69	51.66	165.2	149.6	174.4		41.4	
Ilmenite	Ore (10^4t)	35,195.9	161.9	0.46						161.9
Navajoite	Ore (10^4t)	2,587.8	125.9	4.87	Small	125.9				

XJ: Xinjiang; GS: Gansu; IN: Inner Mongolia; NX: Ningxia; QH: Qinghai; SHX: Sha'anxi (Source: National Reserves from: National Mineral Data, 1998; other Data cited from Zhu, 1999a)

3.5.1.2 Non-ferrous metal minerals

Various non-ferrous metals are widely distributed in the drylands of China. Almost all metals can be found in the drylands, but the distribution of ore varieties is uneven. The ore varieties with exploitation potential include nickel, cobalt, zinc, mercury and lead, while bauxite and tungsten ore deposits are small. The regional distribution of the different ores in the drylands is variable, with a wide distribution of copper, lead and zinc, while molybdenum, tin and nickel are only distributed in one or two provinces or autonomous regions (Table 3.30).

3.5.1.3 Precious metal resources

Most varieties of precious metal resources can be found in the drylands of China, and the deposits are comparatively rich. These metals have provided a good resource base for industrial development of both the country and the drylands.

Precious metals make unique contributions to the promotion of regional development. Therefore it is one of the most important tasks to develop the resource using strategies depending on the ore deposits and the exploitation

Table 3.30 Non-ferrous metal minerals in the drylands of China

Ore	Unit	Reserves		
		National total (a)	Drylands (b)	b/a (%)
Copper	Cu (10^4 t)	6,307.2	1,053.90	16.7
Lead	Pb (10^4 t)	3,511.0	782.10	22.3
Zinc	Zn (10^4 t)	9,244.9	2,227.80	24.1
Bauxite	Ore (10^4 t)	22.7	Small	
Nickel	Ni (10^4 t)	771.0	567.40	73.6
Cobalt	Co (10^4 t)	47.5	20.08	42.3
Tin	Sn (10^4 t)	385.3	32.87	8.5
Tungsten	WO_3 (10^4 t)	532.0	33.10	6.2
Molybdenum	Mo (10^4 t)	836.3	139.41	16.7
Antimony	Sb (10^4 t)	269.7	24.69	9.2
Mercury	Hg (10^4 t)	8.14	1.83	22.5

Ore	XJ	GS	IM	NX	QH	SHX
Copper	217.41	377.02	284.35		184.28	10.83
Lead	119.90	167.94	291.18		126.76	76.29
Zinc	222.49	628.51	970.51		161.68	244.59
Bauxite						
Nickel	89.40	478.00				
Cobalt	2.35	14.38			3.35	
Tin			32.87			
Tungsten		22.29	10.81			
Molybdenum			30.11			109.30
Antimony		15.29			1.53	7.87
Mercury		0.05			0.31	1.47

XJ: Xinjiang; GS: Gansu; IN: Inner Mongolia; NX: Ningxia; QH: Qinghai; SHX: Sha'anxi (Source: The Data of Reserves of Molybdenum are cited from the Special Report in Western China: China's Ore Report, Ministry of Land Territory, 2000; other data cited are from Zhu, 1999a)

conditions. The status of the precious metals can be seen in Table 3.31.

Table 3.31 shows that all the main precious metals, including gold, silver and platinum groups (platinum, palladium, iridium, rhodium, osmium, and ruthenium) can be found in China's drylands. In terms of reserves, gold mines contain 13.1% of the total gold resources of China, the proportion of silver is 17.7% of the national resource and the proportion of the platinum group metals is as high as 59.1% of the national resource. However, the regional distribution of minerals is variable. The provinces with the largest gold reserves are Shaanxi, Gansu, Qinghai and Xinjiang. Silver is mainly distributed in Inner Mongolia, Gansu and Shaanxi, and platinum group metals are mainly distributed in Gansu, Xinjiang, and Inner Mongolia.

3.5.1.4 Rare metal resources

In this category there are seven metals: niobium (Nb), lithium (Li), tantalum

Table 3.31 Distribution of precious metals in the drylands of China

Ore	Unit	Reserves			XJ	GS	IM	NX	QH	SHX
		National total (a)	Drylands (b)	b/a (%)						
Gold	Au (t)	4,157.5	559.3	13.1	72	146	41.2	0.1	94	206
Silver	Ag (t)	117,676.0	20,867	17.7	①	5,126	8,864.0	②	③	2,257
Platinum group	Metal (kg)	310,086.0	183,307	59.1	3,901	177,513	1,893.0			

XJ: Xinjiang; GS: Gansu; IN: Inner Mongolia; NX: Ningxia; QH: Qinghai; SHX: Sha'anxi (Source: The data of reserves of Au/Ag are cited from the Special Report in Western China: China's Ore Report, Ministry of Land Territory, 2000; other data cited are from Zhu, 1999a; the total of ①+②+③is 4,620 t).

(Ta), beryllium (Be), strontium (Sr), rubidium (Rb) and cesium (Cs). The quantity and distribution of the first five metals can be seen in Table 3.32.

Table 3.32 Distribution of rare metals in the drylands of China (Zhu, 1999a)

Ore form	Unit	Reserves		
		National total (a)	Drylands (b)	b/a(%)
Ore lithium	Ore (10^4 t)	100	15.5	15.5
Bittern Lithium	Li (10^4 t)	1,000	800	80
Beryllium	Be (10^4 t)	<100		57.2
Columbium	Nb (10^4 t)	385.6	278.1	72.1
Tantalum	Ta (10^4t)	8.5	2.1	24.7
Strontium	Sr (10^4 t)	3,290.86	2,095.32	63.7

Ore form	XJ	GS	IM	NX	QH	SHX
Ore lithium	15.5				800	
Bittern Lithium						
Beryllium	29.4	Small	27.8			
Columbium	Small		278.1			
Tantalum	0.04		2.06		1,591.15	504.17
Strontium						

XJ: Xinjiang; GS: Gansu; IN: Inner Mongolia; NX: Ningxia; QH: Qinghai; SHX: Sha'anxi.

Table 3.32 proves that the majority of the country's rare metal resources, except tantalum, are located in the drylands in the form of mineral resources. The distribution of the minerals is variable. Lithium is most commonly found in Qinghai (QH) and Xinjiang (XJ); while beryllium is mainly in Inner Mongolia (IM) and Xinjiang (XJ). Niobium and tantalum are found in Inner Mongolia and strontium reserves in Qinghai (QH) and Shaanxi (SHX). Inner Mongolia (IM) has the most abundant rare metals based on quantity, followed by Qinghai (QH) and Xinjiang (XJ).

3.5.1.5 Rare earth metal resources

Rare earth metal resources are often referred as rare earth mineral resources. This group contains 16 rare metals. They are named from the fact that their oxides cannot be dissolved in water (just like earth) and there are scarce reserves. The 16 metals can be divided into light, medium and heavy groups. Light rare earth metals are lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), and promethium (Pm); the medium rare earth metals are samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb) and dysprosium (Dy); and the heavy rare earth metals are holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu) and yttrium (Y). These metals have unique features and they are widely used in industrial applications such as the making of fluorescent materials, batteries, electric lights, permanent magnets, hydrogen storage, catalytic materials, lasers, superconducting materials, magnetostrictive material, magnetic refrigeration materials, fiber optic materials, and are essential metals for construction and modernization of the country.

China has rich rare earth metal resources, most of which are found in the drylands. Prior to 1994, China's total identified reserves of lanthanum oxides was 107,353,400 tons, reserves were 92,308,900 t, and 29,769,600 t were classified as A + B + C grades. The deposits of the rare earth metal resources are almost all in the drylands, with 96% of the total deposits found in Inner Mongolia alone. The main production sites are located in Bayan Obo County, Zhaluteqi County and others near Baotou City of Inner Mongolia.

3.5.1.6 Rare dispersed metal resources

Rare dispersed metal resources and rare earth metal resources are usually discussed together in literature. In this chapter, the rare dispersed (or scattered) metals will be treated separately due to their special functions and features, which make them difficult to exploit because they tend to form independent deposits. Rare dispersed metals usually include gallium (Ga), indium (In), thallium (Tl), germanium (Ge), selenium (Se), tellurium (Te) and rhenium (Re) elements. Because of their unique features, they are the indispensable and essential metals in modern communications technology, computers, aerospace development, medicine and health care, photosensitive materials, optoelectronic materials, energy materials, and catalyst materials. Therefore, they are extremely important and valuable worldwide.

The deposits of rare dispersed metals in China are comparatively rich, but with an uneven distribution. The confirmed deposits in drylands of China are shown in Table 3.33.

Table 3.33 shows that China's drylands include the major deposits of indium, selenium, rhenium and tellurium. A comprehensive reclamation of the scattered metals is also carried at the end of the process, thus an increase in the recycling and recovery process is the main direction for the rare dispersed

Table 3.33 Reserves of rare dispersed metals in drylands and in China (Song, 1997)

Element	Obtainable reserves (t)	Obtainable reserves in drylands (%)	Element	Obtainable reserves (t)	Obtainable reserves in drylands (%)
Germanium	3,055	Small	Selenium	13,395	Gansu 41.2 Qinghai 8.8
Gallium	98,300	Small	Rhenium	237	Sha'anxi 44.3
Indium	13,014	Inner Mongolia, 8.2, Qinghai, 7.8	Tellurium	13,395	Gansu 10.7
Thallium	8,302	Small			

metal production.

3.5.2 Non-metal mineral resources

3.5.2.1 Non-metal mineral resources as auxiliary metallurgical raw materials

There are three kinds of mineral resources which are auxiliary metallurgical raw materials, and their distribution in the drylands of China can be seen in Table 3.34. Of these materials, the deposits of fluorite are abundant, accounting for 23.8% of China's total deposits (25.93 million tons). The fluorite is mainly located in Inner Mongolia. The reserves of refractory clay are rich and mainly located in Inner Mongolia (IM), which accounts for 10.1% of the total reserves in China, and 77.1% of the reserves in drylands. Magnesite resources are scarce in drylands, which only accounts for 1.95% of the total national resources, and located in Xinjiang (XJ) and Gansu (GS).

Table 3.34 Non-metal mineral resources in the drylands of China (Zhu, 1999b)

Ore	Unit	Reserve		
		National total (a)	Drylands (b)	b/a (%)
Magnesite	Ore (10^8 t)	30.01	0.584 7	1.95
Fluorite	Ore (10^8 t)	1.09	0.259 3	23.80
Refractory clay	Ore (10^8 t)	21.28	2.787 7	13.10

Ore	XJ	GS	IM	NX	QH	SHX
Magnesite	0.315 3	0.269 4				
Fluorite		0.023 7	0.231 5			0.004 1
Refractory clay	Small	Small	2.149 3	Small		0.324 3

XJ: Xinjiang; GS: Gansu; IN: Inner Mongolia; NX: Ningxia; QH: Qinghai; SHX: Sha'anxi.

3.5.2.2 Resources for raw chemical resources

There are nine non-metal mineral resources which can be used as raw chemical materials, and their distributions in the drylands are shown in Table 3.35. The non-metal mineral resources which have a large proportion of reserves in the drylands are sylvite (KCl), Glauber's salt (Na_2SO_4), sodiumsalt (ore), boron (B_2O_5) and barite with proportions of the national reserves at 98.2%, 95.4%, 80.1%, 24.7% and 20.4%, respectively. These resources can all contribute to the economic development in the drylands of China. The distribution of these resources is variable, with potassium, sodium, boron and Glauber's salt mainly found in the Qaidam Basin of Qinghai Province; pyrite and graphite crystal mainly located in Inner Mongolia; and small quantities of pyrite and graphite crystal found in Xinjiang (XJ), Gansu (GS), Shaanxi (SHX) and Ningxia (NX).

Table 3.35 Other chemical resources in the drylands of China

Ore	Unit	Reserves		
		National total (a)	Drylands (b)	b/a (%)
Sulfurous iron ore	Ore (10^8 t)	46.34	4.960	10.7
Mirabilite	Na_2SO_4(10^8 t)	105.32	100.460	95.4
Barite	Ore (10^8 t)	3.61	0.735	20.4
Sodium salts	Ore (10^8t)	4,075.00	>3,262.600	80.1
Sylvite	KCl (10^8 t)	4.57	4.487	98.2
Boric oxide	B_2O_5 (10^8 t)	4,670.60	1,154.500	24.7
Phosphorus ore	Ore (10^8 t)	151.98	10.810	7.1
Diamond	Ore (kg)	4,179.00	slim	
Graphite	Crystal (10^4 t)	17,317.00	1,002.000	5.8
	Noncrystal (10^4 t)	4,493.00	224.600	5.0

Ore	Xinjiang	Gansu	Inner Mongolia	Ningxia	Qinghai	Sha'anxi
Sulfurous iron ore	small	small	4.96	small	small	small
Mirabilite	1.40	small	12.00	small	87.06	small
Barite		0.37				0.365
Sodium salts					3,262.60	
Sylvite	0.06	small	small		4.427.00	
Boric oxide	small	small			1,154.50	
Phosphorus ore	small	small	small	small	5.11	5.700
Diamond	slim		small			slim
Graphite	a few	a few	548	a few	a few	a few 224.600

3.5.2.3 Building materials and other non-metal mineral resources

There are 14 varieties of non-metal mineral resources that can be used in the building industry and other sectors, 11 of which are important. The distribution of these 11 minerals in the drylands can be seen in Table 3.36. Of these resources, asbestos, mica and glass siliceous materials have the highest proportions of the national reserves found in the drylands at 78.4%, 75.0% and 49.5%, respectively. Kaolin, bentonite and limestone are also commonly found in drylands, with 20–30% of the national reserves found in the drylands. The abundance of these minerals has provided a good foundation for the economic development of the drylands. There is a shortage of marble and granite resources in the drylands. The distribution of the resources between regions is variable. Qinghai has the majority of the steatite; in Inner Mongolia, mica, gypsum and bentonite are the key mineral resources; in Xinjiang, mica is the main resource; in Shaanxi, lime cement, kaolin are the major resources; and Ningxia has relatively scarce mineral resources used in the building industry.

Table 3.36 Non-metal minerals used in the building industry in the drylands of China (Zhu, 1999b)

Ore	Unit	Reserves		
		National total (a)	Drylands (b)	b/a (%)
Tabular spar	Ore (10^8 t)	13,265	1,580	11.9
Steatite	Ore (10^8 t)	24,777	4,117	16.6
Asbestos	Ore (10^8 t)	9,061	7,104	78.4
Mica	Ore (10^8 t)	63,147	47,339	75.0
Gypse	Ore (10^8 t)	576	84.8	14.7
Limestone	Ore (10^8 t)	524	106.5	20.3
Glass: Raw siliceous material	Ore (10^8 t)	39.97	19.8	49.5
Kaolin	Ore (10^8 t)	14.3	3.93	27.5
Bentonite	Ore (10^8 t)	24.6	6.51	26.5
Marble	Ore (10^8 m^3)	108,400	Unsure	
Granite	Ore (10^8 m^3)	94,977	4,749*	5.0

Ore	Xinjiang	Gansu	Inner Mongolia	Ningxia	Qinghai	Sha'anxi
Tabular spar	a few		265		1,315	
Steatite	a few		a few		4,117	
Asbestos	272				5,799	1,033
Mica	40,411		5,874		1,054	less
Gypse	a few	14	32	12.3	22	4.5
Limestone	16.0	12	14	2.5	13	49.0
Glass: Raw siliceous material	0.3	0.2	0.7	0.1	16.5	2.0
Kaolin			0.10			3.83
Bentonite	3.44	0.33	2.11			0.63
Marble						
Granite	Unsure	Unsure	Unsure	Unsure	Unsure	Unsure

*Figure is estimated after subtracting 75% of the storage of Northern China and Eastern China.

3.5.3 Energy resources

Energy resources are abundant in the drylands of China. It is important to study the quality, quantity, distribution and use of energy resources in the drylands of China. According to China's energy consumption, the main energy resources can be divided into three categories, i.e., coal, oil and natural gas.

3.5.3.1 Coal resources

The drylands of China are rich in coal resources, and coal has a dominant position in energy composition at a national level. The coal reserves in the drylands are 527.3 billion tons, which is 52.6% of the entire national reserve. In the drylands, the reserves in Inner Mongolia are 224.7 billion tons, 161.9 billion tons in Shaanxi, 95.2 billion tons in Xinjiang, 30.9 billion tons in Ningxia, 10.2 billion tons in Gansu, and 4.4 billion tons in Qinghai. This means that the drylands could be described as being the center of coal energy. There are some super coal reserves, including the Shenmu-Fugu Coal Mine in Shaanxi, the Dongsheng Coal Mine in Inner Mongolia, and the Hedong Coal Mine in Urumqi, Xinjiang. There are other coal reserves in Tongchuan and Hancheng in Shaanxi Province, Jingyuan of Gansu Province, Shizuishan of Ningxia, Yaojie of Qinghai Province, Hami of Xinjiang, and Baotou and Wuhai of Inner Mongolia.

Although China's drylands have a long history of development of coal resources, the exploitation of coal is relatively small scale due to traditional and low–technology methods. For instance, in 1995, the output of coal from the drylands was only 170.38 million tons, or 13.19% of the total national production. Of that production, 64.45 million tons were from Inner Mongolia, 39.57 million tons from Shaanxi, 26.93 million tons from Xinjiang, 22.09 million tons from Gansu, 14.46 million tons from Ningxia and 2.88 million tons from Qinghai. Overall, the supply of coal resources in the drylands exceeds demand. However, there is an obvious difference between supply and demand in the different provinces and autonomous regions in the drylands. In Gansu and Qinghai provinces, coal production cannot meet the local demand, and some coal supplies need to be transported from other provinces. The need to import coal resources limits the economic growth in these regions (Table 3.37).

3.5.3.2 Oil resources

The oil resources in China's drylands are mainly stored in several large basins (Table 3.38), and have several main characteristics including:

(i) A large proportion of the total oil resources in China are found in the drylands. The total oil resources of China are 93.03 billion tons, while oil resources in the drylands are 30.497 billion tons, accounting for 32.78% of the total. The largest reserves in the drylands are found in the Tarim Basin in the Xinjiang Autonomous Region (10.76 billion tons), followed by the Junggar

Table 3.37 Production and sale status of coal supplies in the drylands of China

Program	Sale in the drylands							Sales country-wide	Drylands/ Entire nation (%)
	XJ	GS	IM	NX	QH	SHX	Total		
Production in 1995 (10^4 t)	2,693	2,209	6,445	1,446	288	3,957	17,038	129,208	13.19
Export (+) or import (–) quantity in 1995 (10^4 t)	+176	–389	+1,626	+486	–81	+662	2,480		
Export (+) or import (–) quantity in 1990 (10^4 t)	+170	–399	+729	+547	–164	+208	1,091		

XJ: Xinjiang; GS: Gansu; IM: Inner Mongolia; NX: Ningxia; QH: Qinghai; SHX: Sha'anxi.

Basin (6.935 billion tons) in Xinjiang and the Ordos Plateau Basin (6.195 billion tons) in Inner Mongolia. The Turpan-Hami Basin covers a smaller area, and its oil reserves are relatively small (1.575 billion tons).

(ii) The reserves which can be exploited in the near future in the drylands are approximately 2.054 billion tons, which is 37.42% of the total exploitable reserves of China. This proportion is larger than any other part of the country, which means the drylands are main focus for developing oil production.

(iii) The amount of the exploited oil is small, and the potential resources are huge. After nearly 50 years of exploitation, China's oil industry has produced 3.036 billion tons of oil, mainly from eastern China. Prior to 1996, only 238 million tons of oil has been exploited from the drylands, accounting for 7.84% of the national production.

Table 3.38 Oil reserves and production status in the drylands of China (Zhu, 1996c)

Name of the basin	TR (10^8 t)	DR (10^8 t)	AEQ (10^4 t)	EQ (10^8 t)
Tarim Basin	107.60	1.66	1,000	1.56
Junggar Basin	69.35	12.64	14,000	12.50
Turpan-Hami Basin	15.75	1.62	852	1.54
Ordos Plateau Basin	61.95	2.74	3,647	2.38
Hexi Corridor Alxa	37.07	Not sure	3,000	Not sure
Qaidam Basin	13.25	1.88	1,300	1.75
Total in drylands	304.97	20.54	23,799	19.73
National	930.32	52.6	303,600	22.24
drylands reserves/National reserves (%)	32.78	37.42	7.84	88.71

TR: Total resources; DR: Detected Reserve; AEQ: Accumulative exploited quantity; EQ: Exploitable quantity; The data are accurate as of 1996.

This means that oil production in the drylands is only a small proportion of the total oil production in China, but the drylands have an abundant oil reservoir and the proportion of the reserves is also high. The reserves are 2.054 billion tons, only 11.59% of the oil resources have been exploited, and 1.973 billion tons are retained for future exploitation. There is significant potential in the oil production in the drylands of China.

3.5.3.3 Natural gas (hydrocarbon) resources

Broadly speaking, natural gas refers to gas formed within the atmosphere and earth's crust, and includes nitrogen, carbon dioxide, hydrogen, helium and hydrocarbons. Commonly, the phrase "natural gas" refers specifically to hydrocarbon gas, and this is the definition used below.

Like the oil resources, natural gas is widely used in all aspects of daily living, not only in the energy sector, but also in chemistry and the military and it is one of the most popular energy sources for the reconstruction and development of the country.

Natural gas in China is mainly found in basins that have suitable conditions for oil and gas production. The basins where natural gas is found often share the same or similar geological characteristics with the basins storing oil resources. The natural gas in the drylands of China is mainly located in several large basins (Table 3.39).

Table 3.39 Natural gas resources and production status in the drylands of China (Zhu, 1996c)

Basin	TRA (10^8 m^3)	DER (10^8 m^3)	PQ (10^8 t)
Tarim Basin	83,896.2	971.6	1.31
Junggar Basin	12,289.0	1,031.55	10.52
Turpan-Hami Basin	3,650.2	217.42	2.3
Ordos Plateau Basin	41,797.4	1,363.15	1.03
Hexi Corridor Alxa	3,142.1		0.12
Qaidam Basin	2,937.6	580.24	1.27
Total in drylands	147,712.5	4,163.96	16.55
National resources	379,198.3	19,430.3	201.30
Drylands/Whole nation (%)	38.95	21.43	8.22

TRA: Total resource amount; DER: Detected exploitable reserve; PQ: Production quantity in 1996; The data are up to 1996.

Table 3.39 indicates that: (i) In China, a high proportion of the natural gas resources can be found in the drylands, with the total volume of natural gas estimated at 1,477.125 billion m^3, which accounts for 38.95% of the national resources; (ii) The natural gas resources in the drylands that are exploitable in the near future are about 416.396 billion m^3, which is the largest quantity of any area in the country, providing 21.43% of the exploitable natural gas in China; (iii) The Ordos Plateau Basin has the most abundant reserves (136.315 billion m^3), followed by the Junggar Basin (103.155 billion m^3) and the Tarim Basin (97.16 billion m^3). These regions will be the priority areas for natural gas development and exploitation in the future. The natural gas resources in the Hexi Corridor and in the Turpan-Hami Basin are comparatively scarce; therefore, they will be supplementary regions for gas development and exploitation in future.

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4 Sandy Deserts, Gobi, Sandlands and Sandified Land in Dryland

Xiaohui Yang, Huanshui Zhou, Sen Li and Kebin Zhang

In China, the areas of dryland and susceptible dryland (hyperarid area excluded) are 357.05 and 331.70 million ha, respectively (CCICCD, 1997;), and 263.62 million ha had suffered or were suffering from desertification, covering 12 main deserts and sandlands (Taklimakan Desert, Gurban Tonggut Desert, Kumtag Desert, the Deserts in Qaidam Basin, Badain Jaran Desert, Tengger Desert, Ulan Buh Desert, Qubqi Desert, Mu Us Sandland, Otindag Sandland, Horqin Sandland, and Hulun Buir Sandland.) (Zhu, 2006), in which majority is related to sand-covered land. In this chapter, we focus on the introduction of sandy deserts, Gobi, sandlands and sandified land in drylands.

4.1 General situation of sandy deserts, Gobi, sandlands and sandified land

China is one of the countries in the world most severely affected by desertification and sand encroachment (Zhu, 2006). The area of Gobi, sandy deserts, Gobi, sandlands and sandified land in China is about 1.688 million m^2, which covers 17.6% of the national territory. The drylands are mainly distributed in the interior basins and plateaus between 35°N and 50°N, forming a sandy desertification belt about 4,500 km long and up to 600 km wide. The western end is near the western Tarim Basin in Xinjiang, and the eastern end is on the western Songnen Plain. This vast region encompasses the three northern areas of China (northwest, north and northeast China). Isolated patches of sandified land are also distributed on the coastal, river and lake areas. Gobi is distributed in the high and cold area of the Qinghai-Tibetan Plateau (Fig. 4.1).

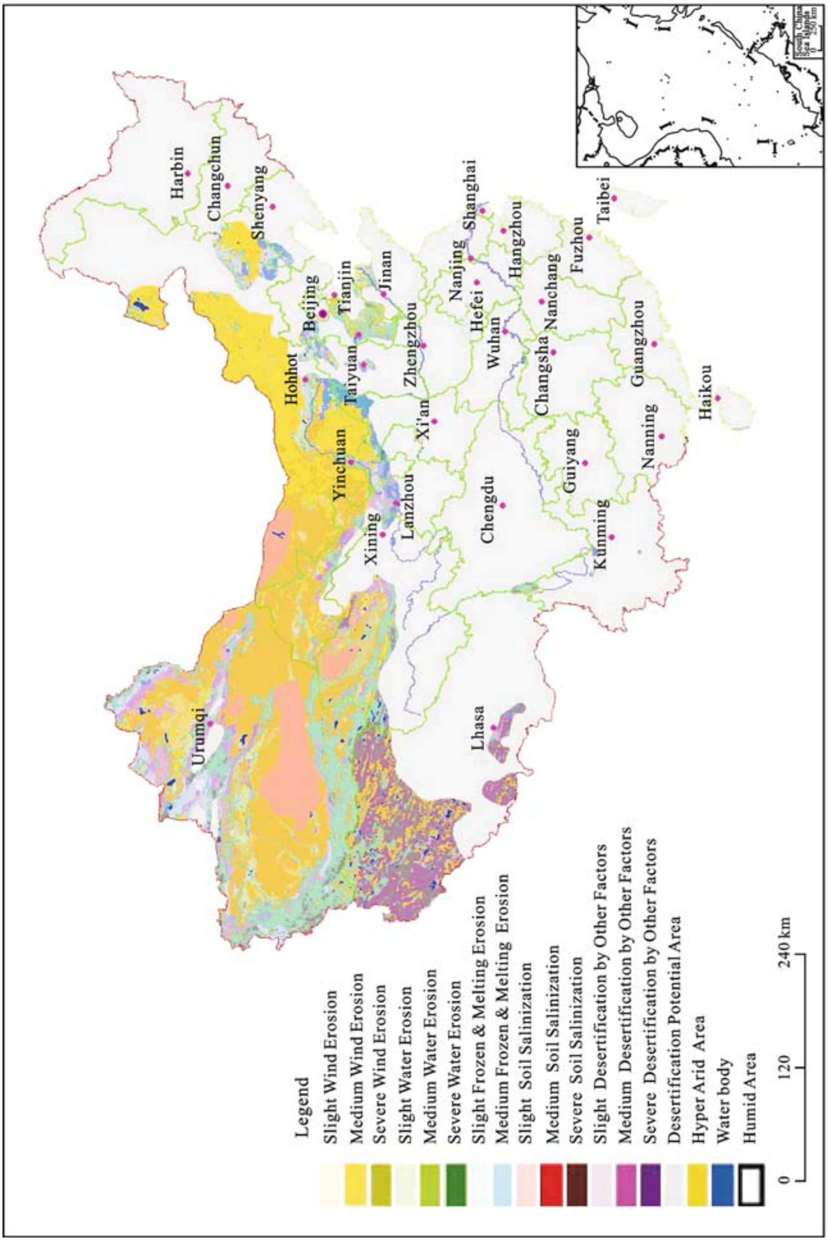

Fig. 4.1 Desertification distribution map in China (CCICCD, 1997; Yang et al., 2005, with permission from authors)

4.1.1 General distribution range of sandy deserts, Gobi, sandlands and sandified land

Sandy deserts, Gobi, sandlands and sandified land in different natural zones exhibit different manifestations of aeolian landforms.

North of the western desert region is the China-Mongolian boundary, to the south is the west end of the Yinshan Mountains, the Helan Mountains, Wuqiaoling Mountain, Qinghai Lake, west of Zhaling Lake and south of the Tianshan Mountains. This area contains several deserts including the Taklimakan, Kumtag, Qaidam, Badain Jaran, Tengger and Ulan Buh deserts. Its chief feature is the dry climate and recurring droughts. The average annual precipitation is below 250 mm and is extremely variable. Precipitation in some desert areas is only a few millimeters each year. The mobile dunes and longitudinal dunes are the most common dune forms on river banks, while in the sink area fixed or semi-fixed dunes are present, characterized by the high water table and the good vegetation growth.

North of the Tianshan Mountains in Xinjiang is the northeast sandy region, including the Gurban Tonggut Desert, Akkum Desert and Barikun Basin Desert. Although located in the arid zone belt, the seasonal distribution of precipitation is quite even, with snow occurring during winter and spring and rain in the summer. This moisture regime favors the development of fixed and semi-fixed dunes in this region.

Sandlands are also located in arid, semi-arid and dry sub-humid areas. Locations include the Songnen Sandland, Hulun Buir Sandland, Horqin Sandland, Otindag Sandland, Qubqi Desert, Mu Us Sandland, Ningxia Hedong Sandland, Qinghai Lake and Gonghe Basin. Here the wind-drift sand distribution is generally patchy, and the scale is small. Sand dunes are commonly interspersed with rivers, lakes and bogs. For example, there are dunes in the southeast of the eastern region, some paleochannels and floodplains on the Sanjiang Plain, Huang-Huai-Hai Plain and the middle and lower reaches Yangtze River Plain, as well as the seaside belt in some coastal provinces.

In summary, the sandy deserts, Gobi, sandlands and sandified land in China are broadly distributed, spanning many ecosystems and climatic zones. Their origin and the complexity of the landforms are unique in the world (Yang et al., 2008).

4.1.2 Distribution of sandy deserts, Gobi, sandlands and sandified land

Sandy deserts, Gobi, sandlands and sandified land in China (comprising 172,799,072 ha) are spread over 13 provinces or autonomous regions: Beijing, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Qinghai, Gansu, Shaanxi, Ningxia, Xinjiang and Tibet. The seven provinces or autonomous regions with the largest areas of sandy deserts, Gobi, sandlands and sandified land are, from largest to smallest, Xinjiang, Inner Mongolia, Tibet, Gansu, Qinghai, Shaanxi and Ningxia. The total area of sandy deserts, Gobi, sandlands and sandified land in these provinces includes 96.40% of the sandy deserts in China. The total area in the other provinces, autonomous regions and cities is 6,288,566 ha (3.60%).

The "Three North" Shelter Forest Project area is the central area of sandy deserts, Gobi and sandland in China. The project area includes 13 provinces or autonomous regions, which contain 551 counties. Sandy deserts, Gobi, sandlands and sandified land are found in 322 counties in this area. The total area is 1.48 million ha, accounting for 84.5% of the total area of sandy deserts, Gobi, sandlands and sandified land in China.

In the Inner Mongolia-Xinjiang Plateau area, sandy deserts, Gobi, sandlands and sandified land are mainly located in the Tarim Basin, Junggar Basin, and Turpan-Hami Basin of Xinjiang, stretching eastward across Gansu's Hexi Corridor, then north through Ningxia, reaching the western regions of the Yellow River valley, and western part of Inner Mongolia, reaching into the eastern part of the steppe zone, through northern Shanxi to the west of Jilin. The total area of sandy deserts, Gobi, sandlands and sandified land in this region is 1,296,000 ha.

In the Qinghai-Tibetan Plateau, sandy deserts, Gobi, sandlands and sandified land are found mainly in the Qaidam Basin of Qinghai Nali area, the northern part of the great Qiangtang Plateau of Tibet, the river valley of the "three rivers" in eastern Tibet, and the northwest Sichuan Plateaus. There is also a patchy distribution of other arid areas. The total area of sandy deserts, Gobi, sandlands and sandified land is 334,200 ha.

In the eastern region, sandified land of the river, lake and coastal areas, covers 57,600 ha, including the Songnen Plain, Huang-Huai-Hai Plain, Yellow River, Yangtze River and its branches, and other river deltas. Sandlands in the coastal area is mainly located in the coastal plains and coastal beaches, including Liaodong Beach, Changli and Shanhaiguan in Hebei, the Jiaodong Coast, Dongtai and Dafeng in Jiangsu, Putuo in Zhejiang, Changle and Jinjiang in Fujian, Leizhou in Guangdong, Beihai in Guangxi, and the Hainan Island. Sandlands in this area covers 10,100 ha.

The total length of China's sandy coastline is 3,216 km (18% of the national coastline) and mobile dunes occur on 585 km (18.47%), semi-fixed dunes on 584 km and fixed dunes on 1,671 km. The provinces with the longest sandy coastline are listed in descending order as Hainan (23.26%), Guangxi (21.27%), Guangdong (21.55%), Jiangsu (14.55%), Fujian (9.95%), Liaoning (4.10%), Shandong (3.67%), Hebei (1.2%) and Zhejiang (0.35%).

Sandified land in lake areas occurs on lakeside plains and along the lakeshore in areas like Poyang Lake and Dongting Lake which are primarily associated with lakeside plains. The total area of sandified land in lake areas is 108,020 ha (1.94%) in the humid and semi-humid region (Zhou et al., 2002).

Sandy desert and Gobi are mainly distributed in arid areas, sandlands are found in semi-arid and dry sub-humid areas and sandified land is found across all climatic zones from arid to humid zones in China (Yang et al., 2005).

4.1.3 Development trend and current situation of land sandification

Since the 1950s and 1960s, intense over-cutting and overgrazing have destroyed vegetation and caused the former semi-fixed and fixed dunes (sandland) to lose the protection of vegetation. The area of land degraded in this way totaled 3,294,293.5 ha (an increase of about 73,206 $ha \cdot a^{-1}$). However, measures such as artificial reforestation, grass plantation and grazing bans have worked to restore the land productivity, improve the ecological benefits of sandstorm control, resist the spread of shifting sand and reduce damage from sandstorms, by gradually fixing some shifting sand and helping some semi-fixed dunes become fixed. The treated area is 6,168,013.4 ha (which equates to a restoration rate of about 137,067 $ha \cdot a^{-1}$). Fortunately, now, the area where sandification is reversing is bigger than the area of sandification expansion in restoration areas. This shows that the area of sandification in these lands has reduced year by year, and that the land productivity is gradually being restored and improved. The physico-chemical properties of the soil in land where sandification has been reversed have not been essentially changed. The sandland ecological environment is still very fragile. If the vegetation is destroyed, the fixed sand will be become mobile again.

The sandification process is leading to a rapid increase in the area of newly sandified land, and is also causing the reactivation of fixed sand dunes. This means that more land will face the full impact of wind erosion, sand dunes will grow gradually and the productivity of the land will decrease and may even be completely lost. Eventually, the soil will be totally changed, leading to irreversible sandification.

According to the 1999 national desertification monitoring, the area of sandified land increased by 1,718,200 ha compared with 1994, which was an average rate of increase of 343,640 $ha \cdot a^{-1}$ (about 0.20%). This dynamic process mainly occurs in the 13 northern provinces and autonomous regions. According to case studies in 214 counties of 13 provinces and autonomous regions, the sandified land area increased by 149,590,981 ha. The areas of sandified land in Inner Mongolia, Gansu, Qinghai, Xinjiang, Tibet, Heilongjiang and Liaoning are enlarging at average annual rates of 0.86%, 0.08%, 0.21%, 0.003%, 0.2%, 0.2%, and 0.08%, respectively, whilst in Ningxia, Hebei, Shaanxi, Shanxi, Beijing, and Jilin there has been a slight decrease in the area of sandified land (generally less than 0.5%).

Sandification in Qinghai-Tibetan Plateau and Inner Mongolia-Xinjiang Plateau is increasing each year. The net rates of increase are 0.16% and 0.24%, respectively. For the 12 main deserts and sandlands, the Mu Us Sandland and the Horqin Sandland are reducing in area, and the others are increasing. In the Taklimakan Desert the yearly net expansion rate is 0.09%, the Gurban Tonggut Desert is 0.91%, Kumtag Desert is 0.001%, Qaidam Basin Desert is 0.05%, Badain Jaran Desert is 1.04%, Tengger Desert is 1.32%, Ulan Buh Desert is 1.78%, Qubqi Desert is 1.46%, Otindag Sandland is 1.84%, Hulun Buir Sandland is 0.67%, Mu Us Sandland is –0.03%, and Horqin Sandland is –0.65%.

4.2 Sandy deserts, Gobi and sandified land in Xinjiang Uygur Autonomous Region

The sandy deserts, Gobi and sandified land in Xinjiang can be found in 80 counties with a north-south area covering 1,200 km from 47°30′ N in the southern Altai mountains to 36°20′ N in the north of the Kunlun Mountain, and an east-west area covering 1,700 km from 96°21′ E near the border with Gansu Province and the China-Mongolian border to 75°50′ E connecting with the Kazakhstan desert.

4.2.1 Sandy deserts, Gobi and sandified land status and distribution

4.2.1.1 Type and area of sandy deserts, Gobi and sandified land

Xinjiang's sandy deserts, Gobi and sandified land areas cover 76,920,460.3 ha, of which wind eroded relic hill areas are 928,980.8 ha (1.21%), Gobi is 32,808,486.3 ha (42.65%), sandy deserts cover 34,929,174.8 ha (45.41%), and sandified land is 8,253,818.4 ha (10.73%).

Sandy deserts and sandified land cover 43,182,993.2 ha, of which mobile dunes are 32,116,354.4 ha (74.37% of the total area), semi-fixed sand dunes are 8,419,937.9 ha (19.50%), fixed dunes are 2,527,715.5 ha (5.85%); non-bioengineered control sand is 70,314.9 ha (0.16%), bare sand is 46,620.2 ha (0.11%) and sandified cropland is 2,050.3 ha (0.01%).

4.2.1.2 Distribution of sandy deserts, Gobi and sandified land

Xinjiang can be divided into four regions with total area of 67,465,844.0 ha (87.7% of total sandy deserts and sandified land areas). Patchy areas of sandy deserts and sandified land in the other parts of Xinjiang occupy 9,454,616.3 ha (12.3% of the total area).

(i) Sandy deserts, Gobi and sandified land in northern Xinjiang

The Gurban Tonggut Desert of the Junggar Basin is a desert in the northern Xinjiang arid zone. It covers six administrative prefectures, four cities and 36 counties. In this region, there are five main sandy deserts: the Gurban Tonggut Desert, Burqin-Haba River-Jimunai Desert, Fuhai-Fuyun Desert, Wusu Desert, and Takeermohuer Desert.

i) Gurban Tonggut Desert

The Gurban Tonggut Desert is located in the middle of the Junggar Basin, and is China's second largest desert. Its total area is 8,225,224.9 ha. There are 384,189.6 ha of mobile dunes, 3,592,253.9 ha of semi-fixed dunes, 802,629.4 ha of fixed dunes 1,795.0 ha of sandified farmland and 353.7 ha of bare sand, Gobi covers 3,374,436.6 ha (41.03%), and wind eroded relic hills are 66,751.5 ha (0.81%).

The Gurban Tonggut Sandy Desert consists of four main components. To the east of Qitai is the Huojingnielixin Sandy Desert located in the Junggar Plateau Corridor in a belt 220 km long and 40–50 km wide. The main body of the Gurban Tonggut Desert extends south of the three spring wadis. This desert is about 200 km long and 135 km wide. The Suobuguerbugelai Desert is located between the west bank of the Manas River and the east bank of Kuitun River. The Kuobubei-Akekumu Desert is located to the north of the three spring wadis.

The Gurban Tonggut Desert has a reasonable amount of precipitation, up to 70–150 $mm \cdot a^{-1}$, which falls mainly as snow. Snow falls on average about 30 days per year and the land remains snow covered for 100–160 days to a depth of more than 20 cm. Annual evaporation is 1,400–2,000 mm and the aridity index is 2–10. The spring rain promotes a vigorous growth of ephemeral plants and vegetation coverage is greater than 50%.

There are many plant resources in the desert, including *Haloxylon ammodendron*, *Ephedra distachya*, *Hedysarum scoparium*, *Calligonum mongolicum*, *Haloxylon persicum*, *Artemisia santolina* and many kinds of ephemeral plants such as *Portulaca grandiflora* and *Eremosparton songoricum*.

The Gurban Tonggut Desert has a fairly simple landform pattern, which consists of tree-like dune ridges in the middle and northern parts and honeycomb sand dunes in the south. The dune height is generally 10–30 m, the ridge height of the sand dune chains is 5–8 m, and the vertical sand dunes are about 20 m high. There are fixed and semi-fixed dunes with heights of 2–4 m at the edge of the desert.

ii) Burqin–Haba River–Jimunai Desert

Burqin–Haba River–Jimunai Desert is located in the northwest of the Junggar Basin, the west of Burqin County and both sides of the Irtysh River. Its total area is 858,898.0 ha, of which mobile dunes are 105,383 ha (12.27%), fixed dunes are 166,054 ha (19.33%), semi-fixed dunes are 202,356 ha (23.56%), Gobi is 366,215 ha (42.64%) and wind eroded hills are 18,890 ha (2.20%).

In this region, the Kumtag and Tazikumu Deserts are located at the tilt tableland of the northern foothills of Sawuer Mountain, and these deserts mainly consist of crescent shaped (or barchan) dunes and dune chains. The Tunkekumu and Akekumu Deserts are located on the hilly piedmont slope of the Altai Mountains and there are sand ridges 50 m high in the foothill belt.

The mobile dunes are on the piedmont pitch and the higher elevation terraces. Because of the northwest wind in the river valleys in winter and spring, snow cannot accumulate on the ground surface. Ephemeral plants that normally depend on snow-melt water cannot grow, and shrub survival is also difficult, making the sand dunes bare and quite mobile. Generally, the height is 10–20 m, with some as high as 50–100 m. Vegetation is sparse, with only a few *Phragmites communis*, *Phragmites communis* and *Allium mongolicum* on the windward and leeward slopes; *Calligonum* spp. on the windward slopes of the low mobile dunes, and *Artemisa arenaria*, *Stipa tianschanica* and *Inula aspera* on the flat interdunes. The fixed and semi-fixed sandy mounds of the Irtysh River terraces have a height of 3–5 m, and are covered with *Populus euphratica*, *Salix cinerea*, *Halimodendron halodendron* and *Atraphaxis jrtyschensis*.

iii) Fuhai-Fuyun Desert

The Fuhai-Fuyun Desert is located between the Irtysh and Ulungur Rivers to the east of Buluntuo Lake. It includes Fuhai Desert and desert between two rivers in the south of Fuyun County. The total area is 1,268,780 ha, in which Gobi covers in 1,195,862 ha (94.25%), fixed dunes cover 20,259 ha (1.60%) and semi-fixed dunes cover 52,659 ha (4.15%).

iv) Wusu Desert

The Wusu Desert is located to the northwest of the Junggar Basin, between the Guertu and Kuitun Rivers, and the southeast part of marshland around the Aibi Lake. Its total area is 786,380 ha, of which Gobi covers 566,481 ha (72.04%), mobile dunes cover 69,122 ha (8.79%), fixed dunes cover 70,070 ha (8.91%), and semi-fixed dunes cover 80,707 ha (10.26%). The sand ridges are generally 10–15 m high and some can reach 35 m high. The ridge tops are bare and *Haloxylon persicum*, *Calligonum mongolicum* and *Artemisia santolina* can be found on gentle west-facing slopes while on the leeward slopes there are many ephemeral plants such as *Semen trigonellae*. Ephemeral plants, desert lichens and desert shrubs can also be found on the low-lying sand ridges, and include *Haloxylon persicum*, *Artemisia vulgaris*, *Haloxylon ammodendron*, *Reaumuria soongarica*, and *Anabasis aphylla*.

v) Takeermohuer Desert

The Takeermohuer Desert is in the northwest of Huocheng County. It meets the old Huocheng city in the north, the bank of the Yili River to the south, and extends along the Yili River of Chabuchaer County. It consists of two desert patches, the Takeermohuer Desert and the Bajitai Desert. It covers about 40 km wide and 15–40 km long with the desert area covering 46,720 ha. The fixed dunes cover 11,380 ha (24.36%), semi-fixed dunes cover

34,408 ha (73.65%), and Gobi covers 932 ha (1.99%).

(ii) Sandy deserts, Gobi and sandified region in southern Xinjiang

This region is located in the Tarim Basin. The Tarim Basin is an enclosed inland basin, surrounded by mountains on three sides. It has an arid climate with great temperature fluctuations. It is one of the most arid regions in China. There are 40 counties in this region.

i) Taklimakan Desert

The Taklimakan Desert is located in the warm arid region with altitude of 800–2,500 m. The Taklimakan Desert, in the center of the Tarim Basin, is the largest mobile sandy desert in China. It includes the Kuluke Desert in the west of Lop Nor and the lower reaches of the Tarim River; the Alakumu Desert in the north Altun Mountain and south Qiemo River; the Tuokelake Desert; and the Buguli Desert in the delta plain of the Kashi River. The total area of the main body of the Taklimakan Desert is 41,088,083.9 ha. Mobile dunes cover 29,431,000.4 ha (71.63%), Gobi covers 6,035,567.1 ha (14.69%), abandoned cropland covers 135.3 ha, bare sand covers 13,444.5 ha (0.03%), and wind eroded hills cover 52,203.6 ha (0.13%).

In the Taklimakan Desert, the sand dunes are large with complex shapes and a general trend of low sand dunes (less than 25 m) near the desert margins, and high dunes (50–80 m) in the interior, with a few as high as 200–300 m. Using the Keliya River as a boundary, there are large, complex northeast-southwest sand ridges in the east, and barchan dunes, barchan dune chains and complex sand dune chains in the west. In the north of the Mazhatage Mountain, the sand dune types from north to south are sand mounds, barchan dunes and barchan dune chains, fish scale sand dunes and complex barchan dune chains. There are quaquaversal sand dunes and complex barchan dunes downstream of the Tarim River, the Keliya River and the old Tarim River bed, and there are pyramid sand dunes in the Qiemo-Yutian region.

Green corridors are formed by the rivers downstream of the Tarim, Niya, Hetian and Qiemo Rivers in the Taklimakan Desert, with many fixed and semi-fixed sand dunes located along them.

ii) Akebiele Desert

The Akebiele Desert is located to the east and south of Bositeng Lake, and consists of the Akebiele Desert and the Maertazining Desert, with a total area of 643,477 ha. Gobi covers 517,694 ha (80.45%), mobile dunes cover 64,712 ha (10.06%), fixed dunes cover 17,697 ha (2.75%), semi-fixed dunes cover 43,254 ha (6.72%), and abandoned cropland is 120 ha(0.02%). The Akebiele Desert is 75 km long and 3–10 km wide on average, and stretches from Ahongkailedi to the southeast of Bositeng Lake. The Maertazining Desert goes from the southeast to the north along eastern shore of the Bositeng Lake, and is 20 km long and 4 km wide on average.

Sand dunes to the southeast of Bositeng Lake are mainly pyramid shaped and ridge shaped with heights of 100–150 m. To the south of the lake the dunes are mainly barchan dune chains 40–150 m high and 1–2 km wide.

(iii) Kashun Deserts, Gobi and sandified region

The Kashun desert, Gobi and sandified region is located in the east of Xinjiang in the Turpan-Hami Basin of the eastern Tianshan Mountains, in the Kashun arid denudation mountains and the Lop Nor marshland in the southeast of Xinjiang. The area has an arid climate with little precipitation and frequent sandstorms due to scarce vegetation in the grasslands, low mountains, Gobi and deserts. Its administrative areas include Turpan and Hami, and include the Kumtag Desert and the Shanshan-Kumtag Desert.

i) Kumtag Desert

The Kumtag Desert is located in the eastern part of the Tarim Basin, and southeast of Lop Nor, north of Altun Mountain, in the east it extends to Dunhuang in Gansu Province. Its total area is 6,972,489.2 ha, of which Gobi covers 4,743.287.5 ha (68.03%), mobile dunes cover 1,559,325.4 ha (22.36%), and wind eroded hills cover 669,876.3 ha (9.61%).

This desert lies in an inland area with a hyper-arid climate, and the natural environment is extremely harsh with a mean annual precipitation below 10 mm. The desert was formed by deposition of materials blown from neighboring areas. The Kumtag Desert consists mainly of feather-like sand dunes, and pyramid and barchan dune chains. The relative height of the dunes is 100–200 m and the highest is 300 m, with the majority of these sand dunes located in a rocky mountainous region with an elevation of 1,250–2,000 m, and on ancient diluvial-alluvial plains.

ii) Shanshan-Kumtag Desert

The Shanshan-Kumtag Desert is located in the Turpan Basin, mainly in Shanshan County. Its area is 4,072,277 ha, in which Gobi covers 3,743,109 ha (91.92%), mobile dunes cover 221,859 ha (5.45%), fixed dunes cover 420 ha (0.01%), semi-fixed dunes cover 7,773 ha (0.19%) and wind eroded hills cover 99,116 ha (2.43%).

Dense sand dunes now cover the whole region except the center Youkelake rock area, formed by the combination of prevailing winds from the northeast and northwest and rich wind-eroded fine material from diluvium and deposition. In the north, the desert mainly consists of sand ridges, which are 15–20 m high, and pyramid sand dunes are formed in the south and northeast. The desert is very arid, and there are only a few plants such as *Tamarix chinensis* and *Alhagi pseudalhagi* at the edge of desert. The desert is mainly moving to the south, which is not damaging the Shanshan oasis.

(iv) Kunlun Mountain alpine deserts and sandified region

In general, the Kunlun Mountains are a desert and semi-desert mountain range with low precipitation and a dry and cold climate year round. The deserts and sandified region are concentrated in the Kumukuli Basin, and the administrative areas include the whole of Tashikuergan County, and mountain regions of Ruoqiang, Qiemo, Minfeng, Yutian, Cele, Hetian, Pishan and Yecheng counties.

The Kumukuli Desert, located in the Kumukuli Basin in the eastern

Kunlun Mountains, has a total area of 3,503,514 ha, in which Gobi covers 3,180,962 ha (90.79%), mobile dunes cover 190,361 ha (5.44%) and semi-fixed dunes cover 132,191 ha (3.77%). The elevation is 3,900–5,100 m, making this the highest desert in China. The Kumukuli Desert is an alpine desert, and has a cold, dry climate with annual precipitation of 240 mm, mainly falling in April, July and August. The annual mean temperature is 0–1 ℃. The prevailing wind is westerly (80% of the time), and the maximum wind speed can reach 8 $m \cdot s^{-1}$ in March and April. The desert plants are scarce, and common plants include *Oxytropis aciphylla*, *Salsola collina*, *Stipa* spp., and *Carex moocroftii*.

(v) Sporadic deserts and sandified land

The total area of sporadic deserts and sandified land in Xinjiang is 9,454,616.3 ha, of which Gobi covers 9,083,940.1 ha (96.08%), mobile dunes cover 90,402 ha (0.96%,), fixed dunes cover 64,103.8 ha (0.68%), semi-fixed dunes cover 158,373.5 ha (1.67%), non-bioengineered fixed sand covers 2,831.5 ha (0.03%), bare sandland covers 32,822 ha (0.35%) and wind eroded hillock covers 22,143.4 ha (0.23%).

4.2.2 Effects of sandification

(i) Changes to river flows and lakes

In the 1950s, Xinjiang had 52 lakes covering more than 5 km^2 each, and total lake area was 9,700 km^2. By the late 1970s, the lake area had declined sharply to 4,748 km^2. The famous Lop Nur, Manas, Aiding, and Taitema Lakes had dried up. The area of the Ulungur, Bositeng, and Aibi Lakes had also declined sharply. The amount of water in the Tarim River reduced year by year, and the Kashgar River ceased flowing into the Tarim River in 1990. In the 1950s, the Yarkant River had an annual water volume of 1.0–1.5 billion m^3 flowing into the Tarim River but as a result of dam construction in its upper reaches, no water has flowed into the Tarim River since 1979.

The annual mean water volume of the Hetian River flowing into the Tarim River was 1.1–1.2 billion m^3 in the 1950s but since the 1980s it has reduced to an average 0.8 billion m^3 with only 0.04 billion m^3 in one year. The Tarim River, the longest inland river in China, has been dry for more than ten years in the lower reaches from Daxihaizi, and in these areas, vegetation has declined, the sandification of "the green corridor" has become more serious and 160 km of river course has been buried by sand.

"The green corridor" of the lower reaches of the Tarim River is located between the Taklimakan and Kuluke Deserts, and is the second most important corridor from Xinjiang to Qinghai and inland, and is also another shortcut to the southern edge of the Tarim Basin. Its strategic position is very important. Before the 1920s, "the green corridor" had been prosperous. At that time, the water volume in the Tarim River was high, and there were abundant aquatic plants along both banks. As a result of a change to the river course in the mid-1920s, the corridor habitat deteriorated. The Luntai Dam was constructed in the Layin River estuary in Weili County in 1952, and river water was forced to flow into Taitema Lake, restoring the corridor habitat. By the 1970s, construction of the Daxihaizi Reservoir reduced the flow of the Tarim River, and the groundwater level dropped rapidly, *Populus euphratica* forest degraded at a large scale, pasture became seriously degraded, and sandification developed rapidly in the corridor. In the Alagan region there were almost no blown sand events 100 years ago, and good quality natural pastures were common 40 years ago. After the Tarim River dried up in 1972, irrigation ceased and the area of abandoned farmland increased rapidly. Due to shrub over-cutting outside the farming area, the originally fixed and semi-fixed dunes reactivated and encroached on farmland in five farms. At the same time, part of the farmland was abandoned because of water scarcity, and the loose ground surface formed the sandified land. It is estimated that more than 8,600 ha of farmland was abandoned or left uncultivated, of which nearly 2,000 ha was buried by the shifting sand.

(ii) Degradation of vegetation and expansion of sandified land

The Tarim River area is China's largest and the most concentrated area of *Populus euphratica* forest. In the 19th century it was described as "dense trees make beautiful forest" and "flourishing forest". In 1958, the Tarim River watershed had 400,000 ha of *Populus euphratica* forest, but by the 1990s it was found that only 358,000 ha remained. In the Bayinguoleng region, about 10,000 t of *Glycyrrhiza glabra* was dug up each year, leading to the destruction of 110,000 ha of vegetation in the middle and lower reaches of Tarim River, and sandification of the area. The Hetian area suffers from a shortage of energy, so fuelwood was supplied from the *Populus euphratica* forest and desert forests. In just three counties (Hetian, Moyu and Luopu), fuelwood collection was 300,000 t each year, resulting in a large area of barren land.

(iii) Sandification of artificial oases

During development of artificial oases, people destroy the forest, exploit wastelands, and transform grassland into farmland. Because of the scarcity of water resources for irrigation, some arable land had to be abandoned soon after ploughing. Because of vegetation destruction and the vulnerable surface soil exposed to wind erosion, most abandoned cropland became sandified land.

The Hetian region, at the southern edge of the Taklimakan Desert, is a typical example of oasis agriculture in a sandy desert region. There are hundreds of pieces of oasis of different sizes which form an oasis belt about 600 km long from west to east. There is about a 2,000 km belt of wind eroded landscape and Gobi around these oases.

In Pishan County, for example, there are 53 pieces of oasis within a perimeter of 516 km. Here, the forest area is 1,340,000 ha, and the desert area is 11,669,000 ha. Because the oasis area is small and fragmented, and the surrounding desert vegetation has been almost destroyed, there is now no buffer zone between the artificial oasis and the mobile desert. The invasion of shifting sand into the oasis has interfered with agricultural production and animal husbandry at the edge of the oasis and also adversely affected people's lives. Since 1949, about 28,000 ha farmland within the oasis area has been degraded. In mid-May 1986, a strong wind damaged more than 90% of the cotton fields including 50% of the fields in the area in the center of the oasis.

(iv) Disruption to industrial and agricultural production

Blown sand events are the biggest natural disasters in Xinjiang. For example, a cold air and sand-dust storm swept across more than 60 counties in 13 regions on April 9–11th 1979, and the wind force reached 8–9 on the Beaufort scale and as high as 12 in some areas. In eastern and southern Xinjiang, more than 30 counties were affected by the strong winds on May 17–20th 1986, 153,000 ha farmland was affected severely, 16 people died, 94,000 head of livestock died or were lost, and 800,000 trees, 3,000 telephone poles and nearly 2,000 houses were blown down.

The Turpan Basin has special topographical features and climate characteristics, and is one of the areas most seriously affected by sand-dust storm in Xinjiang. On April 24th 1984, a sand-dust storm destroyed 1,334 ha farmland in Turpan, affecting 17.6% of the sown area. The sand buried 69 qanats, obstructed 63,850 m of irrigation channels, killed 132 head of livestock, 90 houses collapsed, 88,000 m forest belts were buried by sand and 23,820 trees were blown down.

(v) Sand dunes reactivated and moving along the traffic lines

Road construction often destroys vegetation, causing the fixed and semi-fixed sand dunes to reactivate, which in turn endangers the roads. In the windy season of 1987, 95 road surfaces accumulated sand over a length of 100 km from Alagan to Luobuzhuang on the Kuruo highway, and six areas were completely buried by sand which seriously affected transportation.

At the southern edge of the Taklimakan Desert, a 350 km section of national highway No.315 from Qiemo to Ruoqiang is affected by serious shifting sand which endangers more than 40 km of this road. For example, about 17 km long between milestones 32 and 49, southeast of Qiemo County where the road is threatened by mobile barchan dunes that bury the road.

The Alakumu Desert moves from northeast to west, and forms several shifting sand belts which go straight to the nearby Cheerchen River. Barchan dunes and barchan dune chains move to the southwest with annual speed of 49 m and the mobile sand dunes have reached the highway in five places affecting 4.05 km of highways within Qiemo County. In the 180 km stretch from Qiemo to the Andier River, three mobile sand belts are encountered. There are mobile sands covering on the road surface in many places.

Soon after development, the Hami section of the Lanzhou-Xinjiang railway was seriously affected by sand movement. Since late 1970s, damage to the railroad from shifting sand has occurred again because the land surface and its vegetation were destroyed by digging licorice in the previously stable

Gobi on the both sides of the railway. When a strong wind occurs, sand-dust storms become more serious. On May 19–20th, 1986, a grade 12 wind (on the Beaufort scale) blew for 28 hours which led to serious sand accumulation in 59 places over a total length of 40.7 km with a sand volume of 74,918 m^3. Some equipment was destroyed and the railway transportation system was interrupted for two days, causing serious economic loss.

The railway is endangered by shifting sands in the Hami region, especially from Hexi station to Yaziquan station with total length of 259.9 km and 130.8 km from Yanquan to Hexi which comprises stone Gobi. All these areas are at risk from varying degrees of sand damage over a total distance of 226.1 km.

(vi) Dry and hot winds

The main crops in Xinjiang that suffer from dry and hot winds are wheat, cotton and corn. Because of the high temperature and high evapotranspiration rates, the plant root systems cannot meet the transpiration needs and the crop's physiological balance cannot be maintained. This leads to crop withering and atmospheric droughts. When the wind speed is $> 4\ m \cdot s^{-1}$ the damage is greater. These high wind speeds are common: in the Turpan Basin they occur, on average, 40 days per year; and in the Hami Basin they occur approximately 10 days per year. Therefore, dry and hot wind weather is one of main meteorological disasters that affect high value and stable crop production in this area. For example, in Tuokexun County, on June 4th 1978, a strong dry and hot wind blew for 20 hours over the whole county and about half the crop (1,000 t) was lost. The dry and hot wind is a widespread natural disaster in the Tianshan area in northern Xinjiang from May to August every year, where it causes damage during the crop growing season. Dry and hot wind can burn crop stems and leaves, cause seeds to wither and have the overall effect of decreasing yield. In July, 1989, Urumqi County, for example, 500,000 kg of wheat was lost because of the dry and hot wind.

Drought is also a common natural disaster in the northern Xinjiang deserts and sandified regior desert area. Especially during May and June, drought can cause extensive yield reductions to agricultural production. During 1960 and 1961, in the Yili, Tacheng, Bole and Changji regions, about 87,000 ha farmland was affected by serious drought; in the Miquan region, 929 ha was affected by drought in 1962, of which 392 ha suffered total crop failure; 5,179 ha was drought affected in Urumqi County also in 1962; in 1963 about 53,000 ha in the Altai, Yili and Changji regions were affected by drought; in 1974 the Altai and Tacheng area suffered from a drought affecting 80,000 ha, with a greater than 50% reduction in yield; in 1977 24,000 ha in Changji and Shihezi were affected by drought; in 1982, the Yili area was affected by drought covering an area of 67,000 ha, and reducing grain production by 50 million kg; in 1985 Yiwu County had a drought that resulted in the deaths of 9,331 head of livestock; and in 1989, drought in Balikun affected 14,000 ha and crop production was reduced by 20 million kg with a direct and indirect economic loss of 25,000,000 RMB.

4.3 Inner Mongolia Autonomous Region

The Inner Mongolia Autonomous Region is located along the northern border of China, with the exception of the northern Da Xing'anling Mountains in the east of the autonomous region. The majority of the region is located in the center of the arid and semi-arid region. From west to east there are five major deserts, which are the Badain Jaran, Tengger, Bayinwenduer, Ulan Buh and Qubqi Deserts, and five sandlands which are the Mu Us, Otindag, Wuzhumuqin, Horqin and Hulun Buir Sandlands. There are also large areas of wind eroded sandified land north of the Yinshan Mountains. Some fragmentary sandified lands are also distributed around these deserts and sandlands. Desert and sandland region are the predominant eight leagues, four cities and 76 banners or counties covering a total area of 74,186,594.2 ha, or 62.7% of the total area of the autonomous region.

4.3.1 Present situation, type and areas of deserts, Gobi, sandland and sandified land

4.3.1.1 Types and areas of deserts, Gobi, sandland and sandified land

The total area of deserts, Gobi, sandland and sandified land in Inner Mongolia is 35,551,035.0 ha, of which deserts occupy 10,791,957.0 ha, accounting for 30.4% of the deserts, sandlands and sandified land in the region; Gobi occupies 6,541,908.0 ha (or 18.4%); wind eroded monadnocks covers 151,166 ha (or 0.4%); and sandlands cover 18,066,004.0 ha (or 50.8%). Within the deserts, sandlands and sandified land, the mobile dune area is 9,223,690.0 ha (25.9%), the semi-fixed dune area is 3,013,934.9 ha (8.5%), the fixed dune area is 11,666,627.6 ha (32.8%), abandoned farmland covers 4,404 ha (0.01%), and bare sand covers 4,949,304.5 ha (13.9%).

In the fixed and semi-fixed deserts, sandlands and sandified land, dunes fixed by trees cover 1,234,368.8 ha, (or 8.4%), dunes fixed by shrubs occupy 2,421,115.8 ha (16.5%), and dunes fixed by herbage cover 11,025,077.9 ha (75.1%). Of the fixed and semi-fixed dunes with trees, artificial forest is 744,495.8 ha, natural forest is 489,833.0 ha, and the air seeding area is 40.0 ha. In the areas of dunes fixed by shrubs, the artificial plantings are 778,277.0 ha, the natural plantings are 1,624,751.8 ha, and the air seeding area is 18,087.0 ha. In the herbage fixed and semi-fixed dunes, artificial plantings cover 229,507 ha, natural plantings cover 10,778,315.9 ha, and the air seeding area is 17,255.0 ha.

4.3.1.2 Distribution of deserts, sandlands and sandified land

Inner Mongolia has a vast territory with diverse natural and social conditions, and this diversity is also reflected in the distribution of land resources. The Inner Mongolian deserts, sandlands and sandified land can be divided into 4 regions according to the type of deserts, sandlands and sandified land, climate and landform conditions.

(i) West of Da Xing'anling Mountains, east of Helan-Zhuozi Mountains and north of Yinshan Mountains

In this region, the deserts, sandlands and sandified land area is 5,147,754.2 ha, occupying 14.5% of the total area of deserts, sandlands and sandified land in Inner Mongolia. In this area there are the Hulun Buir Sandland, the Wuzhumuqin Sandland, Otindag Sandland and the 12 banners wind eroded sandified area (also called the north Wumeng league area) in the north of the Yinshan Mountains. The total area of mobile dunes is 51,049 ha (1.0%), Gobi covers 2,023 ha (0.4%), and bare sand covers 1,439,512.5 ha (28.0%). In addition, abandoned farmland occupies 3,354 ha and wind eroded monadnock covers 132.0 ha.

(ii) Liaohe River Plain

The Horqin Sandland is located within the Liaohe River Plain which is south of the Da Xing'anling Mountains. The sandified land area is 4,820,873.0 ha, 13.6% of the entire deserts, sandlands and sandified land in Inner Mongolia. Fixed dunes cover 3,051,825 ha (63.3% of desertified land in this area), semi-fixed dunes cover 582,798 ha (12.1%), mobile dunes cover 420,244 ha (8.7%), abandoned farmland is 1,050 ha (0.02%), and bare sand is 764,956 ha (15.9%).

(iii) Ordos Plateau

The deserts, sandlands and sandified land area in this region is 5,818,400.0 ha, occupying 16.4% of the total deserts, sandlands and sandified land area in Inner Mongolia, the Mu Us Sandland and Qubqi Desert distribute in this region. Fixed dunes are the main landform type in the Mu Us Sandland with an area of 2,922,728 ha. Mobile dunes cover 710,409 ha, semi-fixed dunes cover 185,271 ha and bare sand covers 123,415 ha. The Qubqi Desert has a larger area of mobile dunes occupying about 907,426 ha, the fixed dunes cover 776,831 ha, semi-fixed dunes cover 167,528 ha, wind eroded monadnocks cover 3,604 ha, and bare sand covers 21,188 ha.

(iv) Alxa Plateau and west Wulanchabu Plateau, west of the Helan and Zhuozi mountains

This area encompasses the largest area of deserts and Gobi in Inner Mongolia. Deserts, Gobi, and sandified land account for 14,337,827 ha (40.3% of the deserts, Gobi, sandlands and sandified land area in Inner Mongolia). There are several sandy deserts: the Ulan Buh, Bayinwenduer, Tengger and Badain Jaran Deserts. Mobile dunes are the main landform type, followed by Gobi. Mobile dunes cover 7,051,734 ha (49.2% of this area), Gobi covers 3,665,496 ha (25.6%), semi-fixed dunes cover 1,542,180 ha (10.8%), fixed dunes cover 1,313,754 ha (9.2%), wind eroded monadnocks cover 147,430 ha (1.0%), and bare sand covers 617,233 ha (4.3%).

The Badain Jaran Desert is the biggest desert in the Inner Mongolia. The geographic coordinates are 39°28′–40°58′N, 99°20′–100°08′E. The total desert area is 703,000 ha, the mobile sandy dunes have an area of 194,975.4 ha, the non-bioengineered sand control area is 118 ha, and Gobi covers 340,689.2 ha. The main characteristics of the Badain Jaran Desert are the large sand mountains, and the dense distribution of dunes. There are crescent sand dune chains around the big sand mountains, with a height of 20–50 m.

There are also fragmentary sandified lands located at the periphery of the main sandy desert regions, with a sandified area of 5,426,180.8 ha (15.3% of the entire deserts, Gobi, sandlands and sandified land area in Inner Mongolia). Gobi is the main landform with an area of 2,856,129 ha. It is mainly located to the west of the Ejina Qi in the Alxa League. Other landforms are fixed dunes occupying 373,677.8 ha (6.9%), semi-fixed dunes occupy 130,546 ha (2.4%), mobile dunes cover 82,828 ha (1.5%), and bare sand covers 1,983,000 ha (36.5%).

4.3.2 Effects of sandification

Damage caused by sandification is the main constraint in this region on economic development. Almost 50% of the poor people in Inner Mongolia live in deserts, Gobi, sandlands and sandified land areas and sandification threaten agriculture and animal husbandry, and also puts cities, villages, communication lines and water conservation systems at risk. About 3,000 km of railway pass through the deserts, Gobi, sandlands and sandified land region of Inner Mongolia and there are also extensive highways. The Wuda to Jilantai railway is 131.7 km long and the sand-damaged section is 89.7 km. Derailments occurred 22 times from 1967 to 1982 because of sand on the tracks. In the old city of Sunite Zuo Banner, more than 500 houses were buried, compelling the banner government to relocate. On May 5th 1993, 100% of the pastures of Alxa League were affected by a strong sand-dust storm which caused a loss of forage amounting to 1,320,000 t. This storm also buried or destroyed 35,000 ha crops, killed 8,000 head of livestock, buried more than 80 irrigation wells, damaged more than 100 sections of road and destroyed more than 200 livestock sheds and 100 houses. The direct economic loss from this storm was 176,000,000 RMB. The annual direct economic loss in the whole Inner Mongolia which is caused by blown sand disaster was estimated at 6,970,000,000 RMB.

Some areas, such as Ulan Buh Desert, suffered from shifting sand as early as the late 10th century A.D. In 981 A.D., during the North Song Dynasty, official records show that “the sand was 3 feet deep, the horse cannot go through, travelers all rode on camel”. In 1926, Mr. Feng Yuxiang built a road from Yinchuan to Baotou which passed through Dengkou. The shifting sand was still 3–4 kilometers away from Dengkou town. After 1937, all the roads were cut off completely by the sand making them impassable to vehicles. The shifting sand has reached the river bank in many places, and by 1958, during construction of the Baotou-Lanzhou Railway; the railway was detoured to the east bank of the Yellow River at Bayangaole because of the shifting sand. During the 1950s the government established three farms in Ulan Buh Desert and attempted to develop agricultural production in this area. The shifting sand buried irrigation channels, roads and buildings. Also, the combination of poor soils and unreasonable water use led to widespread soil salinization and many production teams had to completely move out.

The Hulun Buir Sandland has better natural conditions than the Alxa Plateau area. However, human impacts and inappropriate development and management have caused grassland degradation and sandification, causing shifting sands to endanger the railways and roads. At the Heerhongde station on the Binzhou railway, several hundred meters of track are frequently covered by sand. Roads in the grassland are often buried by shifting sand and grassland is also often buried by shifting sand which has caused degradation to 880,000 ha of pasture. The quantity and quality of pasture in this area has decreased on a large scale. In the past 20 years, the upper 20–30 cm of the black soil layer in farmland surrounding Hailaer City have been eroded by wind, and many areas of farmland have become sandified. The annual yield decreased by 750 $kg \cdot ha^{-1}$, and some of the farmland has become wasteland. Some houses in Harigantusu, in the northwest of Chenbaerhu Banner have been buried and the people have been forced to leave. The northern wall of the town of Amugulang was buried in sand about 1 m thick. Therefore, damage by shifting sand has caused significant harm in this pasture region and combating further desertification is imperative.

4.4 Tibet Autonomous Region

The Tibetan Plateau is important as the headwaters of major trans-boundary rivers and as an ecological origin for China and South Asia. Eco-environmental issues caused by desertification on the Tibetan Plateau are extremely serious and they threaten and impact vast regions beyond the plateau. Should desertification develop further in the future on the Tibetan Plateau, this could have significant effects on regional economic development, and cause tremendous negative effects to the balance between the eco-environment and socio-economic development.

4.4.1 Bioclimatic zones of desertified land on the Tibetan Plateau

The Tibetan Plateau is a huge geomorphologic unit that is located at 26°50′–36°20′ N latitude, with an average elevation of about 4,500 m above sea level. Under the effects of atmospheric circulation, elevation and plateau topography (landform), a specific plateau monsoon climate occurs on the plateau. It is characterized by different temperature and moisture conditions varying from a warm, wet climate in the southeast to a cold, dry climate in the northwest part of the Plateau.

It is calculated that the total area of desertified land on the Tibetan Plateau is approximately 516,147.15 km^2, which include 42.84% of the total land area of Tibetan Plateau. Of these, the dry sub-humid area is 142,753.18 km^2, the semi-arid zone represents 264,082.66 km^2, and the arid zone covers about 109,311.31 km^2, representing 27.66%, 51.16% and 21.18% of the desertified climate zones of the Tibetan Plateau, respectively (Ci and Wu, 1997). The latent desertification land areas on Tibetan Plateau include all three climatic zones, as shown in Table 4.1 (Li et al., 2001b).

Table 4.1 Potential areas of latent desertification on the Tibetan Plateau

Climate zones	AZ	SAZ	DSHZ	SDO
Moisture indicators	0.05–0.20	0.21–0.50	0.51–0.65	0.05–0.65
Areas (km^2)	109,311.31	264,082.66	142,753.18	516,147.15
Percentage of total land area of the plateau (%)				42.84
Percentage of desertification-prone areas (%)	21.18	51.16	27.66	35.49

AZ: Arid zone; SAZ: Semi-arid zone; DSHZ: Dry sub-humid zone; SDO: Scope of desertification occurrence

The latent desertification land areas on Tibetan Plateau include: (i) North Tibet–Northwest Tibet; (ii) Pengqu Valley; (iii) the central part of the middle reaches of the Brahmaputra River; and (iv) the dry valley of the Jinsha River in Eastern Tibet.

4.4.2 Types of desertified lands on Tibetan Plateau

The desertified lands in Tibet can be classified, depending on cause, into four types: (i) desertification from dune movement and sand accumulation; (ii) water erosion; (iii) salinization; and (iv) freezing-thawing processes. Desertification caused by dune movement and sand accumulation processes is the main cause of desertification in Tibet.

4.4.2.1 Desertified land caused by wind erosion

Desertification caused by sand dune movement and sand accumulation affects the largest area of desertified land in Tibet and is widely distributed. The total area is 123,460.77 km^2 representing 67.24% of the total area of desertified land in Tibet. The level of desertification can be classified as: very severe, affecting 1,159.24 km^2 (0.94% of total sandy desertified area); severe, affecting 2,389.30 km^2 (1.94%); medium, affecting 58,169.38 km^2 (47.12%); and slight, affecting 61,742.85 km^2 (50.01% of the total area of sandy desertified land in Tibet).

4.4.2.2 Desertified land caused by water erosion

Desertification caused by water erosion affects the smallest area of affected land in Tibet and covers only 2,662 km^2 (1.45% of the total area). The very severely desertified area is 16.65 km^2 (0.63%); the severely affected area is 175.16 km^2 (6.58%); the medium severity affected area is 1,248.95 km^2 (46.90%); and the slightly affected area is 1,222.04 km^2 (45.89% of the total water erosion desertified area).

4.4.2.3 Desertified land caused by salinization

Salinized land is one of the causes of desertification in Tibet. The total affected area is 9,604.03 km^2 comprising 5.23% of the total area of desertified land in Tibet. The very severe salinized land covers 593.90 km^2 or 6.18% of the total salinized land area.

4.4.2.4 Desertified land caused by freezing and thawing processes on the Plateau

There are approximately 47,895.59 km^2 of desertified caused by freezing-thawing processes on the Tibetan Plateau, which comprise 26.08% of the total desertified land area on the plateau. Of the land desertified by freezing and thawing, the very severely affected land area is 101.11 km^2 (0.21% of its total affected land areas), with the medium and slightly affected land categories comprising the majority of the total area affected by this form of desertification. By analyzing the rate of development of this type of desertification and the percentage of land affected, it can be seen that under the prolonged effects of both regional climate warming, aridization and human factors, the area of desertified land on the Tibetan Plateau, caused by the dynamic pressure of freezing-thawing processes will be accelerated.

4.4.3 Driving force of desertification

4.4.3.1 Dynamic effects of increased temperatures and dry climate

The Tibetan Plateau is a region that is sensitive to environmental change and its response to global warming is significant. During the last few decades the climate of the Tibetan Plateau has been affected by global change. Recently, the Tibetan Plateau has shown signs of a significant warming and drying trend brought about by rising temperature and a reduction of humidity, and this becomes an important driving force for the development of desertification.

From the 1950s to 1990s, the general characteristics of temperature change and rainfall variation on the Tibetan Plateau were increasing temperature and decreasing humidity. In most districts, precipitation decreased on a large scale while the temperature was higher (Li et al., 2001a).

4.4.3.2 Rainfall reduction and climate aridization

The historical record shows that the Tibetan Plateau has experienced a series of changes of alternating dry and wet periods. In recent decades the dry period has been longer and humid period has been shorter, with the climate tending toward aridization.

4.4.3.3 Soil erosion caused by water

The normal processes of desertification caused by water erosion, are driven by the rainfall and runoff in the affected areas causing of soil erosion. Interactive effects of rainfall and runoff are closely related to soil, vegetation and topography. Soils in the desertified areas of the Tibetan Plateau are mainly composed of newly formed skeletal soils such as cold desert soils and frigid desert soils. These were formed recently, mostly by physical weathering (efflorescence) because chemical weathering and other soil-forming factors are weak.

Slope gradient and topographic features are some of the other fundamental elements leading to runoff and soil erosion.

4.4.3.4 Human activities accelerating soil erosion

Inappropriate human activities are the driving force behind the acceleration of soil erosion. Human actions such as overgrazing, undue collection of fuelwoods and inappropriate construction and reconstruction increase the effects of water causing soil erosion.

4.4.3.5 Freezing-thawing processes affected desertified lands

In recent decades, under the effects of climate change, inappropriate human activities and rodent damage, the permafrost of the Tibetan Plateau is being degraded and large areas of desertified land have been caused by freezing-thawing processes (Fig. 4.2).

Climate warming has increased of the depth of seasonal melting layers, decreased the groundwater, increased soil aridity and the formation of freezing-thawing processes causing desertified lands.

Climate warming led to an increase in runoff flow, the freezing-thawing interface of permafrost melts causing land the surface to subside, break and

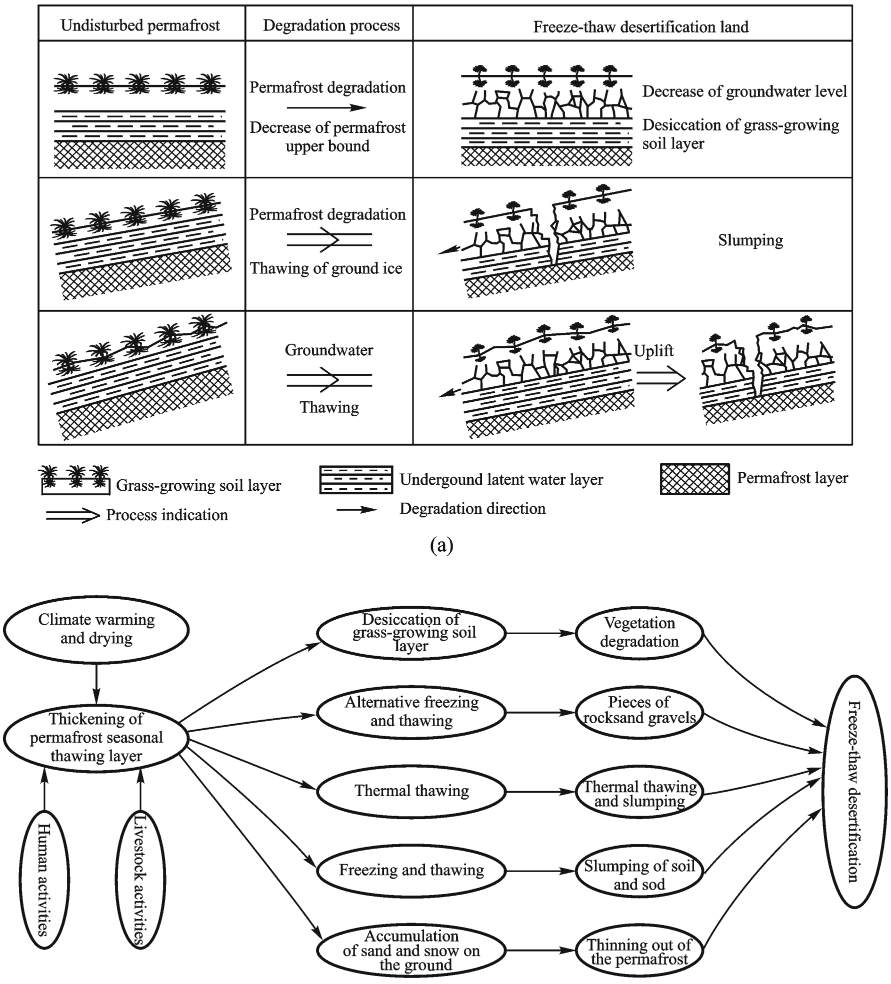

Fig. 4.2 Formation of desertification caused by freezing-thawing processes (Li et al., 2005, with permission from authors)

then form soil erosion.

Climate warming and increasing local temperatures accelerate the freezing-thawing processes which interacted through the overlapping of freezing and melting processes, thus expediting desertification (Li et al., 2004).

4.4.4 Hazards and pressures of desertification on the environment and development

The occurrence and development of desertification on the Tibetan Plateau has resulted in damage and destruction to the headwaters of important rivers, and the ecological origins of the plateau. The damage to the ecological environment has lead to harm and threats to human existence and caused significant economic loss and environmental pressure. Desertification is a huge obstacle to protection of the eco-environment and socio-economic development of the Tibetan Plateau.

4.5 Gansu Province

The distribution of deserts, Gobi and sandified land in Gansu can be divided into four geographical zones. The first zone is on the inclined plain north of the Qilian Mountains in the Hexi Corridor. There are a series of low lying areas within the low mountains and knolls which are affected by denudation and dryness. These areas are located at 37°01′–42°46′N and 92°12′–104°30′E, and include five prefectures, 20 counties and 171 townships in Hexi Corridor. The second zone is in the north of the Qingyang region, located at 36°13′–36°51′N and 106°22′–107°32′E, and including 12 townships of Huanxian County in the Qingyang region. The third zone is at the eastern end of Qinghai-Tibetan Plateau, located at 33°06′–34°23′N and 100°46′–102°29′E, and including four townships of Maqu County, in the northwest of the Gannan Tibetan Autonomous Prefecture. The fourth zone is the middle of Gansu and the north area of Jingyuan, located at 35°22′–37°15′N and 104°25′–105°16′E, and including 13 townships in the north of Pingchuan, Jingyuan and Jingtai counties.

4.5.1 Current situation and distribution of deserts, Gobi and sandified land

4.5.1.1 Type and area of deserts, Gobi and sandified land

The total area of deserts, Gobi and sandified land in Gansu Province is 11,669,064.0 ha, of which Gobi occupies 7,059,465.0 ha (60.50% of the total area); wind erosion and remnant earthen mounds (yardangs) cover 60,186.7 ha (0.52%); desert occupies 1,816,373.4 ha (15.56%) and sandified land covers 2,733,038.9 ha (23.42% of the total area).

In the deserts and sandified land areas, mobile dunes cover 1,967,412.8 ha (16.86%); semi-fixed sand dunes cover 1,027,267.8 ha (8.81%); fixed sand dunes occupy 1,458,530.9 ha (12.51%); non-bioengineered controlling sands cover 4,686.3 ha (0.04%); abandoned farmland covers 15,588.7 ha (0.14%); and the bare sand area is 75,925.8 ha (0.65%).

Of the 1,458,530.9 ha of fixed sand dunes, those fixed by trees occupy 37,950.2 ha (2.60%); those fixed by shrubs occupy 376,271.0 ha (25.80%); and dunes fixed by herbaceous plants cover 1,044,309.7 ha (71.60%). Dunes fixed by human activities cover 114,003.6 ha (accounting for 7.82% of the fixed dunes) while naturally fixed dunes occupy 1,344,527.3 ha (92.18%).

Within the 1,027,267.8 ha of semi-fixed sand dunes, those fixed by trees, shrubs and herbaceous plants account for 34,893.3 ha, 183,205.6 ha and 809,168.9 ha (or 3.40%, 17.83% and 78.77%) respectively. The semi-fixed dunes fixed by human activities and natural processes account for 101,159.3 ha and 926,108.5 ha (or 9.85% and 90.15%), respectively.

4.5.1.2 Distribution of deserts, Gobi and sandified land in Gansu

(i) Tengger Desert

The west part of the Tengger Desert is in Gansu Province, while the eastern part of the Tengger Desert is in the Inner Mongolia Autonomous Region. The geographical coordinates of the Tengger Desert region are 37°01′–39°28′N, 101°41′–104°30′E, and the desert covers a total area of 2,642,000 ha, stretching across 50 towns associated with six cities, which cover Yongchang, Jinchuan, Wuwei, Minqin, Gulang and Jingtai counties. The Tengger Desert comprises 977,632.9 ha of mobile dunes, 247,676.8 ha of semi-fixed sand dunes, 414,851.6 ha of fixed sand dune, 896.7 ha of non-bioengineered controlling sands, 4,617 ha of abandoned farmland, 169,144.1 ha of Gobi, and 8,639.5 ha of bare sand. The sand dune heights range from 3 m to 10 m. The main soils are gray desert soils and gray brown soils. The ground water level is 10 m and the annual rainfall is 100 mm to 200 mm.

(ii) Kumtag Desert

This region mainly located in the southwest of Dunhuang County and includes eight villages and towns. The geographic location is 39°03′–40°56′N, 92°12′–94°56′E. The total area of desert is 3,593,000 ha, in which desert and sandified land area is 1,187,166.2 ha. Of the deserts, Gobi and sandified land, mobile sand dunes are 345,760.6 ha, semi-fixed sand dunes cover 21,729.4 ha, fixed sand dunes are 43,121.0 ha, abandoned farmland is 72.8 ha, and Gobi is 776,482.4 ha. The sand dune types include sand hills, sand piles, and sand ridges. Sand hills are the most common landform in this region, such as Mingsha Mountain in the south of Dunhuang County which has a relative height ranging from several dozen meters to more than one hundred meters, with the highest at 170 m. It is basically fixed. The prevailing wind directions are northeast, southwest and north. The groundwater is deep and with high degree of mineralization.

(iii) Deserts, Gobi and sandified land region in western Gansu Hexi Corridor

This region is located in the western part of the Gansu Hexi Corridor, and includes the Yumen-Anxi-Dunhuang Oasis basin in the middle and lower reaches of the Shule and Heihe Rivers, and downstream of the Danghe River system. The geographical location is 38°14′–42°46′N, 93°46′–100°06′E, and includes 70 villages and towns. The deserts, Gobi and sandified land area is 15,583,000 ha, of which there are 396,388.7 ha of mobile dunes, 1,555.6 ha of non-bioengineered controlling sands, 60,186.7 ha of wind erosion remnant earthen mounds (yardangs), 5,569,312.0 ha of Gobi and 38,627.5 ha of bare sand. The deserts, Gobi and sandified land are dominated by a type of Gobi which concentrated in this region of Gansu Province. This vast region is one of the most seriously desertified regions in Gansu Province. With fierce changes in the climate and shifting sand flow, the Gobi is unstable, resulting in serious wind erosion and active desertification.

(iv) Deserts, Gobi and sandified land region in central section of Heihe River catchment of Gansu Hexi Corridor

The geographic location of this region is 38°30′–39°52′N, 99°23′–101°26′E, and includes 42 villages and towns which belong to five counties (Zhangye, Linze, Gaotai, Minle and Shandan). The total deserts, Gobi and sandified land area is 1,114,000 ha. There are 50,426.1 ha of mobile dunes, 91,757.0 ha of semi-fixed sand dunes, 33,770.4 ha of fixed sand dunes, 2,116.0 ha of non-bioengineered controlling sands, 47 ha of abandoned farmland, 203,837.3 ha of Gobi and 16,027.9 ha of bare sand. The terrain is flat with a rich water source in the Heihe River, which makes this region important for provision of food in the Hexi area. Due to meanders in the river bed, sand sources are exposed and many sand zones have developed.

(v) Deserts, Gobi and sandified land region in North Huanxian County

This region is located in the east of Gansu Province. The geographic coordinates are 36°13′–36°51′N, 106°22′–107°32′E, and the region includes 12 villages and towns. The climate is dry and the vegetation is sparse in this region. The total area of this region is 541,000 ha, in which 210,494.7 ha is desertified, occupying 38.91% of total area. There are 333.1 ha of mobile sand dunes, 76,170.3 ha of semi-fixed sand dunes, 123,139.4 ha of fixed sand dunes and 10,851.9 ha of abandoned farmland in this region.

(vi) Maqu deserts, Gobi and sandified land region

This region is located in the northwest of the Gannan Tibetan Autonomous Prefecture, at the eastern end of the Qinghai-Tibetan Plateau. The geographic coordinates are 33°06′–34°23′N, 100°46′–102°29′E. The region is bordered by Luqu County to the northeast; connects with Ruoergai and Aba counties of Sichuan Province in the southeast; neighbors Jiuzhi, Gande, and Maqin counties of Qinghai Province to the southwest and northwest; and adjoins the Henan Mongolian Autonomous County of Qinghai Province to the north. The Maqu deserts, Gobi and sandified land region encompasses four villages and towns, which are located in the east of Maqu County. It is a high and cold area with an altitude of 3,400–3,430 m in an ancient bed of the Yellow River. The total land area is 385,000 ha, of which 2,590 ha is deserts, Gobi and sandified land, occupying 0.67% of total land area, and there are 1,896 ha of mobile dunes and 694 ha of fixed sand dunes.

(vii) Pingchuan-Jingyuan deserts, Gobi and sandified land region

This region is located in the north of Pingchuan and Jingyuan counties which are situated in the middle of Gansu Province, adjoining the Ningxia Hui Autonomous Region in the northeast, and bordering Jingtai and Baiyin counties in the southwest. Administratively, it includes four villages and towns of Pingchuan County (Baoji, Gonghe, Shuiquan and Wangjiashan) and four villages and towns of Jingyuan County. The geographic location is 35°22′–37°15′N, 104°25′–105°16′N, which means that this region is part of the connecting belt of the Longxi Loess Plateau and the Mengxin Plateau. There are interleaving gullies of various lengths and widths, resulting in fragmented and complex terrain in this area. Because of its location at the edge of Tengger Desert, where it is influenced by the atmospheric circulation around the Mongolian Plateau, the climate is dry. Furthermore, the grey calcium soil has poor structure and is easily eroded by wind. The total land area is 297,000 ha, of which 29,174.8 ha deserts, Gobi and sandified land, occupying 9.8% of this region. There is 181.0 ha semi-fixed sand dunes, 16,362.9 ha fixed sand dunes, and 12,630.9 ha of bare sand.

4.5.2 Effects of sandification

The Gansu deserts, Gobi and sandified land regions are characterized by vast territory and a sparse population, with water and plant resources suitable for raising livestock. In ancient times it was a fine animal husbandry region for semi-nomadic minority groups who followed a transhumance system of altitudinal migration to find water and grass. With the expansion of communication and prosperity derived from trade along the Old Silk Road, agriculture was promoted. More than two thousand years ago the Han Dynasty successively set up four counties (Wuwei, Jiuquan, Zhangye, and Dunhuang) in the Hexi area, developed agriculture and brought in people, which boosted the development of agriculture. However, thousands of years of inappropriate human activities, and especially in the past 50–60 years, poor cultivation practices, overgrazing and over-collection of firewood have caused a series of consequences, such as a deficiency of water resources, changing and drying of river courses, wind erosion and sand deposited, shifting sand burying infrastructure and so on, which have destroyed many towns and turned the oasis into a desert. The main effects of sandification are as follows:

(i) Shifting sand burying farmland

According to measurements made by the Minqin County forestry department, shifting sand moves 6–10 m each year in a southeast direction in areas where the desert vegetation has been destroyed. Since 1949, because of burial by shifting sand and serious sand-dust storms, approximately

127,000 ha farmland has been abandoned in oasis edge of Hexi region. By 1985 more than 3,300 ha of farmland had been buried by shifting sand.

(ii) Sand-dust storms causing human and livestock casualties

Strong sand-dust storms occur in the Hexi Corridor region. For example, on May 5th 1993 the area was subjected, to a force 12 gale that persisted for 60 hours. The sky became dark with flying sands and stones, crops were destroyed and people were killed or injured. The direct economic loss amounted to 162,000,000 RMB.

(iii) Wind erosion and sand blasting reducing agricultural output

Bare soil at the oasis edge and on some farms, especially those on sandy soil, is particularly susceptible to wind erosion. More than 20,000 ha of farmland have suffered a reduction in yield owing to wind erosion and sand blasting which has caused losses of more than 10,000,000 kg of grain and more than 15,000 kg of cotton.

(iv) Shifting sand in Gobi threatening the development of agriculture and animal husbandry

There is a large area of Gobi Desert in the west of the Hexi Corridor. When wind blows across the sandy ground surface, sand is removed from the land surface and enters the air current which leads to wind erosion; the transported sand materials are deposited when they encounter an obstruction. Sometimes the shifting sand can form a big sand dune, or even a sand hill. Such dunes move quickly, and can threaten farmland and pasture. According to county statistics, the effects of shifting sand on any farm can cause harm in the whole province desert region. The farmland suffering from shifting sand damage covers an area of 213,400 ha (43.4% of the existing farmland); while the affected pasture covers 4,063,700 ha (55.3% of pastureland). The number of villages affected by shifting sands are 4,366 (15.6% of the total villages); 713.9 km of railway are affected (52.6% of the total length); 2,813.9 km of highways (or 41.1% of the total length) are affected; and 8,749.8 km (or 37.1%) of canals.

4.6 Qinghai Province

Qinghai Province has a large deserts, Gobi and sandified land area. They can be found in eight counties, two cities and three towns. These deserts, Gobi and sandified land areas mainly include the Qaidam Basin, Gonghe Basin and Qinghai Lake and these are situated at $90°30'$–$101°05'$E and $35°30'$–$39°00'$N. The deserts, Gobi and sandified land stretches from the west of Mang'ai, to the eastern border of Mugetan's Huangshatou in the shape of a strip that is wider in the west and narrower in the east, with a length from west to east of nearly 1,000 km. The width from north to south is approximately 300 km. Patches of sandified land occur also in Maduo of south Qinghai, south of $35°30'$N.

4.6.1 Current situation and distribution of deserts, Gobi and sandified land

4.6.1.1 Types and areas of deserts, Gobi and sandified land

The total area of deserts, Gobi and sandified land in Qinghai is 11,627,229.2 ha, of which sandy desert covers 27,140.0 ha (or 0.23%); wind eroded monadnocks cover 2,045,341.2 ha (17.59%); Gobi is 4,591,188.9 ha (39.49%); and sandified areas cover 4,963,559.1 ha (42.69%).

Of the 4,963,559.1 ha of deserts and sandified land, mobile sand dunes cover 1,825,052.9 ha (36.57%), semi-fixed dunes are about 1,236,864.4 ha (24.78%), fixed dunes are about 945,382.3 ha (18.94%); non-bioengineered controlling sands cover 40 ha; abandoned farmland covers 1,668.0 ha (0.03%); and bare sand is about 981,691.5 ha (19.68%).

Of the fixed dunes, those fixed by trees cover 20.0 ha and those fixed by shrubs are about 23,314.8 ha (or 2.47%), while those fixed by herbage plants are about 922,047.5 ha (97.53%). Dunes fixed by artificial plantings cover 87.4 ha (0.01%), while dunes fixed by nature is 945,294.9 ha, and accounts for 99.99% of the total fixed dunes.

Of the semi-fixed dunes, those fixed by trees cover 9,119.2 ha (0.74%), dunes fixed by shrubs cover 374,678.2 ha (30.29%), and those fixed by herbage plants occupy about 853,067.0 ha (68.97%). Dunes fixed by artificial plantings cover 149.5 ha (0.01%), while dunes fixed by nature is 1,236,714.9 ha, accounts for 99.99% of the total semi-fixed dunes.

4.6.1.2 Distribution of deserts and sandified land

(i) Qaidam Basin

The Qaidam Basin is in the northeast of Qinghai Province and is surrounded by the Qilian, Altun and Kunlun Mountains. It is an inland plateau basin and also the highest desert area in China. The total area of deserts and sandified land is 11,103,464.4 ha, with 1,535,797.6 ha of mobile dunes, 1,168.772.7 ha of semi-fixed, 916,262.7 ha of fixed dunes, the non-bioengineered controlling area is about 40 ha, abandoned farmland is about 1,668 ha, bare sand covers 852,206.3 ha, there is 4,583,375.9 ha of Gobi, and 2,045,341.2 ha of wind eroded monadnocks. The Qaidam Basin can be subdivided as follows:

Wutumeiren Sandified area. Starts from Gansenhu in the west, is connected with the northern foothills of Bokaleiketage Mountain, and the eastern Kunlun Mountains to the south, the eastern boundary is Dagele and the northern boundary is near the towns of Lenghu and Dachaidan. The length from west to east is approximately 500 km and the width from north to south is approximately 250 km. The total area of deserts, Gobi and sandified land is 3,415,293.0 ha, of which mobile dunes cover 846,373 ha (24.78%); fixed dunes cover 849,438.9 ha (24.87%); semi-fixed dunes cover 816,548.1 ha (23.91%); Gobi covers 802,618 ha (23.50%); abandoned farmland is about

400 ha (0.01%); and the bare sand area is about 99,915.0 ha (2.93%). The types of sand dune include crescentic dunes, chains of crescent dunes and sand ridges. The sand is moving about 5–10 m annually.

Lenghu sandified area. Includes the area west of Mang'ai town, the foothills of Qimantala Mountain, extends north from Altun Mountain and Danghe'nanshan Mountain, is connected to Zongwulongshan Mountain in Delingha in the east, and the southern boundary is close to the Wutumeiren sandified area. It is approximately 500 km long from west to east and 160 km from north to south. The lowest elevation is about 2,800 m and the highest elevation is about 5,798 m. The total area of deserts, Gobi and sandified land is about 5,101,169.0 ha, of which there are 393,626.4 ha of mobile dunes (7.72%); 2,045,341.2 ha of wind eroded monadnocks (40.10%); and 2,662,201.4 ha of Gobi (52.18%). Crescent dune chains and sand ridges are the main dune types and are about 5–25 m high. The dunes are moving at a rate of about 5–10 $m \cdot a^{-1}$, and in some places up to 10–20 $m \cdot a^{-1}$.

Tiekui sandified area. Starts from Dahala River in the west, and extends east near to Ela Mountain, the northern boundary is near Amunike and Buguote mountains, and the south is connected to Burhan Mountain. The lowest elevation on the sandified area is at Huobuxun Lake which 2,675 m above sea level and the highest elevation, in Yaladaze Mountain, is about 5,214 m. It has a typical cold region, plateau continental climate. It is approximately 300 km from west to east and 200 km from north to south. The total area of deserts, Gobi and sandified land is 2,587,002.4 ha, of which Gobi is 1,118,556.5 ha (or 43.24%), mobile dunes cover 295,798.2 ha (11.43%); semi-fixed dunes cover 352,224.6 ha (13.62%); fixed dunes occupy 66,823.8 ha (2.58%); non-bioengineered controlling dunes are 40 ha; and abandoned farmland is about 1,268 ha (0.05%). Crescent dunes, sand ridges and sand piles are the primary sand dune types, and they are moving at 5–10 $m \cdot a^{-1}$.

(ii) Sandified area in the Gonghe Basin

The Gonghe Basin is located at the southern part of Qinghai Lake. Its northern border is the south mountains of Qinghai, the southern border is Ela Mountain, a branch of the Kunlun Mountains, to the east is Xiqing Mountain and western boundary is connected with Qaidam Basin. It is administered by Gonghe and Guinan counties. The basin is approximately 280 km long from west to east, and 60 km wide from north to south. The total area of deserts, Gobi and sandified land is 321,251 ha, of which mobile dunes comprise 155,571.5 ha (48.43%), semi-fixed dunes cover 32,091.7 ha (9.99%), fixed dunes occupy 29,119.6 ha (9.06%), Gobi is 7,813 ha (2.43%), and the bare sand area is 96,655.2 ha (30.09%). The main dune landforms are crescent dunes, chains of crescent dune and sand piles. The desert is moving to the southeast with a speed of 7–12 $m \cdot a^{-1}$ for the 5–10 m high dunes, and 18–77 $m \cdot a^{-1}$ for the smaller dunes that are 2–5 m high. The highest speeds may reach 81 $m \cdot a^{-1}$.

(iii) Sandified area around the Qinghai Lake

This region extends north to the Datong Mountains, east to the Riyue

Mountains, south to Nanshan in Qinghai, and west to the Hala Lake valley. The altitude is 3,194–5,174 m and it has a high, cold, semi-arid grassland climate. The total area of deserts and sandified land is about 75,855 ha, of which mobile sand dunes comprise 32,955 ha (43.44%); semi-fixed sand dunes are 10,070 ha (13.28%); and the bare sand area is 32,830 ha (43.28%). The sand dune types are mainly crescent dunes, sand mountains, sand ridges and sandified land, with the highest sand mountain reaching up to 160 m. Qinghai Lake, which is oval-shaped, is the largest inland saline lake in China. It is approximately 108 km from west to east and approximately 60 km from north to south, with a perimeter of approximately 360 km and an area of 4,304.5 km^2. The elevation of the lake surface is 3,193.78 m. The lake has been affected by sand-dust storms and drought, and the lake level has fallen 10.53 cm every year from 1956–1986 and is still falling.

(iv) Maduo sandified land

This region is located in Maduo County and Maqin County of the Guoluo Tibetan region. The area of deserts and sandified land is 126,658.8 ha. Of which mobile dunes are 100,728.8 ha (79.53%) and semi-fixed dunes are 25,930 ha (20.47%). The main dune shape is undulating and ridge sand dunes.

4.6.2 Effects of sandification

4.6.2.1 Harming agriculture and livestock production

The shifting sands and sand-dust storms cause harm to agriculture and livestock production that reduces the area of arable land and also reduces the land's productive capacity. The frequency of disastrous sand-dust storms is also increasing. As a result of wind erosion, the sand flow spreads and the mobile sands bury land. Many fixed and semi-fixed sand dunes become destabilized and become shifting sand. At same time, wind erosion will remove soil organic matter and clay particles and the land will become poorer and have a coarser texture. During 1979–1983, shifting sand accumulated on arable land to a depth of 10 cm causing 6.7 ha farmland in Zhabuda Village of Shazhuyu Town to be abandoned. In Qinghai Province, there are about 213,000 ha of farmland affected by wind erosion to different degrees.

4.6.2.2 Burying buildings

There are hundreds of households in Shangqialigang Village in Shazhuyu Town of Gonghe County that were affected by shifting sand and they have been compelled to move four times within the past 40 years. In Geermu Farm the equivalent of 39,000 workdays are used cleaning up accumulated sand at the edges of fields and canals every year. The shifting sand in northwest of Dulan County is moving to the city at a speed of 8–12 cm every year, which will endanger the county seat directly.

4.6.2.3 Disrupting traffic

It is very common for shifting sand to accumulate on the road surface when sand flow stops or mobile dunes move forwards. Almost every year, and in any season, shifting sand buries roads. In May 1985, sand buried the railway to a depth of 70 cm deep in Fushaliang Region. The traffic was stopped 34 times in eight sections because of sand burying the railway. Four trains were obstructed in Fushaliang area in one night in May 1985. In March 1986, sand buried railway lines in Taoli Station at night and cargo train No.3461 was derailed on the third rail switch, which caused four oil tanks to catch on fire and one exploded. About 300 m of railway line were destroyed, three signal poles burned, 220 t of gasoline was burnt and traffic was interrupted for 15 hours and 45 minutes. The direct economic loss was more than 300,000 RMB.

4.6.2.4 Silted lakes and reservoirs

Shifting sand has threatened Qinghai Lake seriously for many years. The quantity of shifting sand and sediment going into the lake is 9,870,000 $t\cdot a^{-1}$, which has reduced the average depth of the lake from 37.5 m to 25.28 m. In past century, the water level has decreased by 12.22 m and the exposed area of lake bed reached 359.4 km^2. The famous Bird Island has become a peninsula.

4.7 Ningxia Hui Autonomous Region

Ningxia Hui Autonomous Region is located between the middle and upper reaches of the Yellow River and transitional belt between deserts and Loess Plateau. There are extensive deserts, Gobi, sandlands and sandified land in its central and northern parts, including the Mu Us Sandland, the Tengger Desert and fragmented pieces of sandified land within its 185 villages and towns of 13 counties.

4.7.1 Current situation and distribution of deserts, Gobi, sandlands and sandified land

The total area of deserts, Gobi, sandlands and sandified land in Ningxia Hui Autonomous Region is 1,235,773.9 ha, of which sandy desert covers 81,934.0 ha; Gobi is 208,404 ha (16.9%); and sandland is 945,435.9 ha (76.5%). Mobile sand dunes cover 206,884.9 ha (16.7%); semi-fixed sand dunes cover 233,471.3 ha (18.9%); fixed sand dunes cover 531,490.4 ha (43.0%); abandoned farmland is 55,402.8 ha (4.5%), and the non-bioengineered sand control area is 120.5 ha (0.01%).

Deserts, Gobi, sandlands and sandified land in Ningxia Hui Autonomous

Region can be divided into three parts: the Mu Us Sandland, the Tengger Desert and dispersive sandified land in the middle of Ningxia and the Yinchuan Plain.

Part of the Mu Us Sandland is located in northeast Ningxia. It includes most of Taole County, Yanchi County and Lingwu County with a total area of 1,047,378.5 ha, of which the sandy area is 735,024.2 ha, or 70.2% of the land area in this region. The area of mobile sand dunes is 118,961.2 ha (16.2%); semi-fixed sand dunes cover 217,636.7 ha (29.6%), fixed dunes cover 353,928.1 ha (48.1%); farmland is 42,442.9 ha and Gobi is 2,055.3 ha. The region is part of the area southwest of the Ordos Tableland, and common landforms are low mountain hills, low slope hills, wind eroded sand platforms, alluvial plains and lakes. The altitude is between 1,095 m and 1,600 m and has a central temperate zone arid climate. The main types of soil are Sierozem, aeolian sandy soil and small areas of loess and halomorphic soil. The main vegetation types on saline-alkali soils are *Glycyrrhiza glabra*, *Artemisia* spp., and *Cynanchum* spp. The other main vegetation types are *Glycyrrhiza uralensis*, *Caragana* spp., *Artemisia* spp., *Oxytropis aciphylla*, *Sophora alopecuroides* and *Peganum harmala*.

Part of the Tengger Desert is located in the northwest of Zhongwei County with the Yellow River as its boundary. Its total area is 177,273.0 ha, of which deserts, Gobi and sandified land occupy 124,047.0 ha, accounting for 70.0% of total land area in this region. Within the deserts, Gobi and sandified land, the mobile sand dunes area is 61,287.0 ha (49.4%); semi-fixed dunes cover 9,155.0 ha (7.4%); fixed dunes cover 50,838.5 ha (41.0%); Gobi covers 2,493.0 ha (2.0%); non-bioengineered controlling sand is 114.5 ha (0.1%); and abandoned farmland is 159.0 ha (0.1%). Its climate is arid with annual mean precipitation only 170 mm. The main soil types are brown calcic soil, meadow soil, swamp soil, saline meadow soil and takyr solonetz. The main vegetation types are *Caragana korshinskii*, *Hedysarum scoparium*, *Agriophyllum arenarium*, *Oxytropis aciphylla*, *Artemisia* spp., *Cynanchum komanovii*, *Nitraria tangutorum*, *Carex duriuscula*, and *Calystegia hederacea*.

There are also many scattered and different types of sandified land in Ningxia with a total land area of 1,530,510.7 ha, of which sandified land comprise 376,702.7 ha, accounting for 24.6% of the total land area.

4.7.2 Effects of sandification

The main effects of sandification are the shifting sands that threaten farmland, villages and houses, as well as destroying infrastructure. The surface of some land becomes exposed gravel under the action of wind, and areas of grazing land become sandified land which means that the grassland livestock carrying capacity is decreased. According to the historical data, Shapotou which means “sand starts here” used to be a flourishing town on the ancient road from

Ningxia to Lanzhou. Due to the Tengger Desert moving southward, many towns were buried. Sand dunes can be more than 100 m high in this area, and form a band that is 10 km long from east to west with the southern end near the Yellow River. Sand-dust storms events occur on average for 200 days each year, which causes parts of Zhongwei County to face serious sand-dust storm damage. Losses of land because of sand-dust storms account for 198.3 ha of farmland and 1,814.5 ha of grassland, and have affected 668 villages, 122 km of railway, 875 km of highway and 1,912 km of canals. The annual economic loss is 61.07 million RMB.

4.8 Shaanxi Province

The sandlands and sandified land of Shaanxi province is most common in Yulin and Yan'an in the north of Shaanxi. This area includes the southern part of the Mu Us Sandland (the northern part is in Inner Mongolia), and extends south to the loess hilly sandy area and the "shayuan" in Dali County at the intersection of the Luohe, Weihe and Yellow Rivers. 199 villages and towns in 14 counties are affected by sandification.

4.8.1 Distribution of sandlands and sandified land

The total area of sandlands and sandified land in Shaanxi province is 1,462,803.5 ha, accounting for 7.1% of the total land area. Mobile dunes occupy 144,609.5 ha (9.9%); semi-fixed dunes cover 303,257.5 ha (20.7%); fixed dunes cover 1,004,286.6 ha (68.7%); abandoned farmland is 1,919.3 ha (0.1%); farmland transformed from sandy wasteland is 2,676.9 ha (0.2%); and bare sandland is 6,053.7 ha (4.1%).

Of the fixed and semi-fixed dunes, 122,815.1 ha are fixed with trees, 624,468.6 ha are fixed with shrubs (47.8%) and 560,260.4 ha are fixed with herbage plants (42.8%). Of the dunes fixed by trees, 121,630.6 ha are artificial plantings, and natural forests cover 1,184.5 ha. The shrub fixed dunes comprise 581,993.3 ha of artificial plantings, 19,789.1 ha of natural forest, and 22,686.2 ha of air seeding. The dunes fixed by herbage plants comprise 166,208.9 ha of artificial grassland, 166,208.9 ha of natural grassland and 166,208.9 ha of air seeding.

In the total area of sandlands and sandified land in Shaanxi province, the Mu Us Sandland area and the loess sandy area account for 1,438,454.7 ha (or 98.3% of the total area of sandlands and sandified land in Shaanxi province). The remaining sandified land is in Dali and comprises 24,348.8 ha (or 1.7% of the total).

In the Mu Us Sandland in Shaanxi province, mobile sand dunes cover

144,609.5 ha (or 9.8% of the total area of the Mu Us Sandland); the semi-fixed dunes cover 297,660.7 ha (20.3%); the fixed dunes cover 988,211.50 ha (67.6%); and abandoned farmland is 1,919.3 ha (0.13%).

4.8.2 Effects of sandification

The strong wind in the sandlands and sandified land leads to wind erosion and causes sand flow. It destroys crops and pastures and buries farmland which is the main negative effect on the production of agriculture, forest and animal husbandry. According to historical data, in 413 A.D., Helianbobo of the Daxia Dynasty founded a capital, named Tongwancheng in Baichengzi on the northern side of Wuding River, which is now located in the north of Jingbian County. At that time, this region was next to a clean river with only a small sandy hill. During the Ming and Qing Dynasties, both sides of the Great Wall were covered in sand without any farming. In the one hundred years preceding the founding of the People's Republic of China, mobile sand spread more than 50 km south of the Great Wall. About 140,000 ha of farmland has been buried by sand and only 410,000 ha farmland is left, most of which is also surrounded by sand dunes. There are 260,000 ha of degraded grassland, and eight towns and 421 villages have suffered from sand-dust storms reducing residents' quality of life.

Prior to 1993, 220,000 ha of farmland, 6,027,000 ha of grassland, 110 villages (about 30% of the total villages in the sandy region), 71 km of railway, 1,659 km of highway (about 38% of highways in the sandy region), and 808 km of canals (about 66% of the total canals in the sandy region) had been affected by shifting sand in Mu Us Sandland, loess sandy area and Dali Shayuan region.

4.9 Other provinces and cities

In addition to the seven provinces discussed above, sandland and sandified land are also located in other regions including Beijing, Tianjin, Hebei, Shanxi, Liaoning, Jilin and Heilongjiang.

4.9.1 Beijing

Sandland and sandified land in Beijing are located in 129 towns in 11 counties and is mainly distributed along the river basins of the Yongding, Chaobai and Wenyu Rivers. Of these, the Yongding River basin has the largest area of sandland.

4.9.1.1 Area of sandland and sandified land

The total area of sandland and sandified land in Beijing region is 58,012.2 ha, of which, the bare sand area is 42.9 ha. Of the stabilized sandland, sand dunes fixed by trees cover 50,508.3 ha (87.13% of whole sandified land).

4.9.1.2 Distribution of sandland and sandified land

The sandland and sandified land of Beijing can be divided into five regions:

(i) Sandland and sandified land along the Yongding River

There are five sand strips as well as the modern riverbed of the Yongding River. The sand source is mainly from the old and new Yongding River beds. The prevailing wind direction is northwest in winter and the minor wind direction is from the north. Blown sand weather is the main hazard in this region.

(ii) Sandland and sandified land along the Chaobai River

The total area of sandland and sandified land along the Chaobai River is 6,917.5 ha and all of it is fixed. The main wind direction is northerly (northeast and northwest) in the Wenyu River basin. Dust days occur 40% to 50% of the time during sandy weather and days when suspended particles occur are recorded as 5–45% of days.

(iii) Sandland and sandified land in the Dasha River area of Huairou and Miyun Counties

This area is located between the Chaohe, Baihe and Yanxi rivers and turns to the south along the Baihe River to Niulanshan. It includes four towns in Huairou County and six towns in Miyun County. The total area of sandland and sandified land is 4,775.3 ha, and all is fixed. The sand particles are very coarse, especially in the front of the mountains, where surface sand and gravel are common. Wind is not very strong here because of its location in front of mountain. There was a high rate of vegetation coverage in the past but this has been destroyed in recent years.

(iv) Sandland and sandified land at Kangzhuang in Yanqing County

The wind is comparatively strong in Yanqing Basin, especially south of Kangzhuang region. Because of diluvial deposits in front of the piedmont and erosion, the land surface is a gravel Gobi formation and the lower area is a fine earth plain.

(v) Sandland and sandified land at Nankou in Changping County

This area is located in the wind corridor of Kangzhuang-Badaling-Nankou. The mean wind speed is 6 $m \cdot s^{-1}$ in spring and the wind has a strong erosion capacity. Its sandland and sandified land area is 635.8 ha and all are fixed.

4.9.2 Tianjin

Tianjin has five suburban counties and three districts along the coast with a total area of 1,092.680 ha. Sandland and sandified land are located in 43 towns of Jixian, Bodi, Wuqing, Beichen, Xiqing and Dongli counties and districts with area of 181,276.5 ha, of which the sandland and sandified land area is 25,695.2 ha, or about 2.4% of the area of Tianjin.

Sandland and sandified land in Tianjin are mostly distributed along the river banks. There are 4,690 ha along the Jiyunhe Canal, 3,082 ha along the Chaobai River banks, 3,093 ha in the catchment of Qinglongwan, 1,557 ha in the Beiyun River catchment, 11,430 ha along the Yongding River, 1,351.2 ha along the Zhanghe, Zhouhe and Linhe Rivers, and 492 ha in the Xinkai River catchment.

4.9.3 Hebei Province

In Hebei province, sandland and sandified land are located in 78 counties of 11 prefectures and includes 1,503 towns, or 41.2% of the total number of towns in the province. Among the counties with sandland and sandified land, 12 are located in northwestern part of the province, including 137 towns, and 66 are located on the plains, including 1,366 towns.

There are 2,931,174.8 ha of sandland and sandified land in Hebei Province. Considering the geographical location, landform type and causes of sand encroachment, sandified land in Hebei Province can be divided into two regions, the northwest sandified land region and the plains sandified land region.

The northwest sandified land region includes 137 townships in 12 counties associated with Zhangjiakou City and Chengde City. The total area of sandified land is 1,552,279.8 ha, of which the mobile sand dune area is 38,117.8 ha (2.46%); the fixed sand dunes are 831,251.8 ha (53.55%); abandoned farmland is 267,288.8 ha (17.22%) and bare sandland is 415,621.4 ha (26.77%).

The plains sandified region includes 1,366 townships of 66 counties, and the total area of sandified land is 1,378,895 ha.

4.9.4 Shanxi Province

In Shanxi Province, sandified lands are mainly located in the north and northwest of the agriculture and pasture transition zone. Sandification along the Great Wall is common. The sandified land area in Shanxi Province ranges from the north of Shanxi Province to the west, bordering with Shaanxi Province and Inner Mongolia. The length from east to west is 300 km, the width from south to north is 230 km and this area has the shape of an inclined long strip. The geographical coordinates of this area are 110°56′–114°32′E and 38°39′–40°44′N. The administrative area involves 249 townships of 18 counties and three cities of Datong, Shuozhou and Xinzhou.

The total sandification area in Shanxi Province is 785,284 ha. Mobile sandified land has an area of 2,273 ha (or 0.3% of the total sandification area); semi-fixed sandified land covers 271,452 ha (34.6%); fixed sandified land covers 390,945 ha (49.8%); and abandoned farmland is 120,615 ha (15.4%).

In Shanxi Province, fixed sandified land covers nearly 50% of the total sandified land. This demonstrates that great achievements have been made in past years in combating desertification. Sandified lands cover about 29.0% of the land in those townships identified in sandification counties, and of the sandified lands, fixed and semi-fixed sandified land comprises 84.4%.

In the counties of Pianguan, Shenchi, Wuzhai, Baode and Zuoyun, all of the sandified land is fixed or semi-fixed. Most of sandified lands have been well controlled, primarily by forestation.

4.9.5 Liaoning Province

Sandland and sandified land in Liaoning Province involves 197 townships of 18 counties. According to the topography and the cause, sandland and sandified land in the province can be divided into three parts: the Horqin Sandland, sandland and sandified land along the Liaohe and Linghe River systems and sandland and sandified land along beaches.

The southern edge of the Horqin Sandland is located in the north of Liaoning Province between 121°50′–124°00′E and 42°25′–43°30′N. Its northern area connects with Inner Mongolia and the central Horqin Sandland, the eastern edge is at the Zhaosutai River, the southern boundary adjoins the sandland and sandified land along the rivers, and the western boundary is the Raoyang River. The Horqin Sandland has the shape of a long, narrow belt extending from west to northeast.

Sandland and sandified land along the rivers is located at the northwest of Liaoning Province, and is concentrated along the Laogu, Benghe, Xiushui, Yangximu, Liuhe, Raoyang, Xihe, Mangniu and Daling Rivers and the plains among the rivers. The geographical coordinates are between 119°15′–122°35′E and 39°30′–42°50′N.

Coastal sandland and sandified land are distributed along the coast of Liaodong Bay on the Bohai Sea from Suizhong in the west to Wafangdian in the east, in a narrow, horseshoe shaped band between 119°50′–122°29′E and 39°30′–41°9′N.

4.9.5.1 Type and area of sandland and sandified land

The total sandland and sandified land area in Liaoning Province is 328,747.2 ha (or 13.6% of the total land area). Mobile sand dunes cover 2,735.1 ha; semi-fixed sand dunes occupy 27,016.4 ha; fixed sand dunes are 295,768.6 ha; abandoned farmland is 2,487.1 ha; and bare sandland is 740 ha.

Sandland and sandified land fixed by trees cover 236,820.2 ha, those fixed by shrubs are 5,759.8 ha, those fixed by herbage plants are 53,188.6 ha. The artificial plantings occupy 235,078.3 ha and the area of natural plantings occupy 60,690.3 ha.

4.9.5.2 Distribution of sandland and sandified land

(i) South edge of the Horqin Sandland

This region is in the northern area of Liaoning Province and includes 26 townships in three counties of Zhangwu, Kangping and Changtu. The total sandland and sandified land area is 130,479.7 ha, of which mobile sand dunes are 1,150.6 ha, semi-fixed sand dunes are 18,670.6 ha and fixed sand dunes are 109,343.9 ha.

(ii) Sandland and sandified land along the river in the Liaohe and Linghe River system

This region is located in the northwest of Liaoning Province centered in the Liaohe and Linghe River system. It includes 112 townships in 11 counties of Jianping, Beipiao, Fuxin, Zhangwu, Yixian, Heishan, Xinmin, Liaozhong, Faku, Kangping and Taian. The total sandland and sandified land area is 164,101.7 ha, of which mobile sand dunes are 715.1 ha, semi-fixed sand dunes are 7,210.8 ha, fixed sand dunes are 155,114.1 ha, abandoned farmland is 321.5 ha and bare sand is 740.0 ha.

(iii) Coastal sandland and sandified land along Liaodong Bay

This region is located along the coastal beaches of Liaodong Bay on the Bohai Sea and includes the six counties of Suizhong, Xingcheng, Lianshan, Longgang, Panshan and Wafangdian. The total sandland and sandified land area is 34,165.8 ha, of which mobile sand dunes are 869.4 ha, semi-fixed sandland is 1,135.0 ha, fixed sandland is 31,310.4 ha and abandoned farmland is 851.0 ha.

4.9.6 Jilin Province

In Jilin Province, sandlands are located at the southwest of the Songnen Plain; in the corridor linking the east Liaohe River and Xiliaohe River which is part of the eastern Horqin Sandland; and the southern area of the Songnen Sandland. The eastern boundary approximately follows the line from Tuanjie of Lishu County to Lianhuashan of Gongzhuling City to Jubao of Changling County to Halahai of Nong'an County to Xiaojia of Fuyu County, and is adjacent to other provinces at the south, west and north. Geographical coordinates are between 122°06′–125°51′E and 43°18′–46°19′N. The administrative region includes 179 townships in the 13 counties of Tongyu, Shuangliao, Zhenlai, Taonan, Taobei, Qianguo, Changling, Qian'an, Fuyu, Lishu, Da'an, Gongzhuling and Nong'an.

4.9.6.1 Sandland type and area

The total area of sandlands is 494,107.8 ha, occupying 12.33% of the entire land area of Jilin Province. Mobile sand dunes occupy 109.0 ha (0.02%); semi-fixed sand dunes cover 16,433.6 ha (3.33%) and fixed sand dunes cover 477,565.2 ha (96.65%).

Of the fixed sand dunes, 430,758.9 ha (90.20%) is fixed with trees, 5,102.8 ha (1.07%) with shrubs and 41,703.5 ha (8.73%) with grasses. Vegetation of artificial origin occupies 370,669.5 ha (77.62%) with vegetation of natural origin occupying 106,895.7 ha (22.38%).

Of the semi-fixed sand dunes, 5,377.1 ha (32.72 %) is fixed with trees, and 11,056.5 ha (67.28%) with grasses. Artificial plantings cover 6,955.1 ha (42.32%) and natural plantings cover 10,478.5 ha (63.76%).

4.9.6.2 Distribution of sandlands

(i) Songnen Sandland

The Songnen Sandland has an area of 222,763.3 ha, which is comprised of 109 ha (0.05%) of mobile sand dunes, 12,267.4 ha (5.51%) of semi-fixed sand dunes, and 210,386.9 ha (94.44%) of fixed sand dunes.

The landform in the Songnen Sandland is relatively smooth as it is a sand covered alluvial plain with an altitude between 120–200 m. It features alternating sandland, farmland, grassland and lakes. The sandland is in a belt that consists of parallel sand ridges and swales, in the form of an arc to the south. The dune size decreases from east to west as the land becomes a gentle plain. There are also some scattered sand dunes in other places.

(ii) Horqin Sandland

The area of the Horqin Sandland in Jilin Province is the eastern edge of the Horqin Sandland, and is situated on the west side of the province mostly distributed to the east and west of the Liaohe River Plain. The geographical coordinates are 122°06′–124°38′E and 43°18′–45°03′N, and include 79 towns of the seven counties. The total area of sandland in this area is 271,344.5 ha, of which the semi-fixed sand dune area is 4,166.2 ha (1.54%) and the fixed sand dune area is 267,178.3 ha (98.46%).

The landform in the Horqin Sandland is relatively smooth, with sand covering an alluvial plain at an altitude between 120–200 m. The key landform in the sandland is a sand belt consisting of parallel sand ridges and swales. The sandland terrain can be divided into gentle plains, isolated sand dunes and complex sand ridges.

4.9.7 Heilongjiang Province

Sandland and sandified land in Heilongjiang Province is located at the eastern edge of a long stretch of blown sand in North China. The geographical location is 122°10′–125°10′E and 45°30′–48°30′N. The region includes 105 townships of nine counties.

The total area of sandland and sandified land is 378,635.7 ha, of which mobile sand dunes occupy 1,198.9 ha (0.32%), fixed sand dunes cover 364,968.4 ha (96.39%), and abandoned farmland covers 3,580.0 ha (0.95%). sandland and sandified land are mostly located in the southwest semi-arid alluvial plains of the lower reaches of the Nenjiang River and cover an area 165 km wide and 400 km long along Nenjiang River tending from northeast to the southwest.

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5 Water Erosion in the Drylands of China

Keli Zhang and Baoyuan Liu

China is one of the most serious water erosion countries in the world. In this chapter, we overview regional distribution characteristics of water erosion, analyze the damage from water erosion and introduce some successful water control measure in drylands of China.

5.1 Distribution of water erosion and its regional characteristics

China is located on the eastern inclined plane of Eurasia where it grades towards the Pacific Ocean. Its mountainous area accounts for approximately two thirds of the total territory. The landform is divided into three large terraces from west to east that extend throughout the entire country. The regional distribution of soil erosion is controlled by the geomorphological features of the terraces.

The first terrace is the Tibetan Plateau with an elevation of more than 4,000 m. It is surrounded by mountains, of which the Kunlun and Qilian mountains border the north, the Himalayan mountain system borders the southwest and the Hengduan mountain region borders the southeast. In the central part of the plateau, mountains, platforms, hills, basins and lakes are interspersed throughout the region.

The second terrace is located in the western part of China along the route of the Da Xing'anling and Taihang mountains and the Wushan and Xuefeng mountain region, and is bordered by the eastern and the northern sections of the Tibetan Plateau. Mountains, plateaus and basins are widely interspersed throughout the terrace with the Altai, Tianshan and Qinling mountains, Yunnan-Guizhou Plateau, the Loess Plateau and the Inner Mongolian Plateau with an elevation of more than 1,000 m, and the Junggar Basin and Tarim Basin with an elevation of less than 1,000 m.

The third terrace is located at the eastern boundary of the second terrace.

Typical topographic features of this terrace are rivers, plains, valleys, basins, low mountains and hills. The elevation of the majority of the hills is less than 500 m while the less mountains exceed 1,000 m. The elevations of plains and valleys are less than 200 m, and the majority of area within the Huang-Huai-Hai Plain and the middle and lower reaches of the Yangtze River Plain have elevations of less than 50 m. Hills cover a wide range of the area of the terrace, interspersed with valleys and basins.

Topographic characteristics give rise to complex inclined planes which allow all types of erosion mechanisms. Due to the different natural conditions that occur in the different regions and to human activities, the soil erosion zone is widely spread throughout the three terraces. Soil erosion regions are divided on the basis of regional similarities and discrepancies in terms of soil erosion forces, types, and intensity as well as natural and socioeconomic factors. The study of soil erosion regionalization began at the end of the 1950s as part of the Yellow River disaster control planning where soil and water conservation was introduced as a part of the strategic plan.

5.1.1 Distribution scope

In 1955, Huang (1955) compiled a soil erosion map of the middle reaches of the Yellow River in which soil erosion regions were divided into three different categories: class, region, and subregion. The class was further divided into two types: the vegetated class and the non-vegetated class. The vegetated class was then divided into three regions, i.e., alpine grassland, rocky mountainous forest and loess hill forest, while the non-vegetated class was divided into seven regions according to geological and topographic factors. These were finally divided into subregions by land use and landform where, for example, the loess hill forest region was divided into five subregions. The map has been widely applied due to its clarity and simplicity and its ability to illustrate key points (Fig. 5.1). In 1956, Zhu (1956) developed the principles of soil erosion regionalization and summarized five classification categories: zone, region, subregion, section, and subsection. These five classification categories have become the fundamental basis for national and regional soil erosion regionalization.

The soil erosion zone is divided by the driving forces of erosion and the bioclimatic zones, according to the principle that topographic features and natural forces (e.g., water, and wind) are the main elements that cause large-scale soil erosion in many regions of China. The three soil erosion regions (the water erosion region, the wind erosion region, and the freezing-melting erosion region) were divided by Xin and Jiang (1982). Xinjiang, the Hexi Corridor of Gansu, the Qaidam Basin of Qinghai and the sandy areas of Ningxia, the northern area of Shaanxi, Inner Mongolia, and the western area of northeast China are all part of the wind erosion region. The Tibetan Plateau, glacier ar-

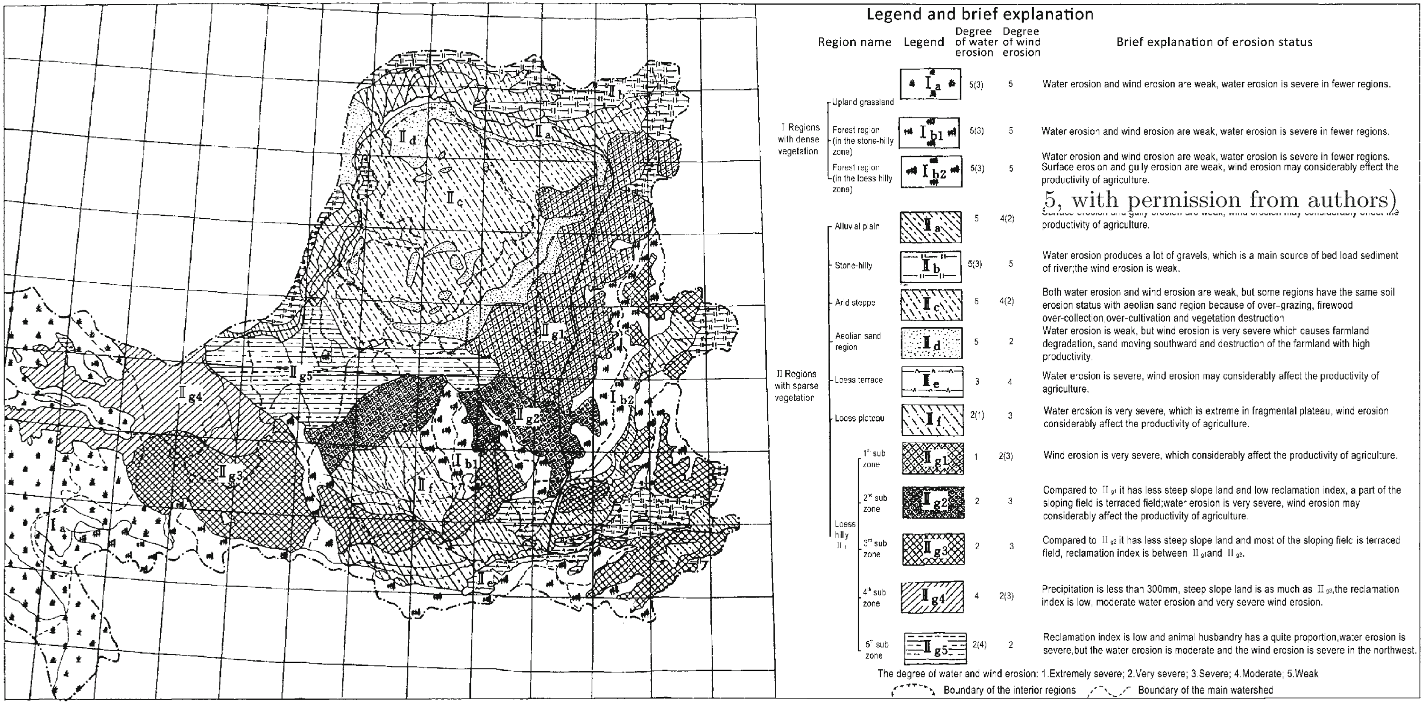

Fig. 5.1 Soil erosion regions in the middle reaches basin of Yellow River (Huang, 1955, with permission from author)

eas, uplands and the high mountainous areas of Xinjiang, Gansu, and Yunnan are all part of the freezing-melting erosion region. The other parts of mountainous and hilly areas of China are part of the water erosion region. Water erosion regions are distributed on the eastern part along the Da Xing'anling, Yinshan and Helan mountains as well as the Qinghai-Tibetan Plateau. The water erosion region includes six subregions, i.e., the Loess Plateau, the low hilly and mountainous areas in northeast China, the mountains and hills of north China, the mountains and hills of the south China, the Sichuan Basin and its surrounding hills and lowland area, and the Yunnan-Guizhou Plateau. The national soil erosion zones described in the "Standards for classification and gradation of soil erosion" enacted by the Ministry of Water Resources in 1997 (MWR, 1997), and the National Ecological Environment Improvement Plan issued by the State Council of China in 1998 applied the erosion regionalization described in Table 5.1.

Table 5.1 National water erosion regions (MWR, 1997)

Region	Scope and features
Loess Plateau in Northwest China	The eastern side of the Da Xing'anling, Yinshan and Helan mountains, the eastern edge of the Qinghai-Tibetan Plateau, and the Riyue Mountains of Qinghai are the western border, the Helan Mountains are the northwestern border, the Yinshan Mountains are northern border, the Guanqin Mountains and the Taihang Mountains are the eastern border, and the Qinling Mountains are the southern border. The Great Wall forms the center line, the northern part is the Ordos Plateau, and the southern part is the Loess Plateau. In the early and middle periods of the late Pleistocene, aeolian loess approximately 100–200 m thick accumulated on the Shaanxi-Gansu-Ningxia Basin. Since the Quaternary Period, new tectonic movement has largely occurred by means of intermittent uplift. The basin became the Loess Plateau. Zonal soil types from west to east are grey drab soil, black loam soils and drab soil in the sub-humid climatic zone, and grey calcium soil, brown calcium soil and chestnut soil in the arid and semi-arid climatic zones. Soil erosion on the Loess Plateau is extremely severe. Among the nine sub-regions, the loess hilly and gully sub-region and the plateau gully sub-region have the most severe soil erosion. An 110,000 km^2 area in the Hekou-Longmen catchment section of the Yellow River is the most severely eroded region and the main source of coarse and silt sedimentation in the Yellow River. The main watershed covered is the middle reaches of the Yellow River.
	The southern part of Jilin Province is the southern border and the Changbai, Da Xing'anling, and Xiao Xing'anling mountains are the borders in the other three directions.

Continued

Region	Scope and features
Black soil region (low mountains and hills and the rolling hill region) in northeast China	Songnen Plain is a rolling hill region. The topography of the diluvial and alluvial piedmont tablelands of the extension of the Da Xing'anling and Xiao Xing'anling mountains inclines roughly from northeast to southwest, interspersed with hilly ridges. The main geographic feature of this area is gullies alternating with hillocks. The typical well-developed black soil on the sandy shale on the second tableland of the Songhua River is eroded (moderately to severely). Northeast rolling hills and adjacent areas include (i) The Da Xing'anling and Xiao Xing'anling mountainous area which is part of the forest zone. The third uplift zone of the geologic Neocathaysian structure is where granite and shale predominates and dark brown soil is developed. Soil erosion is slight to moderate. (ii) The hilly areas of the Changbai-Qianshan Mountains are composed of forest and grassland. Granite, shale, and gneiss predominate, and dark brown soil and brown soil are well developed. Soil erosion is slight to moderate. (iii) The Sanjiang Plain area (alluvial plain of the Heilongjiang, Wusuli and Songhua rivers). Ancient riverbeds and low hillocks form a natural mound. Swamp meadows prevail in the bottomlands between rivers with plains distributed between them. Soil erosion is slight. The main watershed is Songhua River basin.
The earth-rock mountainous regions in north China	The rolling hills of northeast China are the northern border, the Loess Plateau is the western border, the Huaihe River is the southern border, and the region includes the southern part of northeast China and parts of Hebei, Inner Mongolia, Henan, and Shandong. The Taihang Mountain area is part of the warm temperate and subhumid zone and includes the Wutai, Xiao Wutai, Taihang, and Zhongtiao mountains, and the headwaters of five branches of the Haihe River. The area is mainly composed of gneiss and carbonate rocks. Brown soil is the main soil type. It has moderate to severe erosion and is the most seriously eroded region in northern China. The western Liaoning and northern Hebei mountainous area. Brown soil and chestnut soil are well developed on granite, gneiss, and sandy shale. Debris flows occur frequently. Soil erosion in the Chaoyang region is the most serious. The entire region suffers from moderate erosion. The hilly area of Shandong (located on the Shandong Peninsula). Thin brown loam soil and brown soil are well developed on gneiss, granite and other rock types, particularly in the Yimeng Mountains. Soil erosion is moderate. The Altai Mountain area is located on the southern slopes of the Altai Mountains in Xinjiang and is a part of the Irtysh River watershed where alpine forest-steppe is the main vegetation. Soil erosion is slight.

Continued

Region	Scope and features
	Songliao Plain is the alluvial plain of the Songhua River and Liaohe River, excluding the Horqin Sandland. Thick black calcium soil and meadow soil are well developed. Soil erosion is slight in the lower hillocks. The Huang-Huai-Hai Plain. The alluvial plain of the Yellow River, Huaihe River and Haihe River. The Taihang and Yanshan mountains are the northern border and the Huaihe River and Hongze Lake are the southern border. Only slight erosion occurs in the hillock areas of ancient riverbeds. The main areas include the middle and lower reaches of the Yellow River, and the Huaihe and Haihe River watersheds.
The red soil hilly regions in south China	Dabie Mountain is the northern border, the Bashan and Wushan mountains are the western border (including the whole of western Hubei), the Yunnan-Guizhou Plateau is the southwestern border (including western Hunan and western Guangxi) and this region extends to the sea in the southeast, including Taiwan, Hainan Island and islands in the South China Sea. Zonal red and yellow soils are widely distributed in tropical and subtropical regions throughout the country, as well as purple soil and limestone soils. Soil minerals weather strongly under high temperature and humidity conditions. The hilly mountain area of the southern Yangtze River region is situated in the southern part of the Yangtze River with the Nanling Mountains as the southern border and the Yunnan-Guizhou Plateau as the western border, including the Mufu, Luoxiao, Huangshan and Wuyi mountains. Granite and clastic rocks constitute the mountains and hills, and small red basins are distributed between mountains and hills. Red soil, yellow soil, and paddy soils are well developed. The plain and hill region in Lingnan includes Guangdong, Hainan Island and eastern Guangxi. Latosolic red soil is well developed on granite and sandy shale, and a thick weathered granite layer exists in some parts. Serious collapsed erosion occurs. The plains area in the middle and lower reaches of the Yangtze River is located in the eastern area from Yichang, including the Hubei and Hunan plains, the Poyang Lake plain, Taihu Lake plain, and the Yangtze River delta plain. Soil erosion is slight. The main scope is the middle reaches of the Yangtze River and the Hanshui River basin, Dongting Lake and the Poyang Lake watershed as well as the middle and lower reaches of the Pearl River.

Continued

Region	Scope and features
	The Loess Plateau is the northern border, the red soil hilly region is the eastern border, and the Qinghai-Tibetan Plateau freezing-melting region is the western border. The region includes the Yunnan-Guizhou Plateau, the Sichuan Basin, and western Hunan and western Guangxi. It is located in the sub-tropical zone. In addition to carbonate rock, there are also granite, purple sandy shale, mudstone, limestone, etc.
	The region is characterized by tall mountains and steep slopes, more stones and less earth, high temperatures and abundant rainfall, karst landforms, and collapsed rocks. Landslides and debris flows occur widely and frequently.
	The Sichuan hilly mountainous area is also known as the Sichuan Basin. In addition to the Chengdu Plain, most of the area is covered by mountains and hills where purple-red sandy shale and clay shale predominate. Paddy soils such as purple soil and purple clay soil are typically well developed. The region is seriously eroded and debris flows occur frequently. It is one of the main silt production sources in the upper reach of the Yangtze River.
The earth-rock mountainous regions in south-west China	The mountainous areas of the Yunnan-Guizhou Plateau include the Xuefeng, Dalou, Wumeng and other mountains. Loess, red, and yellow-brown soils are typically well developed on carbonate rocks and sandy shale. A thin soil cover and exposed bedrock are the main surface features. Calcium soil is distributed in the plain regions. Karst landforms are the primary erosion mechanism. Soil erosion is slight to moderate.
	The Hengduan Mountain area includes the mountains and valleys of southern Tibet, the Hengduan and Wuliang mountains and the Xishuangbanna region. Loess, red, and dry red soils are typically well developed on metamorphic, granite, and clastic rocks. Soil erosion is slight to moderate and serious debris flows occur locally.
	The Qinling and Dabie mountains and the western Hubei mountainous regions are located between the Loess Plateau and the Huang-Huai-Hai Plain in the north and Sichuan Basin and the middle and lower reaches of the Yangtze River Plain in the south. Thick yellow brown soil is typically well developed on the light metamorphic and granite rocks. Soil erosion is slight.
	The western Sichuan alpine meadow region includes the Daliang, Honglai, Daxueshan and other mountains composed primarily of clastic rocks. Brown loam soil and brown soil are well developed. Soil erosion is slight to moderate.
	The main scope is the upper and middle reaches of the Yangtze River and the upper reach of the Zhujiang River.

5.1.2 Regional characteristics (Tang et al., 2004)

Considering that desertification caused by water erosion primarily occurs in arid and semi-arid areas in northern China, this chapter only describes the Loess Plateau, the northeast black loam plain region and the northeast rock mountainous region.

5.1.2.1 Loess Plateau in Northwest China

The Loess Plateau, located on the upper and middle reaches of the Yellow River, includes the western Taihang Mountains, the eastern Helan Mountains, the northern Qinling Mountains and the southern section of the Great Wall of China. The total area is 480,000 km^2. During the national "Seventh Five-Year Plan" (1986 to 1990), the integrated management and development of the Loess Plateau was incorporated into the National Key Science & Technology Research strategy. Taking into account the need for land reclamation and disaster control for the Yellow River, its northern boundary was extended to the southern slope of the Yinshan Mountains, including adjacent areas of northern part of the Loess Plateau, covering a total area of approximately 624,000 km^2, which is known as the Loess Plateau region. Approximately 560,000 km^2 of the total area is located on the upper and middle reaches of the Yellow River between Longyangxia in Qinghai Province and Taohuayu in Henan Province; the remaining 60,000 km^2 is located in the adjacent Haihe River valley. The geographic location of the Loess Plateau is $33°43'$–$41°16'$ N and $100°54'$–$114°33'$ E and stretches across seven provinces and autonomous regions which are Shaanxi, Gansu, Qinghai, Shanxi, Ningxia, Henan, and Inner Mongolia, and 286 counties with a total population of 81 million people (1985).

Based on regional differences in erosion factors and erosion types and intensity, the zoning of soil erosion for the Loess Plateau can be divided into three classes: region, district, and subdistrict. Following comprehensive debate on relevant research, the regional soil erosion characteristics and approaches to erosion control in the Loess Plateau region have been summarized below.

(i) Loess Plateau soil erosion classification and characteristics

From the early 1950s to the period of the Seventh Five-Year Plan (1986 to 1990), the experience and progress of soil and water conservation, especially the massive data accumulated in hydrological stations constructed along the Yellow River valley region, provided significant scientific and practical data for the classification of soil erosion.

A large amount of survey and research data including the background environmental status described above were used to develop the erosion types and intensity levels, also considering the demand for sustainable development of resources in the Loess Plateau region. The principles of soil erosion classification must not only reflect regional differences of soil erosion, but also serve soil and water conservation regionalization and planning requirements.

The principles must also take into account the interdependence between soil erosion control and resource exploitation, and environmental protection and industrial development as well as transitional relationships between water erosion and wind erosion at regional levels.

Tang and Chen (1990), based on their long term field observations and studies on general zonation differences of water erosion and wind erosion, identified that the overlying water and wind erosion belt had particular erosion characteristics which have great significance for the sustainable resource management and development of the Loess Plateau region. Moreover, they classified this belt as a complex water and wind erosion region. Yiduan Huang and Pincang Zhang developed a specific three-class system for soil erosion classification of the Loess Plateau region, i.e., region, district, and subdistrict. Based on intra-regional similarities and inter-regional differences of geomorphology, erosion force, type and intensity, and the development trends and management approach, the former two classes are generally used, while the third class is only used in combination with erosion types for large area erosion regions (Table 5.2) (Tang and Chen, 1990).

Table 5.2 Soil erosion classification of the Loess Plateau region (Tang and Chen, 1990)

Region	District	Subdistrict
I Wind erosion on Ordos Plateau	I_1 Slight wind erosion district in the Helan Mountain area	
	I_2 Slight wind erosion district in the Yinchuan Hetao Plain	
	I_3 Moderate wind erosion district in the foothills of the southern Yinshan Mountains	
	I_4 Severe wind erosion district at the southern edge of the Tengger Desert	
	I_5 Extremely severe wind erosion district in the Hedong Sandland	
	I_6 Severe wind erosion district in the Mu Us Sandland and the Qubqi Desert	
II Complex wind and water erosion districts in the northern part of the Loess Plateau	II_1 Slight wind and water erosion district in the northern Shanxi Basin	
	II_2 Slight wind and water erosion district in the eastern Qinghai Mountains	II_{2a} Daban and Laji mountains subdistrict II_{2b} Yellow River-Huangshui River valley subdistrict
	II_3 Moderate wind erosion and slight water erosion district in the low Mountains and hills of southern Ningxia and central Gansu	

Continued

Region	District	Subdistrict
	II_4 Slight wind erosion and severe water erosion district in the low mountains and hills of southern Ningxia and eastern Gansu	II_{4a} Huang County subdistrict II_{4b} Liangxi subdistrict
	II_5 Moderate wind and severe water erosion district in the gentle hills of northwestern Shanxi Province	
	II_6 Moderate wind erosion and extremely severe water erosion district in the loess hills of northern Shaanxi Province	II_{6a} Baiyu Mountain subdistrict II_{6b} Suide-Mizhi subdistrict
	II_7 Severe wind and water erosion district in the sandy loess hills of Shanxi, Shaanxi, and Inner Mongolia	
III Water erosion areas in the southern part of the Loess Plateau	III_1 Slight water erosion district in the mountains of Shaanxi and Gansu provinces	III_{1a} Guan-Long Mountain subdistrict III_{1b} Northern slope of Qinling Mountains subdistrict
	III_2 Slight water erosion district in the Huanglong and Ziwuling mountains	
	III_3 Slight water erosion district in the valleys along the Fenhe River and the weihe River	
	III_4 Slight water erosion district in the Taihang Mountains	
	III_5 Slight water erosion district in the Luliang Mountains	
	III_6 Slight water erosion district in the valleys and hills of southeastern Shanxi Province	
	III_7 Slight water erosion district in the loess tablelands and low mountains of western Henan Province	
	III_8 Moderate water erosion district in the basins and valleys of central Shanxi Province	
	III_9 Moderate water erosion district in earth-rock hills and low mountains of western Gansu Province	

Continued

Region	District	Subdistrict
	III_{10} Severe water erosion district in the loess hills of western Gansu Province	
	III_{11} Severe water erosion district in the loess tablelands of Shaanxi and Gansu provinces	
	III_{12} Severe water erosion district in the loess hills and relic tablelands of northern Shaanxi and western Shanxi provinces	III_{12a} Liulin-Yanchuan subdistrict III_{12b} Jixian-Yichuan subdistrict

(ii) Outline of soil erosion classification for the Loess Plateau region (Tang et al., 2004)

i) Wind erosion on the Ordos Plateau (I)

The Ordos Plateau is surrounded by Helingeer County and Dongsheng City in Inner Mongolia to the east, Yulin City in Shaanxi Province, and the Helan Mountains to the west, the Yinshan Mountains to the north and the Great Wall to the south. The plateau includes the Mu Us Sandland and the Qubqi Desert, the Hedong Sandland, Yinchuan Hetao Plain and parts of the neighboring mountainous areas. This region is characterized by a desert landscape, arid climate, high transpiration rate, and limited annual precipitation (below 300 mm). Annual days with greater than or equal to force 8 winds (on the Beaufort Scale) can exceed 20 days (even 40 days or more in some districts). Annual dust or sandstorm days are 10 days or more (a maximum of 27 days in some districts). The vegetation is composed of desert steppe. Land management is focused on animal husbandry. Overgrazing can have serious consequences such as steppe degradation, wind erosion and a high rate of desertification spread.

According to the intensity of wind erosion and its particular characteristics, this region can be divided into six erosion districts.

The I_4 and I_6 districts are characterized as having severe or extremely severe wind erosion, and cover the edge of the Tengger Desert, the Mu Us Sandland, the Qubqi Desert and their marginal areas. Large areas of shifting sand and mobile dunes and the reactivation of fixed dunes have resulted in the expansion of desertification to the southeast. Establishment of artificial plantations of sand-fixing plants in Shapotou of Ningxia, for example, has successfully controlled desertification in that region. Taking full advantage of the fields on the plain along the Yellow River valley and the exploitation and utilization of groundwater resources, managed irrigated farming and fruit orchards have become the main agricultural activities in the region. The establishment of windbreaks, sand-fixation vegetation belts and the improvement of natural rangeland should also be promoted.

Districts classified as I_1, I_2, and I_3 are slightly or moderately eroded by wind. Wind erosion in the piedmont hills and the basins near the Helan and Yinshan mountains as well as the Yinchuan Hetao Plain is not severe. The management focus should be on the protection of existing vegetation. Moreover, the advantages of the Yinchuan Hetao Plain irrigation areas should be fully developed for sustainable agriculture.

The Hedong Sandland district (I_5) is extremely eroded by wind. Animal husbandry is the main economic activity, and population growth has resulted in serious over-cultivation and overgrazing, leading to a significant expansion of land desertification and the occurrence of severe wind erosion. The main tasks are to protect and improve rangeland and to control land degradation.

ii) Complex wind and water erosion districts in the northern Loess Plateau (II)

This region is broadly located with the southern boundary of the Great Wall and the northern area along Shenmu and Suide counties of Shaanxi Province; Yanchi, Lingwu, Xingxian and Guyuan counties of Ningxia Autonomous Region; and Qingyang, Dingxi and Dongxiang counties of Gansu Province. The geomorphology is mainly sand-covered loess ridges, hills and gullies. The underlying strata is mainly composed of aeolian sand, sandy loess, and severely weathered and denuded sandy shale.

The region is part of the semi-arid steppe zone and is covered with sparse vegetation where natural rangeland is mostly desertified and degraded. The annual precipitation is 250–450 mm. Water erosion is more prevalent during the summer and autumn seasons while wind erosion occurs in the winter and spring seasons. The total annual number of windy days greater than or equal to force 8 on the Beaufort scale (a fresh gale) are 5–20 days (up to 27 days in some districts). The mean annual days of sandstorms are more than 4 days (15 days in some districts). Water and wind erosions occur alternately throughout the year in the region. The ecological environment is vulnerable, and the erosion that affects the districts of the Loess Plateau is also the main source of coarse sand and silt sedimentation in the downstream riverbed region of the Yellow River.

This region is divided into seven districts and six subdistricts. Regional differences in characteristics are basically divided into three categories. The first category includes wind and water erosion, but the intensity is slight to moderate; the second category borders the water erosion area where intensive water erosion prevails with slight wind erosion; and the third category exhibits intensive wind and slight water erosion processes.

The districts in the first category include the northern Shanxi Basin (II_1) and the east section of the Qinghai Mountain basin valley (II_2) where slight wind and water erosions occur, and the low mountain hilly and gully district in southern Ningxia and the central part of Gansu (II_3) where moderate wind erosion and slight water erosion occur.

The two districts (II_1 and II_2) mentioned above have many basins, valley plains, or earth and rock mountain configurations. The annual precipitation is

300 mm to 400 mm, and the climate is dry and windy. Arable land is mostly located on flat depressions and basin and valley areas where gentle terrains have been affected by slight water erosion. Irrigation conditions also exist in some areas. Natural grazing lands are protected at certain scales, and forests are distributed on the shady hill slopes.

Due to topographic conditions and erosion types, the mountain basin valley districts in eastern Qinghai can be divided into two subdistricts. First is the Yellow River-Huangshui River valley subdistrict where the primary landscape type is farmland with gully and gravity erosion formations in the key cropland areas. The other is the Daban and Laji mountains subdistrict where farmland practices and freezing-melting processes have caused slight erosion to the landscape.

Another district (II_3) is the low mountain hilly and gully areas of southern Ningxia and the central part of Gansu, including all or parts of Lanzhou, Baiyin, Gaolan, Yongdeng, Yongjing, Jingyuan, and Jingtai counties in Gansu Province as well as Tongxin and Haiyuan and other counties (cities) of the Ningxia Hui Autonomous Region. Annual precipitation in the subdistrict is less than 300 mm where stronger winds and serious drought occur. Vegetation coverage is very low and the majority of vegetation is grasses and shrubs. The protection and reintroduction of grasses and shrubs are the key control measures to mitigate drought and control erosion.

The second category in this region includes slight wind erosion and intensive water erosion in the low mountain hilly district in eastern Gansu Province and the southern Ningxia Hui Autonomous Region (II_4); moderate wind and severe water erosion in the gentle hilly plains district in northwestern Shanxi Province (II_5); and moderate wind erosion and extremely severe water erosion of the loess hill district in northern Shaanxi Province (II_6).

In these districts, severe water erosion is the result of sloping farmland erosion caused by deforestation, grassland degradation, and the inappropriate cultivation of hill slopes, as well as gully erosion in the gully tablelands and gravity erosion on the valley slopes. The erosion modulus is typically between 5,000 and 10,000 $t{\cdot}km^{-2}{\cdot}a^{-1}$. An important reason for the accelerating water and wind erosion is the lack of the "three materials" (fuel, feed and fertilizer) which leads to the destruction of vegetation. The Baiyu Mountain subdistrict (II_{6a}) in the II_6 district is the river source for the Wuding, Luohe and Yanhe Rivers. In addition to slope farmland erosion, gully and gravity erosion are also active while wind erosion is relatively strong. Consequently, the terrain is often covered with aeolian sand and the erosion modulus has increased to 10,000 to 15,000 $t{\cdot}km^{-2}{\cdot}a^{-1}$. Slope farmland management should therefore be prioritized, and, at the same time, catchment dams and ponds for watershed management should be constructed.

The third category in this region is the severe wind and severe water erosion located in the sandy loess hills in Shanxi, Shaanxi, and Inner Mongolia (II_7).

This district borders both sides of the Shanxi-Shaanxi Gorge of the Yellow River and along the northern periphery of the Great Wall, including all or parts of Shenmu, Fugu, Jiaxian, Hequ, Baode, Pianguan, Xingxian, Junggar, Dongsheng, Qingshuihe and other counties (banners).

The two landform types in the district are sandy loess hills or loess hills covered with sand. This district is located within the transitional zone between the Ordos Plateau and the Loess Plateau as well as between the arid and semi-arid bioclimatic transitional zones and between the water and wind erosion eco-zones. Agriculture and animal husbandry are the common land uses in the area. Climate change is severe in the district due to the transitional zones, and consequently, it is a typically vulnerable ecological zone.

The mean annual precipitation is 400 mm and the rainfall distribution is typically uneven within the year and between years. Strong wind conditions, dust storms, droughts, floods, and hail storms frequently occur. Soil erosion is active throughout the year while wind erosion occurs mainly in the winter and spring seasons. Denudation is severe and severe water erosion frequently occurs in summer and fall seasons. Wind and water erosions are due to both superposition and interactive acceleration leading to an increase in erosion where the erosion modulus reaches 15,000 to 20,000 $t{\cdot}km^{-2} \cdot a^{-1}$. The district experiences the majority of severe erosion conditions in the Loess Plateau.

The district was a key pastoral area in the past and was once densely vegetated with grasses and shrubs. However, population growth and inappropriate agricultural practices and overgrazing are leading to transition zone vulnerability, and subsequently, the rapid deterioration of the ecological environment. This district contains abundant coal resources, and three large coalfields are presently under exploitation in Hedong, Shenfu, and Dongsheng counties where the largest coal deposits are found. They will be developed in China as energy and chemical industry bases in the 21st century.

Severe water and wind erosion in the border areas of Shanxi, Shaanxi, and Inner Mongolia are not only key sand sedimentation sources for the Yellow River, but also an important constraint for coal mining and the development of agriculture, forestry, and animal husbandry. This district has been listed as a priority area that should be given primary importance for the sustainable development of the Loess Plateau.

The coalfield development project was officially launched in 1987. This state scale project has not only promoted the development of the coal mine industry, migration from rural to urban areas, and the rapid development of railways and highways, but has also targeted the demand for local environmental and agricultural improvement as well as a need for sideline product development. These new situations and perspectives are helpful in developing soil and water conservation to reach to new level of sustainability, accelerating water and wind erosion control and ecological improvement. However, these developments have also caused further soil erosion and environmental deterioration by means of coalfield development.

iii) Southern Loess Plateau water erosion region (III)

The northern section of this region is connected to the wind and water erosion eco-zone while the southern section extends to the northern slopes of the Qinling Mountains. Landform types are complex, such as loess hills, loess tableland, river valley plains, earth and rock hills, and mountains. Annual precipitation varies from 500 mm to 700 mm. The climate is warm and humid. Forest and forest steppe are the main landscape types.

Slight water erosion areas are distributed throughout the mountainous and tableland areas while flat plain areas are typically covered with vegetation. Moderate water erosion areas mainly occur alongside valleys, on earth and rock hills, and lowlying hills. The most severe water erosion areas are distributed on the loess hills. Twelve erosion districts and four subdistricts have been identified according to topography, vegetation, land use, and erosion intensity. They can be divided into four categories.

The first category comprises of the mountainous areas which are well covered with vegetation and shrubland and experience slight water erosion. This includes the water erosion mountain district in Shaanxi, Gansu Provinces (III_1), the slight water erosion district of the Huanglong and Ziwuling mountains (III_2), the slight water erosion district of the Taihang Mountains (III_4), and the slight water erosion district of the Luliang Mountains (III_5).

This category is primarily composed of rocky mountains with some loess hills. Annual precipitation is abundant, varying from 600 mm to 700 mm, while the climate is warm and humid. The region is primarily covered by natural secondary forest or dense forest and shrub vegetation. Water erosion is slight and the erosion modulus is typically less than 1,000 $t{\cdot}km^{-2} \cdot a^{-1}$.

With population growth and migration into the forested regions, forest vegetation has become severely damaged and the cultivation of crops on steep slopes has led to accelerated erosion where frequently occurring mountain torrents and debris flows have been the result. In the forest region of the loess hills on Ziwuling Mountain where deforestation and grassland degradation are severe, the edge of the forest region has receded 20 km in approximately 30 years, leading to the rapid acceleration of soil erosion processes. The protection of the remaining vegetation should be strengthened while deforestation should be strictly controlled. Moreover, forest conservation in these mountain forest regions and the secondary forest regions of loess hills should be continuously supported while existing forests and woodlands must be enclosed to prevent further deforestation.

The second category has slight water erosion, and primarily consists of gentle tablelands, plains, and flat fields. These include: the slight water erosion valley district alongside the Fenhe River in Shanxi Province and the Weihe River in Shaanxi Province (III_3); the slight water erosion districts in the basin valley hilly areas in southeast Shanxi Province (III_6); and the loess tablelands and low mountain district in western Henan Province (III_7).

The main land use in this category is farming. The farmlands that suffer from slight erosion are distributed throughout the gentle flat lands or tablelands which in some areas can be irrigated. Erosion occurring on the side slopes of the tableland and the broken tableland gullies is severe. Erosion developed after brushland and vegetation on local hills were destroyed. Terraced lands on hills should be protected while irrigation projects should be installed to make full use of potential productive land. At the same time, biological and engineering measures to protect tablelands and control gullies should be adopted.

The third category is the moderate water erosion districts of the basin valley hilly region, including the moderate water erosion district of the basin valley hills in central Shanxi Province (III_8) and the moderate water erosion district of the earth rock hills and low mountains in western Gansu Province (III_9).

Most farmland in this category is distributed throughout the tablelands, river valleys, and gentle slopes of hills. Erosion in this region is relatively minor. Gully and gravity erosions usually occur on broken tablelands. The erosion modulus is greater than 2,500 $t \cdot km^{-2} \cdot a^{-1}$ and can reach 5,000 $t \cdot km^{-2} \cdot a^{-1}$ in the earth-rock hilly region of western Gansu Province. Land management practices should be used to improve the construction of basic farmlands so that vegetation is reintroduced to degraded grasslands and degraded shrublands and the further protection of existing forests in the gully and gravity erosion affected areas is enhanced.

The fourth category is the severe water erosion districts of the hilly and gully region of the Loess Plateau, including the severe water erosion district of the loess hills in western Gansu Province (III_{10}), the severe water erosion district of the loess tableland in Shaanxi and Gansu provinces (III_{11}), and the severe water erosion district of the loess hills and the broken tablelands in northern Shaanxi and western Shanxi provinces (III_{12}).

Inappropriate cultivation practices and grassland destruction have led to deforestation and sparse vegetation in the region. Erosion primarily occurs on farmland slopes. The gully density is 3–5 $km \cdot km^{-2}$ where gully erosion has obviously occurred. Landslides, collapses, and other gravity erosion events often take place, particularly on the broken tablelands in the gully region. The erosion modulus is 5,000 to 10,000 $t \cdot km^{-2} \cdot a^{-1}$.

Reintroducing vegetation to steeply sloping land is the key control measure. This includes leveling land on tablelands and basic farmland operation as well as the protection of tablelands and the control of gully erosion. Gully erosion control should be combined with the installation of dams or reservoirs as well as the reintroduction of vegetation. Moreover, cash crop plantations and reforestation to target ecological efficiency and economic benefits should be prioritized. For example, gully slope management in the Luochuan and Changwu uplands has occurred by means of reforestation on a large scale through the plantation of apples, pears, and other fruit trees as well as cash crops.

5.1.2.2 Northeastern low hilly mountains and undulating hilly region

The southern boundary of this region extends to the southern section of Jilin Province while the eastern, western, and northern sections are surrounded by Da Xing'anling, Xiao Xing'anling, and Changbai mountains. Soil erosion occurs to some extent in the region beyond the Heilongjiang, Songhuajiang, and Nenjiang river plains and the forested area of the Da Xing'anling Mountains and the Xiao Xing'anling Mountains. Based on landforms and erosion types, the region can also be divided into four districts: the Da Xing'anling Mountain district, the Xiao Xing'anling Mountain district, the low hilly mountain district, and the undulating hilly district.

(i) Da Xing'anling Mountain district

The geological formation of the district is the third uplift belt of the Neocathaysian system that primarily consists of volcanic rock. The topography is high in the western and northwestern areas and low in the eastern and southern areas where the elevation ranges from 300 m to 1,400 m. Undulating mountain formations are mostly surrounded by low mountain hills and broad valleys. The district is part of the frigid temperate climate zone where the summer season is short and the winter season is long and cold.

The Da Xing'anling Mountains in Heilongjiang Province cover a total area of 84,700 km^2, of which 72,800 km^2 is affected by potential soil erosion. The soil erosion area is 25,300 km^2 (or 29.9% of the total land area), of which 379 km^2 is severe, 583 km^2 is moderate, and 24,370 km^2 is slight, accounting for 1.5%, 2.3%, and 96.2% of the total erosion area, respectively. The primary erosion types include gravel surface erosion, rill and gully erosion, river course erosion, collapse, slump, and freezing-melting process erosion.

Unsustainable forest cutting and bushfire practices have led to further erosion and flood damage in the district. According to local records, during the 32-year period between 1955 and 1986, only eight floods took place causing moderate damage, but during the five-year period from 1987 to 1991 (including the infamous "May 6th" bushfire), three severe floods took place causing massive damage. The extreme flooding seen in 1991 was especially severe in comparison to historical records where Tahe City in Heilongjiang Province was washed away leading to 130,000 people homeless with an associated economic loss estimated at 510 million RMB.

In this region, outcrops of sandstone caused by soil erosion from burning and cutting activities have led to an area of 379 km^2 of open deforested land and sloping farmland where debris and mudflows frequently occur in steeply sloping areas. In addition, collapsed riverbanks and soil roughness on sloping farmland are under serious threat of soil erosion as the erosion modulus of sloping farmland is between 5,000 and 8,000 $t{\cdot}km^{-2} \cdot a^{-1}$, and exceeding 9,000 $t{\cdot}km^{-2} \cdot a^{-1}$ in some seriously affected areas.

(ii) Xiao Xing'anling Mountain district

The Xiao Xing'anling Mountain district is located in the northern part of Heilongjiang Province with a total area of 115,000 km^2. The mountain range extends from southeast to northwest, and the elevation ranges from 250 m to 1,000 m. Broad mountain topography, gentle slopes, and low mountain hilly regions account for 85.3% of the total land mass while pediment tablelands cover 12% and alluvial plains cover 2.7%. The mean annual precipitation is 523 mm. Although forest coverage is greater in this district, the risk of soil erosion prevails in many hilly regions where flood events are frequent natural disasters. For example, in the forest region in Yichun County six floods took place in the 1980s that have caused a direct economic loss of approximately 400 million RMB.

According to a survey done in 1985, the area of soil erosion in the Xiao Xing'anling mountain region was 2,480,900 ha, accounting for 21.55% of the total land area, of which 1,250,900 ha was farmland, 21,100 ha was wasteland, and 1,208,900 ha was woodland and forestland. Rill erosion has occurred on sloping farmland, and fish-scale erosion has occurred in the wasteland areas covered by sparse vegetation. Gully erosion prevails alongside unsealed roads of the logging area, and landslides occur along riverbanks.

The Da Xing'anling and Xiao Xing'anling mountains are important timber bases in northeastern China, an area where forest resources should be continuously supported and illegal cutting should be strictly prohibited. The prevention of bushfires and gully erosion caused by unsealed roads must be undertaken, and a monitoring network should be established.

(iii) Low hilly mountain district

This district contains the central and eastern sections of Jilin Province, the Tangwang River valley located in the southern Xiao Xing'anling mountain region, the upstream region of the Woken River valley on the western periphery of the Wanda mountains, the Mudan River valley, the Mayi River valley, the Ashi River valley, and the Lalin River valley all located in the western Zhangguangcai Mountains. The elevation in the district varies from 200 m to 1,500 m.

The low mountain area is primarily composed of granite, local volcanic rock, and sandy shale. The landform of mountain summits is broad and flat. Soils with weathering crusts and humus layers are well developed. The hilly area is composed of metamorphic rock and red sandy conglomerates from the Tertiary Period with thick tectum structures. Due to a long period of development and a large amount of sloping farmland, sloping land with a gradient of more than 10° has been cultivated with a reclamation rate reaching up to 20%.

The district, however, comprises many natural secondary forests and therefore has a high coverage of vegetation. Most areas are slightly to moderately eroded by soil erosion mechanisms that prevail on land surfaces. Local gully erosion is the most serious erosion mechanism. In the Mudan River valley, the original thickness of the dark brown forest soil was 50 cm or more, and humus content reached up to 50 $g \cdot kg^{-1}$. With erosion, 5 mm of topsoil has washed away annually leading to an annual topsoil loss of approximately 3,000 $t \cdot km^{-2}$

to 5,000 t·km^{-2}. In the low mountainous hills of western Liaoning Province, rainfall is scarce and the rapid development of sericulture has resulted in land degradation and desertification. Large scale sericulture has also caused serious soil erosion in the Liaohe River valley.

(iv) Undulating hilly district

The undulating hilly district is located on the alluvial and diluvial fans of the Xiao Xing'anling Mountains piedmont plains and consists of a gentle and undulating topography. The elevation is between 180 m to 300 m above sea level, the relative difference in height varies from 10 m to 40 m and the boundary between hills and mountains is visible. This district is typical of the luxuriant meadow grasslands seen in the past. The land reclamation coefficient is as high as 0.7 in the district due to reclamation during the last five or six decades, and as result, the affected area and the intensity of soil erosion are increasing and becoming widely distributed in almost 20 counties. Erosion in this district is representative of the black soil region in northeastern China.

Soil erosion is severe along the Wuyu'er and Yanlu river valleys, the Nenjiang River tributary, the Hulan River valley, the Songhua River tributary, and is widely distributed in Keshan, Baiquan, Kedong, Wangkui, Bei'an, Yi'an, Hailun, and Longjiang counties. The area of soil erosion accounts for 40% of cultivated land in Keshan and Kedong counties, 47% in Wangkui County, 56% in Baiquan County, and 80% in Longjiang County. The thickness of soil has been reduced from the original 1–2 m to 0.2–0.3 m in Keshan County.

The slope gradient is less than 7° in the undulating hilly black soil area, and most of the area slopes between 2° and 4°. The length of slope in the area for typically ranges from 1,000 m to 2,000 m with a maximum of 4,000 m. The volume of water flow is significant and the flow rate is rapid, which increases the scouring force of flooding or runoff. The cultivated black soil layer has a total porosity of 60%, and the infiltration rate of topsoil over the 0 cm to 20 cm depth is 96 mm·h^{-1}. For many decades, under the impact of unsustainable indigenous farming practices, approximately 5 cm to 6 cm of plow pan below the fixed plough horizon was formed with a density of 1.5 g·cm^{-3} to 1.6 g·cm^{-3} and an infiltration rate of 2.5 mm·h^{-1} to 8.6 mm·h^{-1}. The subsoil layer and parent material horizon of the black soil terrain are primarily composed of loessial clay which has an inherently slow infiltration rate. When the moisture content of the topsoil reaches saturation, both soil erosion on the land surface and gully erosion will result. Permafrost can linger for almost 6 months during the long and cold winters with a thickness of approximately 2 m, and consequently, a waterproof aquiclude layer within the plough layer will form. Therefore, meltwater in the spring and subsequent rainfall or runoff in summer cannot be absorbed within the short timeframe, and consequently, excessive runoff can occur on slopes and floods in the valleys may also occur, leading to soil erosion and mudslides. The rainy season in this area is in the summer when more extreme weather events occur. Rainfall events occur where 120 mm to 160 mm of precipitation may fall in one session, and on occasion, as much as 200 mm can fall in one event. The maximum rainfall intensity recorded is 1.6 $mm \cdot min^{-1}$. Such concentrated rainfall and water volume has accelerated soil erosion in the black soil region in northeastern China.

The main forms of soil erosion in the district are land surface erosion, gully erosion, and wind erosion. Approximately 0.5 cm to 1.0 cm of topsoil is lost to land surface erosion each year where the erosion modulus ranges from 6,000 to 10,000 $t \cdot km^{-2} \cdot a^{-1}$. Gully erosion is closely related to the intensity and time scale of land reclamation. The average frequency of gully erosion in the southern region is higher than that in the northern region. The gully density typically ranges from 0.5 $km \cdot km^{-2}$ to 1.2 $km \cdot km^{-2}$ and the highest density is 1.61 $km \cdot km^{-2}$. The annual development speed of the gully outlet averages approximately 1 m with peaks at 4 m to 5 m annually.

Long term soil erosion effects have caused the black soil layer to gradually thin and the subsoil to be exposed in some areas. On some soil types with low fertility, such as black loess soil, yellow black soil, and yellowish biological soil, a crust has formed. The deterioration of physical and chemical properties in soil causes further development of soil erosion to the point where the land is abandoned and wasted. For example, the area of abandoned barren land caused by soil erosion around Dongfeng Village in Gubei Township, Keshan County, and Jilin Province is 60 ha, and on average 6 ha to 7 ha is abandoned each year.

The black soil region of northeastern China, where landforms are primarily composed of undulating hills, plains, and platforms, is a key area for the control of soil erosion. This area mainly encompasses the eastern and northern sections of the Songnen Plain distributed between Nenjiang and Bei'an counties in Heilongjiang Province in the north, Siping County in Jilin Province in the south, the edge of Da Xing'anling Mountain in the west and Tieli City and Bingxian County in Heilongjiang Province in the east. It includes 32 counties (cities and districts) and forms an integral black soil zone. In this region, the cultivation rate is as high as 60% to 70%, and soil erosion occurs primarily on sloping terraced farmland which represents 86% of the total erosion area. Due to soil erosion and deterioration of the ecological environment, droughts and floods occur frequently and have become more serious than they were in the past. Management of sloping farmland is a key approach to controlling soil erosion in the black soil zone. Terraces should only be built on sloping farmland with a gradient of less than 15°. Infertile sloping farmland with a gradient greater than 15° must be reintroduced back into forest or grassland. Shelterbelt networks should also be established alongside these soil erosion control measures.

5.1.2.3 Mountainous hilly region in northern China

This region covers the southern undulating hilly section of northeastern China as well as the eastern section of the Loess Plateau and the northern section of the Huaihe River, including the mountainous and hilly areas where erosion prevails in the southern section of northeastern China, Hebei, Shanxi, Henan, Shandong, Inner Mongolia and other provinces and autonomous regions. The topography in this region is characterized by two specific features described below.

First, plains are typically surrounded by mountains and hills. For example, the North China Plain is surrounded by the Yanshan Mountains in the north, the Taihang Mountains in the west and a series of residual ridges formed in conjunction with the curving shape of the Qinling Mountains in the south. Similarly, the Liaohe River Plain is surrounded by the mountains in eastern and western Liaoning Province.

Second, alpine areas, low mountains, hills, valleys and plains are interspersed in terrace formations. For example, the elevation of the mountains in Weichang and Fengning counties in northern Hebei Province is approximately 1,500 m, the elevation of the mountains in Chengde and Qinglong counties is 1,000 m, and the elevation of hills and valleys in Zunhua and Qian'an is less than 500 m. The primary geomorphologic features of the Taihang Mountains in northwestern Henan Province are high and low mountains, hills and intermountain basins where the average elevation of mountains is 1,000 m to 1,500 m, the elevation of the low mountains and hills is typically 400 m to 800 m and the elevation of the Linxian depression is approximately 300 m.

These geomorphologic features suggest that water erosion, and debris flows that prevail in the mountainous and hilly areas have resulted in sedimentation of river courses and show that soil erosion and floods are related to each other. Therefore, floods that occur in the Haihe River Plains region are related to soil erosion that occurs in the Taihang Mountain region; floods that occur in the Liaohe River Plain area are related to soil erosion that occurs in the mountainous areas of eastern and western Liaoning Province; and floods that occur in the Huaihe River Plain area are related to soil erosion that occurs in the mountainous areas of eastern Henan Province.

Taking into account the various landforms in the erosion regions, including erosion formations and the differences in sediment material seen in rock mountains, earth rock mountains and loess hills, this region is characterized by soil erosion in both the earth rock mountains and the Loess Plateau in northern China. Accordingly, the region can be divided into three districts.

(i) Loess covered low mountains and hilly district

The foothills of the low mountains and the uplands of the hills are extensively covered by loess soil. For instance, the hills and piedmont plains on both sides of the Liaohe River Plain, the Taihang and Yanshan Mountains in Hebei Province, and the low mountains and hills in western Henan Province are all covered by loess soil. Further distribution of residual loess soil occurs in some valleys in eastern Liaoning Province and the Shandong Peninsula. The types of erosion in this district are similar to the Loess Plateau region. The thickness of the loess soil varies from a minimum of several meters to a maximum of twenty meters. The mean annual precipitation is 400 mm to 500 mm. Sloping farmland erosion that developed from land surface erosion and gully erosion is the primary erosion mechanism. The erosion modulus is approximately 4,000 $t \cdot km^{-2} \cdot a^{-1}$. Soil erosion and sedimentation occur primarily during the rainy season from June to September and the most severe erosion events take place in July and August. Gravity erosion types like landslides and collapses that are the principle types of erosion on the Loess Plateau can also be seen within this district.

(ii) Rocky and earth rock mountainous and hilly district

The medium and small rock mountains or earth rock mountains and hills are covered in a thin layer of coarse soil, and are composed primarily of sandy shale, limestone, outcrops, and gravel formed under strong weathering and denudation. The bedrock is mostly exposed due to steep slopes and shallow soil layers. Following vegetation loss and heavy rains, all types of severe water erosion can occur and even debris flows can be a result. Disastrous debris flows have occurred in the Xishan Mountain range in Beijing and its adjacent districts, such as Nankou, Zhaitang, Xiangshan, Miaofengshan, and Yanqing. Evidence of ancient debris flows has been found in areas along the Luanhe River valley. For example, four large scale events took place in Luanping, Xinglong and Qinglong between 1958 and 1971. Massive debris flows have been known to wash through and clog up river courses. The riverbed of the Wulie River in Chengde City was clogged with silt between 1–3 m deep when the flood discharge capacity was reduced by one third. The riverbed of the Luanhe River has risen between 0.1 and 0.3 $m \cdot a^{-1}$ on average, greatly reducing the flood control capacity of the river course.

Precipitation and soil erosion intensity in this district are as follows:

In the mountainous areas of Weichang and Fengning counties in Hebei Province, the annual precipitation is 400–500 mm, the mountain slope gradient is up to 30° in most areas, vegetation coverage is as high as 50% to 70% and the annual erosion modulus is 800 to 1,300 $t \cdot km^{-2} \cdot a^{-1}$.

In areas with small mountains, the slope gradient is 20° to 30°, vegetation coverage is approximately 30% to 50%, and the erosion modulus is 1,500 to 1,800 $t \cdot km^{-2} \cdot a^{-1}$.

In the Taihang Mountain district, medium sized mountains, low mountains, hills, basins, and valleys are interspersed and form the headwaters of the most tributaries of the Haihe River. The annual precipitation increases gradually from 500 mm to 600 mm in the southern section and from 700 mm to 1,000 mm in the northern section, where more than 80% of rainfall occurs during storms in the months from June to September. The earth rock mountainous area has an elevation of less than 800 m and has become a barren hilly area due to unsustainable human activities. It is susceptible to floods and debris flow disasters. This area is the most severe soil erosion area within the Taihang Mountain district. These remote mountains with an elevation of 800 m or more are densely vegetated and, without the burden of human economic development activity, soil erosion is slight. Reforestation and the reintroduction of vegetation and other engineering measures should be carried out in this district to increase vegetation coverage to guarantee its water storage capacity and to enhance water and soil conservation.

The headwaters of the Huaihe River are located in the Xiong'er and Funiu mountains in western Henan Province. Soil erosion occurs in some areas due to sparse vegetation. The annual erosion modulus is 1,300 $t{\cdot}km^{-2} \cdot a^{-1}$. This area includes the low mountains and hills of the Songshan Mountains in Henan Province, in addition to local valleys with limited secondary forest coverage. Most mountainous areas are covered in grassland and most hills have bare exposed rocks, resulting in severe soil erosion.

(iii) Severe wind erosion district on the Bashang upland,Hebei Province

The Weichang part of Bashang upland located upstream of the Luanhe River region was a luxuriant grassland in the early 1950s. Now, other than in reserved forests and orchards, severe wind erosion occurs in most sections of the district and serious desertification-prone land area covers approximately 350 km^2. There are as many as 950 sand mounds and sand pits with a volume greater than 100 m^3, and sandy areas cover approximately 67 km^2 in the severely affected areas of Yudaokou.

From the early 1950s to the end of the 20th century, the population of the Fengning part of Bashang upland has doubled. Grasslands or grazing lands have been reduced from 860,000 ha to 510,000 ha. Arable land has increased from 400,000 ha to 700,000 ha and pastures are over-grazed and over-loaded by more than 100%. Severely degraded grazing lands and sandy grasslands are the result of a sharp increase in sand-dust storm frequency and intensity, threatening the natural ecology and the living environment of Beijing, Tianjin, and the adjacent provinces and autonomous regions. The frequency and intensity of all types of natural disasters on the Fengning part of the Bashang upland, has increased from three to five events per year in the 1960s to eight events per year in the 1970s. The frost-free period has reduced from 94 to 80 days, and the number of days of strong winds has increased by up to 40%. During the last three decades, due to the ongoing destruction of vegetation, desertification processes have accelerated and started to expand in the Weichang part of the Bashang upland. The area of desertification-prone land has expanded and now occupies 36.4% of the total area of the affected lands of the county.

This district must be protected against overgrazing and over-cultivation and biological measures such as tree and grass planting should be strengthened. Windbreaks and sandbreaks to stabilize dunes and sand should also be established.

5.2 Damage from soil erosion

Long term soil erosion will result in the loss of land resources as well as the deterioration of soil quality, which may threaten local agricultural production. In addition, large amounts of sediment will be transported into valleys and will clog river courses, causing damage by contaminating rivers, catchments, reservoirs, and lakes, and eventually reducing the availability of the water resource. River courses and reservoirs become blocked with silt, which increases flooding risks and decreases the serviceability of the water system.

5.2.1 Impacts of soil erosion on land productivity

Data from the World Resources Institute (WRI) "Survey Report of the World Observation Research Institute" asserts that 26.4 billion tons of soil is lost globally every year as a result of cropland production. The soil erosion in China is particularly severe where the total area of land affected by soil erosion is approximately 3.56 million km^2, accounting for 37% of the total land territory. It is estimated that the annual volume of soil loss is 5 billion tons, which means that the equivalent of 3 mm of fertilized cropland topsoil is washed away each year over the entire country. The resulting nutrient loss of N, P, and K equals to 40 million tons of fertilizer, exceeding the total production of fertilizer in China. It is also estimated that more than 10 billion RMB has been lost due to the degradation of croplands and the reduction in productivity of arable lands caused by soil erosion since 1950s.

It is estimated that the total volume of organic matter loss, including nitrogen and phosphorus, caused by wind erosion in sandy desertification areas is 55.906 8 million tons, equal to 268.493 1 million tons of chemical fertilizers. Under the impact of wind erosion, crop yields have decreased by 20% to 25% and grassland productivity has been reduced by 30% to 40%. Pasture and grazing lands in the western section of Jilin Province have been reduced by up to 40% in recent years compared to the 1950s, which equates to a rate of decrease of 2% per year. The area of low yield grassland or grazing lands in western Jilin is approximately 689,000 ha and the yield of dried forage material is approximately 750 $kg \cdot ha^{-1}$. This is a 60% decrease in yield compared with the past. In the hilly gully areas of the Loess Plateau region in northern Shaanxi Province, the annual loss of soil nutrients by means of erosion equals to 2,250 $kg \cdot ha^{-1}$. The annual nutrient loss from sloping croplands is 17.9 times higher than the nutrient input from the total annual fertilizer application. The annual nutrient loss contained in sediments of red soil from sloping cropland areas in southern China is 89.8 $kg \cdot ha^{-1}$ of total nitrogen, 16.3 $kg \cdot ha^{-1}$ of hydrolysable nitrogen, 244.4 $kg \cdot ha^{-1}$ of total phosphorus, and 3,870.3 $kg \cdot ha^{-1}$ of total potassium.

Along the Yangtze River valley, there is approximately 11 million ha of sloping croplands and 36 million ha of barren hills as well as sloping land, sparse forest farms, and artificial plantations. The soil erosion modulus in steep croplands and barren lands is greater than 10,000 $t{\cdot}km^{-2} \cdot a^{-1}$. More than 400 million tons of sediments are annually transported into the Yellow River where some sections of the river course in the Shaanxi Province region of the Loess Plateau are clogged with silt.

It is estimated that 500 million tons of topsoil is lost annually in Yunnan Province. This volume is equivalent to the destruction of 160,000 ha of cropland, and also causes an annual loss of 9.75 million tons of organic matter, 720,000 tons of nitrogen, 1.2 million tons of phosphorus, and 5,000 tons of potassium.

In some parts of Zhushan County, Hubei Province (Zhang, 1999a), steeply sloping land has been cultivated and caused soil loss is equivalent to 1,067 ha of the ploughing layer. A heavy loss of soil nutrients has also occurred, equivalent to 14,000 tons of ammonium sulphate and 16,500 tons of superphosphate, 1.47 times and 9.8 times, respectively, of the total amount of the two chemical fertilizers consumed annually in the county.

Research data on the granite denudation area in southern China reveals that the topsoil in the denudation and erosion areas has been totally washed away, accounting for 20% to 40% of the total land area in the severely eroded region. The content of organic matter in the non-eroded red soil is four times higher than that of the severely eroded soil and eight times higher than that of the most severely eroded soil. Similarly, the content of total nitrogen in non-eroded red soil is 3.9 times higher than that of severely eroded soil and 40 times higher than that of the most severely eroded soil. In addition, the content of total phosphorus in non-eroded soil is 4.6 times higher than the severely eroded soil and 16.7 times higher than the most severely eroded soil. The content of organic matter in the severely and most severely eroded sites has decreased to 0.57% and 0.16–0.25%, respectively.

The main consequence of soil nutrient depletion due to soil is a decrease in land productivity, especially a reduction of crop yields. Experimental results in the Weibei Highlands, Shaanxi Province (Liu et al., 1992), showed that the yield of wheat will decrease by 22.5 $kg{\cdot}ha^{-1}$ to 43.5 $kg{\cdot}ha^{-1}$ for every 1 cm of topsoil that is lost under general conditions. Yang (1999) analyzed the spatial differences of N, P, and K content in soil and noted that these available soil nutrients will decrease in erosion conditions, especially on the topside of slopes where nutrients are rarely contained within soils. Erosion can reduce the amount of soil organic matter and change the soil texture (the ratio of sand, silt, and clay materials) causing soil roughness to occur on land surfaces. With the negative impacts of erosion on soil fertility, the reduction of land biomass productivity will result in the reduction of the economic productivity of land.

Water erosion will directly affect soil development and agricultural productivity (Xu, 1999). As the slope gradient increases, the intensity of water erosion will worsen and the humus layer will disappear completely. The thickness of the humus layer on gentle sloping lands with a gradient of less than 3°, for example, is approximately 65 cm to 75 cm, but when the gradient increases to 25° the thickness is only approximately 10 cm thick, which is also the case when intense water erosion occurs. The physical composition of soil is also correlated to the intensity of water erosion. For example, the content of clay particles (<0.01 mm) can be as high as 83.59% in the topsoil of sloping lands with a gradient of 3° to 5°, but can be reduced to 40% at 7° to 15°. Soil bulk density and porosity will also change, and, consequently, the physical and chemical properties of the soil and the nature of how the soil material moves will change. When the slope gradient is more pronounced, soil erosion is more severe, soil development worsens and land productivity decreases. In general, when the gradient increases by 1° in gently sloping areas, land productivity will decrease by 0.5% to 1%. When the slope gradient is greater than 15° and less than 25°, land productivity will decrease by 50% to 100% with an increase in slope of 1°, and when the slope gradient is greater than 25°, land productivity will decrease by 100% to 200% as the slope increases by 1°.

As the fertile topsoil is washed away, the soil layers become thinner. Soil thickness is an important factor for plant growth. When soil is saturated with water, the storage of soil nutrients and the spatial distribution of root systems of plants are primarily affected by soil thickness. Water and nutrients are the fundamental materials that generate plant growth, but growth is limited by soil thickness. The thicker the soil layer, the greater its water holding capacity, and with higher moisture and nutrient contents in the soil, the plants will grow better. Moreover, a thick soil layer is helpful for root development and thus increases the distribution of root systems, providing more space for nutritional uptake. Therefore, a thick soil layer is more helpful to plant growth and regeneration. An effective soil thickness ensures that the root system distribution of crops, timber trees, fruit trees, and grasses is sufficient to maximize growth. A thick soil layer, which allows a wide root system distribution, can hold more water and nutrients improving plant regeneration and growth while enhancing plant suitability, tolerance, and productivity. Effective soil thickness, therefore, is a key factor when trying to identify the suitability and restrictions of land resources. Soil thickness, especially in mountainous regions, is the dominant limiting factor of agriculture, forestry, and animal husbandry. Generally, if soil thickness is less than 30 cm, the capacity of root systems to grow healthy crops, forests, fruit trees, and grasses will be directly limited.

Soil erosion are the primary mechanisms that damage fertile land, wash away ploughing layers and organic materials and, as a result, turn healthy soil into infertile soil and land resources into dead zones. The impact of soil erosion on land quality results primarily in the progressive deterioration of fertile land into unproductive or barren land. According to a survey report of forest resources in Guizhou Province, the rocky hill area has increased from 5% to 9.6% of the total land area in the province between 1975 and 1998. In Nayong County, Guizhou Province, topsoil on 17,000 ha of upland terrain was washed away due to soil erosion. The upland is now completely covered by rocky mulch or rocky desertification, and the productive land used in the past has been completely desertified and turned into wasteland or barren land. From the point of view of flood prevention, Liang and Shi (1998) conducted research on soil erosion. His results show that a topsoil layer with a thickness of 5 cm in moderate erosion zones on the upstream area of the Yangtze River can hold or absorb 7.8 mm of rainfall or runoff. On average, a topsoil layer with a thickness of 4 cm can hold or absorb 6.2 mm of rainfall. Applying this to the moderate soil erosion zone on the upstream area of the Yangtze River with an area of 352,000 km^2 would mean that if 4 cm of topsoil was washed away over a period of ten years, this would equate to a reduction in the total holding and absorption capacity of 2.197 billion m^3 of water. This is equal to 10% of the total water storage volume (22.15 billion m^3) of the Three Gorges Reservoir.

It is evident that the soil's water holding capacity is dramatically reduced due to the thinning of soil layers. According to data from the second national soil survey, the total area of soil resources in the upstream region of the Yangtze River is approximately 963,500 km^2, of which 90% is comprised of the sum of the areas of the 11 main soil types. Based on the weighted average area occupied by soil layers of various soil types, it can be concluded that the average soil layer thickness on the upstream region of the Yangtze River is 78.5 cm in depth. The water holding capacities of these soil layers mean that up to 430 mm of rainfall can be completely absorbed and stored without any runoff occurring. The maximum water storage capacity of the soil is 416.03 billion m^3 or 18.78 times that of the planned flood control storage capacity of the Three Gorges Reservoir.

The thinner the soil layer, the lower its water storage capacity will be, and the lower the soil moisture content, the weaker its ability will be to cope with drought. Consequently, in areas affected by soil erosion, rainwater or runoff will easily flow away as the water storage capacity of the soil is poor, resulting in crop and plant stress caused by drought and the lack of soil moisture. The potential for soil and water conservation, therefore, will obviously be reduced and the severity and intensity of soil loss will, without doubt, increase. These factors will interact with each other forming a vicious cycle.

5.2.2 Water erosion and water quality

Agricultural development brings about an increase in the land utilization rate and increases the use of pesticides and chemical fertilizers so that pollutant contents in cropland runoff also increase sharply. Floodwater or runoff from croplands can contain a large amount of sediment, various sorts of organic matter, inorganic materials, and nutrients like nitrogen and phosphorus as well as pesticide residues, which are important sources of pollutants in water bodies. Unlimited use of large amounts of chemical fertilizers and pesticides will reduce the water quality. Fertilizer runoff also increases the nutrient concentrations in water bodies which can accelerate eutrophication. The leaching of pesticides and chemical fertilizers into groundwater is a primary pollutant source of drinking water bodies. Certain varieties of fish and birds are sensitive and vulnerable to aqueous materials and sediments from foreign sources. Migration or extinction can be the result.

At present, pollution is the primary factor in causing global water quality deterioration. Data from the United States Environmental Protection Agency (US EPA) indicates that 50% or more of the water quality problems that the United States currently faces is probably caused by pollution sources. This shows that pollution sources are harmful to water quality and water body environments. Concerning agricultural development, large areas of wasteland were developed and cultivated increasing the utilization rate of the land, but resulting in further severe water erosion along river valleys and increasing nutrient contamination in the rivers. To add to this problem, both pesticides and chemical fertilizers were extensively used to increase land productivity. During periods of rain, croplands experience a series of physical, chemical and hydrological processes including surface flow, infiltration, scouring, adsorption, and confluence. Following those processes, runoff transports pollutants into rivers and accelerates the severity of water pollution. As a result, even in cases where all point source pollutants were fully controlled, the water quality in rivers, lakes, and reservoirs decreases by 42% to 65% (Zhu et al., 2000).

The World Fertilizer Conference concluded that approximately 30% of grain yield in developing countries is grown from chemical fertilizers. Agricultural land resource utilization in China is at the point of over-development and the irresponsible and increasing use of chemical products for agricultural production are the primary means to raise agricultural output.

Leaching of pesticides and chemical fertilizers into groundwater is another major way in which the water body can become polluted. According to the statistics from concerned agencies in the United States, approximately 10% to 15% of nitrogen fertilizer is leached into groundwater every year. The amount of chemical fertilizer application in China has increased by 90.7% from 1984 to 1994, but grain yield has increased by only 9.1%. Taking nitrogen fertilizers as an example, the total amount of fertilizer applied per unit area in China was 191.6 $kg{\cdot}ha^{-1}$, 3.55 times the world average, but grain yield per kg of added nitrogen was 20.95 kg, less than 50% of that the world average. The leaching of chemical fertilizers is, therefore, a primary factor in the low utilization ratio of nitrogen. According to a survey from the agricultural sector, the average utilization ratio of nitrogen in China is only 20% to 30% while the average leaching ratio of nitrogen is greater than 60%. The annual weight of nitrogen fertilizer applied in China is 20 million tons. It is assumed that if the annual leaching rate is 50%, nitrogen leaching will be as high as 10 million tons per year.

At present, there are more than 1,000 varieties of pesticides used in the world, with the annual weight of applied pesticide being greater than 1.80 million tons. In China, it has been found that more than 150 million ha of cropland uses pesticides to control plant diseases and insect pests, which results in a 7% increase in the total grain yield. However, field experiments show that only 20% to 30% of the pesticides used adhere to crops; 30% to 50% fall to the ground and the remaining pesticide is volatilized into the atmosphere. It is clear that large amounts of chemical fertilizers and pesticides are discharged into rivers, streams, lakes, reservoirs and other water bodies by means of rainfall runoff and leaching.

Nitrogen and phosphorous leaching not only impinges on river water quality, but also results in serious impacts to estuaries and offshore areas. The limiting nutrient of nitrogen and phosphorous for major rivers in China is typically phosphorus (Duan, 1999). The Yellow River contains relatively high amounts of phosphorous and low amounts of nitrogen, while the ratio between nitrogen and phosphorus in the Yangtze River approaches the background value of rivers throughout the world. However, the Pearl River contains relatively rich amounts of nitrogen but is deficient in phosphorous. The Loess Plateau is the most severely affected water erosion region and the silt in the Yellow River primarily originates from the middle reaches of the Loess Plateau. The Yellow River contains rich amounts of phosphorus that are primarily derived from its watershed where soil erosion occurs.

Agricultural land pollution is one of the primary reasons that water becomes eutrophic (Zhu, 2000). Inappropriate use of pesticides and chemical fertilizers, and livestock and poultry feces, can leach and runoff into waterways, accelerating agricultural land pollution. In 1997, 1.2 million tons of pesticides was applied to approximately 9.067 million ha of cropland to control plant diseases and insect pests, polluting the land and resulting in deterioration of the agricultural eco-environment, and also polluting agricultural and associated products. In developed regions with advanced economic growth, an average of 600 $kg{\cdot}ha^{-1}$ to 750 $kg{\cdot}ha^{-1}$ of nitrogen is used each year. The more nitrogen fertilizer used, the lower the effective utilization rate, which is only 20% to 25% on average. Leaching of large amounts of chemical fertilizers into rivers and lakes, in conjunction with water erosion, is one of the primary reasons for high concentrations of total nitrogen in water bodies. Inappropriate use of pesticides, including low utilization rates of application ranging from 40% to 50%, can pollute the atmosphere, soil, agricultural crops, and agricultural sideline products, and also significantly pollute water bodies.

Eutrophication is a phenomenon that is exacerbated by human activity where massive amounts of nitrogen and phosphorous and other nutrient materials are transported into water bodies. This excessive amount of nutrients feeds organisms that flourish in the slow currents of water bodies like lakes, estuaries, and gulfs. Eutrophication also results in the rapid breeding of algae and other plankton which reduces the dissolved oxygen content in water bodies, water quality deteriorates, and in some situations, killing great numbers of aquatic organisms like fish (Chen, 1999). The algal communities of natural water bodies are primarily composed of diatoms and green algae. The appearance of red algae is a sign of eutrophication, while blue algae become dominant in water bodies with the development of eutrophication. Algae breed and mature quickly, feasting on the available nutrient material and reproducing rapidly under appropriate environmental conditions forming algal blooms.

Dead aquatic organisms either decompose by means of microorganism activity exhausting oxygen reserves, or decompose under anaerobic conditions, generating hydrogen sulfide and its noxious odor. Both decomposition methods cause a relative deterioration in water quality. The eutrophication of water bodies often results in distortions to aquatic ecosystems. For example, patina microvesicle algae in eutrophic lakes and reservoirs are extremely poisonous and can result in liver tumors in animals and congestion causing rapid death. The impacts and damages caused by eutrophic water include: (i) noxious odors and water opaqueness; (ii) a change in the dissolved oxygen content as the dissolved oxygen becomes exhausted, causing an anaerobic state to form in deep water when serious, making it impossible for aquatic organisms to survive; (iii) toxic materials leaching into water bodies; (iv) a deterioration in the quality of water supplies, increasing the cost of water treatment; and (v) a decrease in the stability and diversity of aquatic organisms leading to the destruction of the ecological balance of water bodies.

Pollution caused by agricultural fertilizers induced the eutrophic state of Dianchi Lake in Yunnan Province and resulted in a dramatic increase of algal blooms. Guo (2000) studied the pollution load flowing into Dianchi Lake and his results show that of total nitrogen in the surface flow, 53% was sourced from chemical fertilizers, while 42% of the total phosphorus also came from fertilizers. Therefore, the pollution in a water body can be reduced by controlling soil erosion.

Controlling the diffuse source pollution from agricultural runoff is a key method for controlling water pollution and lake water eutrophication. To control the diffuse source pollution caused by chemical fertilizers, and reduce nitrogen and phosphorus leaching, the use of fertilizers must be adjusted so that different types of manure and fertilizers are applied on different soil types and at different rates so that the agricultural development is sustainable, and the water environments remain healthy. Note that chemical fertilizers contribute greatly to the increase of agricultural production, but over-use of agricultural fertilizers can result in huge negative impacts for society in general and the environment in particular. It is estimated that only approximately 15% to 30% of chemical fertilizers applied to croplands are effectively absorbed by crops, while 70% to 85% are leached into rivers, lakes, coastal areas, and underground water tables by means of infiltration, runoff, and water erosion. Fertilizer leaching is a major diffuse chemical pollution source for lakes, rivers, and coastal areas.

In Dali City, Yunnan Province (Du, 1999), the area affected by water erosion is 1.3×10^4 ha. In the Cangshan Mountains in western Yunnan, 11 of the 18 valleys and streams are affected by mudflows or erosion gullies and the annual mud and silt sediments can be as high as 90×10^4 t, of which 0.54×10^4 t is total nitrogen, 0.32×10^4 t is total phosphorus, 58 tons is soluble nitrogen, and 3.5 tons is soluble phosphorus. Annual mud and silt sedimentation in the mountainous regions in eastern Yunnan account for 17.4×10^4 t, of which 0.75 tons is total nitrogen, 0.113 tons is total phosphorus, 56.8 tons is soluble nitrogen, and 3.3 tons is soluble phosphorus. Annual mud and silt sedimentation in the mountainous areas in southern Yunnan are 17.1×10^4 t, of which 0.058×10^4 t is total nitrogen, 0.035×10^4 t is total phosphorus, 67.3 tons is soluble nitrogen, and 4.0 tons is soluble phosphorus.

The sediment and nutrient materials that flow into Erhai Lake in Yunnan Province through streams cause siltation and the increase eutrophication processes and can even destroy croplands while endangering the health and welfare of people and domestic animals alike. It must also be pointed out that pollutant materials (including poison-free materials that can introduce toxic materials from other pollutant sources) that flow into groundwater environments at a remote distance will also either result in an increase in the contamination index or produce associated pollutant effects. For example, detergents flowing into groundwater through sewage water irrigation can transfer pollutants to surface water, increasing the concentration of contaminants 2 to 7 times.

Direct drainage of sewage water and fertilizer and pesticide leaching are the key factors that have accelerated eutrophication in water bodies during the last decade. The nutrient content of major freshwater lakes and reservoirs have basic standardized eutrophication concentrations. Among the 26 lakes that have been surveyed so far, 39% had a medium level of nutrient concentrations and 61% possessed a high or heavy nutrient loads. Eutrophication is therefore a nationwide environmental issue affecting lakes and reservoirs throughout China.

5.2.3 Water erosion and mud and silt sedimentation

Water erosion not only causes a reduction in land productivity, flood overflow capacity, and mud and silt sedimentation in downstream sections of water bodies, it also causes siltation to occur in water channels and reservoirs. This can affect inland water movements, lessen the storage and regulation capacity of reservoirs, erode and damage water conservation devices and hydro-electric facilities, clog riverbeds with silt and block floodflows, increase flood control costs and flooding risks, and endanger the lives and property of people living along river channels.

Siltation and sedimentation in lakes, reservoirs, and catchments weaken flood control capacities. In regions affected by serious water erosion, soil erosion upstream, and sedimentation downstream in water bodies are the rule. Water erosion and the sedimentation of reservoirs and catchments are global issues. Water catchments, reservoirs, and irrigation canals for controlling flood events are often clogged with mud and silt, and as a result, the effectiveness in controlling flooding is reduced and the service life is shortened and these facilities may even be completely destroyed.

Lake and reservoir siltation and sedimentation due to water erosion have raised the beds of rivers and reservoirs, reduced the capacity of reservoirs to store water, and generally reduced the size of these water storage facilities. Consequently, hazards associated with small floods and high water tables have increased, and massive floods along river channels have occurred in recent decades in China. The Yellow River is known as a "suspension river" that stretches for hundreds of kilometers through Henan Province. A suspension river has also formed in Jingjiang along the Yangtze River while Dongting Lake is in the process of becoming a "suspension lake." Since 1949 (Zhu, 1999e), more than 500 lakes have disappeared and 20 billion m^3 of accumulated storage capacity in reservoirs and lakes was lost due to water erosion processes. There are over 80,000 reservoirs of different sizes built along 50,000 rivers nationwide, and the annual loss of storage capacity through siltation and sedimentation is as high as one billion m^3.

The area of water erosion along the Yangtze River has increased from 363,800 km^2 in 1957 to 560,000 km^2 in 1999 (Cheng, 2000). Meanwhile, the rate of siltation in some sections of the Yangtze River is as much as 10 $cm \cdot a^{-1}$. From 1960 to 1979, 20,860 km of shipment routes were reduced. The average annual loss of shipment routes is 1,043 $km \cdot a^{-1}$. The mean annual mass of sediment and silt flowing into existing reservoirs of various sizes in upstream sections of the Yangtze River is 150 million tons and with a further 77.67 million tons flowing into catchments and dams. In the downstream section of the Yangtze River, five major lakes and reservoirs are experiencing severe sediment and silt accumulation due to water erosion, where water storage capacities have declined, flood management capacities are reduced, and the necessity to discharge flood peaks has increased. Under the effects of siltation and sedimentation and the inappropriate act of reclaiming land from marshes or lake systems, flood regulation and water storage capacities of lakes have decreased on a large scale. In 1949, lakes covered a total area of 25,828 km^2 in the middle and lower reaches of the Yangtze River. In 1997, only 14,074 km^2 of lake area remained, representing a loss of approximately 50%.

The sedimentation and siltation of river systems limits shipping enterprises. The available shipping lane span on the Yangtze River was 70,000 km in 1957, but only 35,000 km by the middle of the 1980s, which is a 50%

reduction in access.

During recent decades, an enormous volume of silt and mud has been transported downstream and deposited, accumulating along the river banks of the Yangtze River from water erosion. According to data collected by the Yichang Hydrological Station, Hubei Province, 522 million tons of silt per year flowed down to the middle and lower reaches of the Yangtze River before the 1950s. The silt volume had increased to 720 million tons per year by the 1980s and into the 1990s (a 38% increase). Additionally, 825 million tons of silt flowed into the main course of the Yangtze River from the middle reaches and the downstream area, accounting for a total of 1,545 million tons of silt and sediment deposited into the Yangtze River course in a year. Of this amount of sediment, only 9.3% was carried into the sea while 90% was deposited and accumulated around the Yangtze River mouth. It is estimated that the mean annual silt sedimentation rate is 752,000 $t{\cdot}km^{-2}$. For example, 45 cm deep silt filled the riverbed between Chenglingji to Hankou (a distance of 240 km) with sand dykes and beaches formed along the river course, resulting in direct threats to shipping and harbors. At the same time, the river course narrowed while the flood control and overflow capacity declined, increasing the risk of flood disasters. The siltation of river channels makes them prone to flooding disasters as well as the more narrow shipping channels. The flood discharge that occurred on the Yangtze River in 1998 was less than that of 1954, but the water table in 1998 was higher than it was in 1954. More than 3,000 lives were lost and, the direct economic loss from the 1998 flood disaster was approximately 160 billion RMB. More than 300,000 soldiers and 2 million farm workers were mobilized to meet the emergency. This particular flood disaster severely compromised both economic production and daily livelihoods.

The Gongzui Hydropower Station on the Dadu River was designed with a dam water storage capacity of 350 million m^3, but according to statistics (Zhao, 1999), it has almost turned into a run-of-river power station since it now relies almost solely on runoff due to the effects of siltation and sedimentation following a twenty-year operating period.

Data show that compared to conditions in the 1950s, the current water discharge that flows into Dongting Lake from the Jingjiang River has decreased over 50%. By 1988, the water storage capacity of Dongting Lake reduced by 36.1% to 47.9% compared with the storage in 1952. The relationship between the Jingjiang River and Dongting Lake has altered due to the increase in local sediment and silt flowing into Dongting Lake. According to historical records, a flood occurred once every 41 years on average during the period from 285 AD to 1968. However, floods occur at a rate of more than one every five years today. The surface area of Dongting Lake decreased from 4,350 km^2 in 1949 to 2,740 km^2 by 1977.

The Qili River was severely clogged with silt between 1952 and 1971 and the riverbed was raised by approximately 4.12 m, while its water storage capacity was reduced from 1 billion m^3 to 330 million m^3. The canal built to store water and regulate flood water became dysfunctional.

The annual amount of silt sedimentation that flows into Dongting Lake is approximately 98 to 120 million m^3. Of this sediment 83.5% originates from the Yangtze River and the remainder comes from local siltation from Dongting Lake. Dongting Lake has the most severe silt sedimentation problem in China. The lake is an important pathway for water storage and for flood regulation in the middle and lower reaches of the Yangtze River. Since 1949 the average amount of sedimentation on the lakebed has been as high as 1 m. The western section of Dongting Lake is now mostly clogged with silt and is used as reclaimed land. In particular, since the 1970s, the average annual rise in the lakebed resulting from sedimentation is 3.7 cm and, accordingly, the water storage capacity of the lake has been reduced from 29.3 billion m^3 in 1949 to 17.8 billion m^3 today. It has been predicted by authorized sectors that the eastern and southern areas of Dongting Lake will be completely depleted of water within a short time period.

The average rate of sedimentation and siltation in Poyang Lake has increased from 8 million m^3 in the 1970s to 9 million m^3 in the 1990s. Its function, to store water and regulate flood, has decreased year after year. During the last two decades, the surface area of the lake has been reduced to 1,210 km^2 and 5 billion m^3 of water storage capacity has been lost. From 1950 to 1998, the water table at the intake of Poyang Lake increased in height until it was 20 m higher than that of the Wusongkou outlet of the Yangtze River. Four floods occurred during the years between 1950 and 1973, an average of one flood every 5.8 years. From 1974 to 1998, one flood occurred every 2.4 years. Since the 1990s, an average of one flood has occurred every 1.2 years.

Today, the pressure to control flood events is becoming greater. It is estimated by the scientific community that the service life of the Three Gorges Dam will be less than 30 years if water erosion in the upstream area of the Yangtze River is not effectively controlled. The worsening water erosion in the upper and middle reaches of the Yangtze River is becoming a serious risk throughout the valley and will directly threaten the Three Gorges Dam. Silt and sand sedimentation is a particularly serious problem that the Three Gorges Dam faces. Until now, the area affected by water erosion in the upper reaches of the Yangtze River is 355,000 km^2, accounting for 60% of the total area of water erosion in the Yangtze River valley. Water erosion severely threatens the Three Gorges Dam as well as the entire Yangtze River valley.

An annual silt layer 4–12 cm thick accumulates on the riverbed of the Yellow River. The Yellow River is known as a “suspension river” in China where the riverbed is clogged with silt and narrows to a point where the flood carrying capacity is reduced. When a massive volume of sedimentation rushes down and clogs river courses, peoples’ lives and property are severely damaged and the vicious cycle of “the poorer life is, the faster reclamation is; the faster reclamation is, the poorer life is” is repeated year after year. Due to severe water erosion, the riverbed downstream of the Yellow River has been clogged with silt, and consequently, several massive overflows have taken place. During the last 2,500 years, from the Qin Dynasty to 1949, there were 1,500 floods and overflow events recorded and 26 recorded changed to the river course. On average, one breach on the Yellow River has taken place every three years and one alteration of the river course has taken place every one hundred years. Although no breaches have occurred since 1949, the riverbed is being clogged with silt by about 10 $cm{\cdot}a^{-1}$. As a consequence, in some areas the riverbed is now 3 m to 5 m higher than the terrain outside of the river bank, and as much as 10 m in some parts of the middle reaches of the Yellow River. The riverbed of the Yellow River in Xinxiang City, Henan Province is 20 m higher than the terrain, and the riverbed is 13 m higher than the terrain that surrounds it in Kaifeng City, Henan Province. From 1949 to 1998, the sedimentation in the downstream section is estimated to have increased by nearly 10 billion tons. During recent years, the Yellow River has dried up in the lower reaches due to prolonged dry spells where silt and sand that flow into the river are deposited within the main river course.

Approximately 700 km of the downstream area of the Yellow River is protected by river banks and dykes alongside the river where the riverbed itself is higher than the surrounding land which is a common phenomenon of suspension rivers. The maximum recorded peak flood discharge of the Yellow River is 22,300 $m^3 \cdot s^{-1}$ in 1958 and water flowed unencumbered to the sea through measures that took strict precautions against flood disasters. In 1984, the peak flood discharge was 15,300 $m^3 \cdot s^{-1}$. During this period of time, Dongting Lake was used to divert flood water. By 1996, the peak flood capacity was only 7,600 $m^3 \cdot s^{-1}$, the suspension river had become ineffective at channeling flood flows, and disastrous damage finally occurred. What will happen if two or three times of the amount of flood discharge that occurred in 1996 takes place during another wet cycle?

Silt and sand carried downstream by water erosion are the primary factors reducing the flood carrying capacity of rivers, and therefore increasing the risk of flood damage. The riverbed of the Yellow River was clogged with silt by 2 m to 4 m on average during the last five decades. Artificial dykes and protection measures have thus far guaranteed that the Yellow River has flowed safely during last fifty years, but it is accumulating massive potential energy. Many downstream sections of the Yellow River are clogged with silt up to 5 m to 10 m above its banks, and, in addition, because the river often runs dry, the problems facing the Yellow River are becoming more complex. The issue of flooding on the Yellow River has yet to be resolved and, on the contrary, is worsening and becoming more severe.

Siltation and sedimentation accumulation in reservoirs and water catchments countrywide is also very serious. A total of 997 reservoirs of various sizes were built before 1995 in Shanxi Province with a total water storage capacity of 3.23 billion m^3. The water storage capacity has since decreased by more than 25% due to siltation. In Sichuan Province, there are 73,000 reservoirs and water catchments affected by an annual siltation accumulation of approximately 46.2 million m^3 that has resulted in the loss of 81.3 million ha of irrigation land. In the upstream area of the Yangtze River, approximately 10 billion m^3 of reservoir water storage capacity has been lost due to siltation and sedimentation. In Jiangxi Province, more than 9,000 reservoirs were clogged with silt, and as a consequence, 10.47 million m^3 of water storage capacity has been lost, equivalent to the loss of a medium scale reservoir. In the Songhuaba Dam in Kunming City, Yunnan Province, 52,000 tons of silt and sand flowed into the dam in the 1960s, 73,000 tons in the 1970s, 132,000 tons in the 1980s, and 175,000 tons in 1990s which has greatly reduced the service life of the dam. The renowned Sanmenxia Dam in Henan Province, China, could no longer function as designed due to sedimentation and it had to be completely reconstructed. Due to water erosion alongside the Danjiang River valley, the annual accumulation of silt in the Danjiangkou Dam became as high as 63 million m^3, equal to the loss of a medium scale reservoir. In Shaanxi Province, 192 reservoirs and dams with a capacity over a million m^3 of water storage were built before 1973, of which, 41 reservoirs and dams have become fully clogged due to sedimentation, while 40% of the effective water capacity in the remaining reservoirs and dams has been lost.

Theoretically, the volume of sediment transported from one watershed is not directly proportional to the volume of sediment lost by land surface erosion from that watershed. This is because the sediment that originated from soil erosion processes partially settled within the watershed and thus the sediment volume deposited at the outlet of watershed valley would be less than the sediment volume that originated from soil erosion. The ratio between the two volumes is usually called the "silt-sand transport ratio." It is the criterion for measuring sediment transport from upstream erosion sites to a specified location downstream as a result of deposition. The ratio is usually less than 0.3. The silt-sand transport ratio of a specific watershed is influenced and determined by geomorphological and environmental factors, including the physical condition, scope, and location of the sediment source areas, topography, slope gradient, watershed landform, river course condition, vegetation land use patterns, and soil texture.

5.3 Fundamental water erosion control measures

Major water erosion control measures can be divided into three categories: biological measures, engineering measures, and tillage measures. Biological measures include reforestation, tree plantation, and the reintroduction of grass in water erosion regions to increase vegetative cover, block and store runoff, conserve water resources, regulate hydrological conditions, etc. Engineering measures refer to approaches that act to control water erosion by changing microtopography and microenvironment, as well as blocking and storing runoff, improving agricultural conditions, preventing soil erosion from occurring on terraces, fish scale pits, aclinic strip fields and siltation dams that act to reclaim crop fields. Tillage measures are primarily aimed to heighten crop yield and hold moisture within the soil by means of ploughing, loosening soil with hoes, and raking soil using traditional farming tools. Tillage measures include contour farming, furrow farming, contour strip intercropping, contour crop rotation, and level trenches. Different soil and water conservation measures vary not only in the manner in which they conserve soil and water, but also depending on different environmental conditions.

The advantages of engineering measures are characterized by their effectiveness over short time periods and their wider popularity. However, engineering measures require a massive investment and their service life tends to be comparatively short compared with other measures. Biological measures can rehabilitate ecological environments and control soil erosion at the source of origin. However, they are restricted by a lack of hydrothermal conditions, particularly moisture conditions, and have a limited survival rate. The effectiveness of tillage measures is also limited because they can only control soil erosion on a limited scale. When applying soil and water conservation measures, it is important that appropriate measures are selected specific to local conditions. Moreover, the operation of integrated management approaches must also be applied.

5.3.1 Small watershed management

Experience in successful soil and water conservation projects during the past few decades was developed from the implementation of integrated management to small watersheds that play an important role in controlling water erosion. Small watershed integrated management, developed for small watersheds of a particular size, is a soil and water conservation measure developed scientifically based on the size and configuration of the watershed to provide a comprehensive framework for the effective protection of land resources within these small watersheds. Appropriate cultivation and careful development and land use are promoted for the sustainable development of agriculture, forestry, animal husbandry and other agricultural activities. The central issue for small watershed management is the allocation of soil and water conservation measures which are primarily in the form of land use adjustment and conversion. The main objectives, however, focus on the steady improvement of ecological effectiveness and the growth of economic benefits of watershed systems.

Experiments in the operation and comprehensive management of soil and water conservation within small watersheds were initiated in the 1950s, but it was not until the pilot projects of the early 1980s that the measures became popular and were extended on a large scale. During the last two decades, more than 3,000 small watershed and river systems have been effectively controlled and rehabilitated in the Loess Plateau region. Consequently, the volume of loess silt and sand flowing into the Yellow River has been greatly reduced and the ecological environment of the Loess Plateau region has been remarkable improved by means of this rehabilitation.

As a successful strategy for water and soil conservation, the guiding ideology and implementation of small watershed management have also experienced development and improvement. During the early and mid-1980s, watershed management was focused on accumulating further knowledge and experience. Due to limitations of knowledge and the level of technology at the time, the objectives of small watershed management were primarily focused on the preservation of water and the conservation of soil. A series of suitable control measures were used depending on the topographic and landform features of small watersheds and soil erosion mechanisms, to achieve the targets of storing runoff, floods, and rainwater. Measures included installing multilevel dykes while constructing catchments and storing all surface water inside these water systems. During this period, the Ministry of Water Resources setup 38 small basins in the middle reaches of the Yellow River as key experimental sites to explore the scientific aspects of protection systems. The main objective was to reduce soil erosion and less concern was paid to economic benefits. Thus, many watershed systems were effectively rehabilitated with remarkable efficiency, but economic benefits were ignored.

By the late 1980s, along with the national economic reconstruction, small watershed management was gradually redeployed in a form that included economic benefits. By means of integration of rehabilitation and development, economic benefit was targeted as one of the goals while implementing rehabilitation projects. Some small watershed basins and river systems were gradually rehabilitated with both ecological effectiveness and economic benefits in the Loess Plateau region during this new development stage. From then on, to avoid a traditional single benefit protective system, economic benefits were emphasized as priority targets in the rehabilitation of watershed basins and river systems. However, in the process of securing economic benefits, water and soil conservation efficiency was ignored. Moreover, unreasonably high economic benefit goals were set as targets, ignoring the production, supply, and marketing principles of market economics and as a result, the economic benefit targets were not achieved.

By the 1990s, along with the continuously expanding and developing of market economy in China, more concern and focus were paid to economic benefits in the rehabilitation and management of small watersheds. Since then, rehabilitation of small watersheds has been incorporated into the development of the small watershed economy. According to market demand and practical requirement, the rehabilitation and development of the small watershed basins were undertaken together by combining the responsible allocation of natural and social resources and the establishment of leading estate or pillar industries inside these small watershed basins. It is characterized by the use of valuable experience and technology to rehabilitate small watershed basins with the market itself reoriented to provide targets for the control and management of different parts of small watershed basins. At the same time, both maximum ecological efficiency and economic benefit are set as the decisive goals.

Due to continual changes in perspective in the guiding bodies, the selection and allocation of small watershed management measures have also undergone a continuous process of change and reorientation. During the early stages of implementation of small watershed management projects, engineering measures were extensively publicized and widely popularized to pursue a one-sided control effect. In the hilly gully area of the Loess Plateau region, in particular, soil loss from small watershed basins was effectively controlled by means of terrace construction, building slope trenches, and installing channels and dams. After an experimental period, it was found that the blocking and storage capacity of these engineering measures alone could not meet the necessary requirements for controlling water and soil loss following displacement from root sources. In situations where a severe storm event occurs and a dam collapses or terraces disintegrate and give way, further serious soil loss will undoubtedly occur. Due to these potential scenarios, biological measures and their effects in enhancing water and soil conservation were fully recognized.

A combined model incorporating both engineering and biological measures has gradually been developed and applied to the rehabilitation of small watersheds. It involves the construction of terraces on gentle slopes between gully basins. On steep slopes, grass and shrubs should be planted and check dams should be built. At the bottom of slopes, dams and catchments should be installed. Along with the selection and allocation of water and soil conservation measures, and with the constant pursuit of economic benefit, the percentages of cash crops and fruit trees that have been planted in the past ten years have increased significantly. With the introduction of a policy to revert sloping cropland back into forest and grassland (the 'Grain for Green' project), the structure of small watershed rehabilitation projects and programs will be continuously adjusted to raise and transform the productive values of agriculture and animal husbandry inside small watershed basins.

As a physical geographic unit, the small watershed is also a complete system on its own producing silt and transporting sand. Under the scouring force of rainfall and runoff, topsoil material flows away and is transported into gully ditches or trenches due to the impacts of splash, surface, and gully erosion, and then rushes into water channels and river courses from watershed outlets. With regard to small watershed basins, both the vertical movement of material from the top of the slope to the bottom of the gully and the horizontal movement of material from the gully head to the gully outlet are frequently occurring phenomena. The integrated management of small watersheds is aimed to efficiently utilize natural resources and effectively protect the natural environment.

The integrated management of small watersheds is aimed to use the laws of energy and material cycling to select appropriate land use patterns and continuously regulate and control the movement of materials and energy by human intervention. Precipitation causes soil loss by the impact of splashing on land surfaces that produces a scouring effect on the soil. At the same time, precipitation is the primary source of soil moisture which maintains plant growth. The basic principle of integrated management of small watersheds is to protect land surfaces from splash erosion and to reduce runoff erosion as much as possible through the application of various measures. It is also aimed to lessen or retard the movement and transportation of silt and sand by the regulation and redistribution of runoff in watershed basins. Small watershed basins in the Loess Plateau region display remarkable differences in geological and geomorphological features, land use, and socioeconomic aspects but are all part of a large control area. The features of this area can be generally summarized as: (i) hilly roof, slope and boundary, and gully slope and valley bottom areas; (ii) upland terrace and gully and sloping valley bottom areas; and (iii) rocky hill ridge and earth rocky hillside, loessial slope and ravine land; and other landscape components. It is important to note that different landscape components require different control models.

5.3.2 Small watershed management on the Loess Plateau

5.3.2.1 Hilly roof, slope, and boundary, and gully slope and valley bottom areas

The hilly roof, slope and boundary, and gully slope and valley bottom areas are the primary landscape types in the loess hilly region. Intercropping and rotation of crops and grass can be put into practice at the top of the hilly roof landscape type. Crop and grass rotation planting not only ensures the production of grain or cash crops, but also provides fodder and forage for livestock and domestic animals. The selection of crop species, grass, and shrubs must coincide with local conditions and be appropriate. At the same time, runoff harvesting projects, runoff blocking facilities, and runoff and rain-fed agricultural practices should be encouraged and developed.

Gentle sloping terraces can be constructed in the upper parts of hilly slopes to form the fundamental farmland strips to ensure adequate food availability for farmers. Alternating slopes and terraces separated by shrubs and grass can also be constructed to protect the land from erosion. Intercropping grass and shrubs on shady slopes can provide fodder and forage for livestock and domestic animals. Due to landform complexity and increased gradients, the lower parts of hilly slopes can be reverted into forest and grassland to establish a water and soil conservation belt. Fruit trees can be planted with an undergrowth of grass on the lower gentle hill slopes of hillsides exposed to the sun. Mixed plantings of trees and shrubs should be applied to shady slopes or areas with favorable rainfall conditions, and grass and shrubs should be planted on slopes of hillsides exposed to the sun. A deep rooting shrub shelterbelt should be planted to fix soil in place and/or conserve water or process fodder and provide fuelwood on peripheries or the edges of hill boundaries.

The optimum installation of an ecological economic zone on hilly and gully slopes is an important target for water and soil conservation. This zone should be reintroduced with vegetation and enclosed by fences. Trees and shrubs should also be reintroduced and grass and shrubs should be planted. At the foot of the slope, tree plantations should be incorporated because moisture conditions there are favorable, and shrubs and grasses should be replanted on the upper parts of the slope. Silt should be allowed to accumulate on, or should be transported to, valley bottoms where catchments or dams are installed to reclaim land for farming. People should be encouraged to practice high investment, high yield, and high efficiency intensive economic endeavors in valley and dam areas where silt has accumulated to promote a "virtuous cycle" (in contrast to a "vicious cycle") inside small watershed ecosystems.

A large number of protection shelterbelts or tree networks can be planted on river courses to fix soil and conserve water in narrow and closed valley areas. In combination with the measures described above, reservoirs or catchments should be installed to block surplus flood water. An integrated system composed of blocking catchments and suitable components like crops, trees, and grass will therefore be formed at the various levels from the top of the slope to the valley bottom. This flexible system can reduce runoff and soil nutrient loss or make full use of limited precipitation to ultimately enlarge land productivity and ensure an optimum balance between ecological efficiency and economic benefit.

5.3.2.2 Upland terrace, gully slope and valley bottom areas

The primary landscape components in gully areas of the Loess Plateau region are the upland terraces, gully slopes and valley bottoms. Agriculture, forestry, and animal husbandry should be focused on throughout the terraces of the Loess Plateau, due to the high investment and high yield potential. At the same time, various water conservation facilities should be established to block runoff on upland terraces from flowing into the gully areas. On upland terrace slopes, shelterbelts should be installed first on the edge and periphery of the terraces to stabilize gully head areas. Concurrently, the ratio of agricultural land to forest and grassland should be decreased to accelerate improvements in ecological efficiency. Moreover, belts that increase ecological efficiency and economic benefit, such as forests and fruit tree plantations should be established. Gully slopes are the most complicated part of small watershed rehabilitation. The entire watershed has an increased moisture value that can lead to negative effects. In combination with skeleton projects, valley bottom shelterbelts to control scouring and erosion and other water and soil conservation treatments should be established to block runoff and accumulate silt and sand deposits.

5.3.2.3 Rocky hill ridges and earth-rock hillsides

The primary landscape components in the earth and rock mountainous region are the rocky hill ridges and earth rock hillsides, loessial slopes and ravine land. All hillsides in this region should be seized and trees and shrubs and water and soil conservation shelterbelts should be planted to restore vegetation cover. The ecological improvement of hillsides should be the primary objective in this region and large scale development should be limited. Loessial hill slopes with higher moisture contents should be rehabilitated by means of intercropping of crops and grass and by crop rotation. Grain production and livestock should be taken into account as well. Tree plantations, shrubs, and grass should be developed on sloping land greater than 15°. Animal husbandry and breeding industries should be developed while implementing water and soil conservation projects. Terraced fields with gentle slopes should be constructed in regions with scarce rainfall on sloping land of less than 15° while intercropping of crops and grass and crop rotation systems should be practiced. Diluvial valleys and gully bottoms distributed between the main gullies and piedmont foothills are covered with sandstone and gravel sediments, and the upper parts of open river courses, and the bottomlands are covered by a thin layer of loess sedimentation.

In areas with better moisture conditions, cash crops and nut trees should be planted on a large scale in conjunction with intercropping of forage and other grass to establish livestock breeding centers and cultivation stations. Runoff harvesting projects popularized in recent years not only bring about the hope of development of runoff agriculture in the Loess Plateau region, but also result in a new vitality for small watershed management.

The slope runoff harvesting projects being implemented in Loess Plateau region can change the effective distribution of precipitation because they can control the utilization patterns of water resources or change the regularity of occurrences and development of water and soil loss. According to studies by Qingbo Zeng, the silt and sand volume that flows into gullies along with runoff can account for more than 76% of total silt sediment runoff from small watershed systems. It is estimated that 77.8% of the gully erosion volume will be reduced when the slope runoff is isolated. If the runoff from slopes between gully areas can be effectively blocked and stored, erosion as well as silt and sand volume of the entire watershed system would be largely reduced. Moreover, harvesting slope runoff can reestablish land use patterns. Water restrictions will be alleviated to a certain extent when conducting water and soil conservation planning leading to productive, efficient, and strengthened water and soil conservation measures. Greater economic benefits and ecological efficiency can be obtained using the same natural resources due to an improvement in the land management systems. Therefore, as long as these environmental conditions are available, runoff harvesting technology should become popular in the Loess Plateau region.

Relevant research and experiments should be conducted to discover new approaches to reduce costs and establish sound and sensible integration planning. Like the implementation of the production responsibility system in rural areas, a new approach to implement watershed management by means of a household level contract policy has become widely adapted. This household level watershed rehabilitation policy is aimed to encourage local people to become involved in controlling soil erosion. Due to its suitability and flexibility in selecting appropriate land use systems, household level contracts used for small watersheds have created or enhanced the enthusiasm of people living in mountainous and hilly regions to conduct water and soil conservation projects. Good results are achieved because these contracts are fulfilled through the direct participation of the farmers. Long term consistency and stability of water and soil conservation policies should be encouraged and adhered to. By doing so, farmers will benefit from these development activities and guarantee their future interest in participation.

An integrated plan should be made prior the implementation of the household level contracts used for small watershed management to improve ecological efficiency through legislation and the recognition of the importance of stakeholder obligation. One-sided economic water and soil conservation interests should be strongly avoided while operating and implementing these projects. Moreover, short term and long term goals should be combined so that both economic benefits and ecological efficiency and sedimentation control accrue. Engineering and biological measures should be combined with tillage measures to control soil loss in small, incremental steps. Limited by available labor resources, the area of household-level small watershed management should guarantee the development and utilization of resources and reduce unnecessary risks. From the experience in Shanxi Province, a watershed area of 0.1 km^2 to 1 km^2 is acceptable for household level contracts to conduct small watershed management.

Unified planning and multi-household contracts should be encouraged for watersheds within larger areas. The household level contracts used for small watershed management can also be combined with wasteland (barren hills, barren slopes, barren beaches, and barren sandland) auctions. It needs to be feasible for contractors to use wastelands in conjunction with their interests to generate both economic benefits and general public interest in ecological efficiency. At the same time, central and local governments should strengthen scientific and technological inputs and provide technical assistance and necessary support to farmers and contractors to allow them to make further contributions to the successful implementation of ecological improvement projects (Li, 1989; He and Liu, 2008; Xue and Chang, 2008).

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6 Soil Salinization

Baoguo Li

Land degradation caused by soil salinization is a type of desertification that occurs in China. There are approximately 100 million ha of salt-affected soils in China, accounting for one tenth of the total land area. This chapter gives a brief introduction to causes, geological distribution and control of salt-affected soils in China.

6.1 Causes of soil salinization

Soil salinization is the result of long term interaction among soil, the environment and human activities. There are multiple influencing factors, the main ones being climate, landform and geomorphology, soil parent materials, the hydrological environment and human activities.

6.1.1 Climate and soil salinization

Climate conditions are key factors influencing soil salinization, because precipitation and evaporation of water from the soil are closely associated with soil salinization. The distribution of salt-affected soils, mainly in the arid, semi-arid and coastal areas in the northern part of China, is closely related to the climate conditions. In the southern part of China, the ratio of precipitation to evaporation is greater than one (i.e., more precipitation than evaporation), and the general trend of soil water movement is into deeper soil layers, carrying soluble salts beyond the root zone and, in many cases, out of the soil. Therefore, in most regions south of the Yangtze River, plants do not suffer from soil salinization.

6.1.1.1 Soil salt accumulation in arid climates

Most of the regions north of the Yangtze River have semi-humid, semi-arid and arid climates, where ratio of precipitation to evaporation is less than one. The general trend of soil water movement is up to the soil surface, soluble salts are also brought to the soil surface, and the water is evaporated the salts are left on the soil surface. The long term accumulation and condensation of salts form the salt-affected soils, the more arid the climate, the stronger the evaporation and, therefore, the more severe the salt accumulation. In the arid northwestern area, the evaporation rate can be more than ten times the precipitation rate, making evaporation from the soil surface become the dominant process, and hence, large areas of inland salt-affected soils are formed in northwest China.

6.1.1.2 Soil salt accumulation in monsoon climates

In the semi-humid and semi-arid northern areas, under the influence of the monsoon climate, weather in winter is controlled by high barometric pressures and is characterized by a prevailing northerly wind, lower temperatures and less precipitation. The weather in summer is controlled by low pressure systems and is characterized by higher temperatures and more precipitation. Rainfall in July, August and September is more than 70% of the total annual amount. Therefore, the soil water-salt movement shows obvious seasonal changes. Soil salt movement throughout the year can be divided into several periods which form a yearly occurring cycle: a salt accumulation period in the spring due to the dry climate and low surface cover; a desalinization period in the summer and autumn due to more rainfall; and a salt balancing period in the winter due to less water movement.

6.1.1.3 Soil freezing and thawing processes and salt movement

In higher latitude regions of China, low temperatures result in a long period during which the soil is frozen. Water-salt movement is closely related to soil freezing-thawing processes. In the beginning of the thawing period in the spring, relatively high surface temperatures lead to high rates of evaporation from the soil surface, and therefore, further soil salt accumulation. Due to the existence of a frozen soil layer during this period, the salt accumulation process is unrelated to the groundwater table. However, with soil water above the frozen layer, the salt accumulation process is closely related to the groundwater table during the thawing period in autumn. In the frozen period, there is some hydraulic connection between the frozen layer and the groundwater table. When the upper soil layer is frozen, there is a temperature difference between it and the lower soil layer, and so soil water moves from lower warm soil layer into the frozen cool soil layer and moves soluble salts into the frozen soil layer.

In addition to the climate factors described above which influence soil-salt accumulation, wind is also a key climatic factor resulting in horizontal salt movement. Wind can carry salted soil particles from desert areas into regions with slight soil salinization, and carry salt particles from seawater into the inland parts of China.

6.1.2 Landform, geomorphology and soil salinization

6.1.2.1 Landform, geomorphology and soil salt differentiation

Soil salts mainly originate from the weathering of rock materials. Following water transportation, these salts, which have different chemical properties, will become sediments on various geomorphologic units. From piedmonts to plains to coastal regions, the salt components of soil change in a predictable pattern. Low solubility carbonates and bicarbonates such as calcium carbonate and magnesium carbonate will precipitate first as sediment on diluvial plains. Moderately soluble salts such as sulfates will form sediments on alluvial plains, while highly soluble nitrate and chloride salts will be found in coastal lowlands (Fig. 6.1). The lower the landform is, the higher the rate of salt accumulation and vice versa.

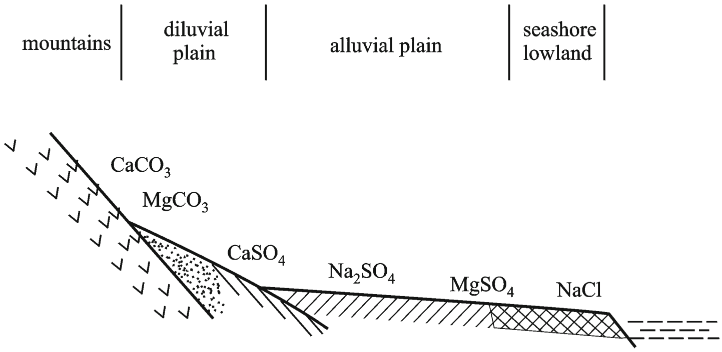

Fig. 6.1 Differentiation features of soil salt distribution on different geomorphological positions (Wang, 1993, with permission from Science Press)

6.1.2.2 Closed inflow basins

Junggar, Tarim, Yanqi, Turpan and Qaidam basins and the Hexi Corridor in northwest China are typical closed inflow basins, surrounded by mountains. Water and salts from the surrounding mountains converge into the basins, where the arid and hot climate results in high levels of evaporation. Salts condense continually and groundwater mineralization increases. For example, on the shore of Ebinur Lake, Xinjiang, groundwater mineralization is currently more than 30 $g \cdot L^{-1}$, and soil salinization is very severe.

6.1.2.3 Semi-closed slow outflow valley plains and alluvial plains

Semi-closed slow outflow valley plains and alluvial plains are regions with uneven outflow conditions such as the Yinchuan and Hetao plains and the Fenhe River-Weihe River valley plain. Normally, there are rivers that cross these plains, and, due to lateral infiltration of river water, irrigation activities channeling water from these rivers, and poor drainage conditions, large areas salt-affected soils are formed. For example, the Houtao Plain is located between the Langshan Mountains and the Ordos Plateau with a topography that slopes from southwest to the northeast. The lowest point on the plain is Wuliangsu Nor and the irrigation drains into this area. Due to poor water-salt drainage in this area, salts accumulate in Wuliangsu Nor, and soil salinization is very severe.

6.1.2.4 Slow outflow fluvial plains

The Huang-Huai-Hai, Songliao and Sanjiang plains are classified as slow outflow fluvial plains. The generally gentle landform and uneven micro-landform result in water-salt redistribution, where salts are concentrated in the lowland river-bend areas and trough-like lowlands, and patches of salt-affected soils appear.

6.1.2.5 Coastal low plains

China has a long coastline along which coastal salt-affected soils are widely distributed. These salt-affected soils are mainly in coastal regions of Liaoning, Hebei, Shandong, and Jiangsu provinces, but also in coastal regions of Zhejiang, Fujian, Guangdong and Taiwan provinces. Coastal lowlands are formed by seawater encroachment. The main components of the salts are chlorides in the coastal regions of the northern part of the Yangtze River, and sulfates in coastal regions of the southern part of the Yangtze River. Depending on the distance from the sea, soil salt content changes following parabola-shaped trend. Normally, the salt concentrations in near-sea locations are relatively high due to the low topography, frequent seawater incursions and long inundation time. In regions a little bit far from the sea which are influenced by the short period of inundation by seawater and strong surface evaporation, groundwater is condensed and soil has the highest salt concentration. Typically locations further from the sea have lower salt concentrations.

6.1.2.6 Alluvial deltas by rivers

Deltas, formed by estuary sedimentation, are normally characterized by a wide and even landform, dense water networks and smooth groundwater drainage. Usually no soil salinization occurs. However, on the outer edge of some deltas, which are influenced by the tide, coastal salt-affected soil landscapes can often be found. For example, in the Yangtze Delta and the Zhujiang Delta, patches of salinized meadow soil and salinized meadow bog soil are distributed along the rivers.

6.1.2.7 Impact of micro-landform on soil salinization

Landforms at a micro-scale can influence the salinization potential because it is common to find drought in higher elevations, waterlogging in lower elevations and salinization in the middle. This occurs because rainstorms or floods result in seasonal waterlogging in lower elevations which leads to soil salt leaching being a dominant process. When the lowland is waterlogged, water will infiltrate laterally into the gently sloping land around the adjacent lowland, resulting in rising watertables and an increase in soil salt accumulation.

Micro-landform change can also result in soil salt redistribution because the salt is concentrated in partially elevated patches, which may only be submerged for a short time, thereby making desalinization by leaching weak. Further, these elevated patches have a relatively large surface area so soil evaporation is somewhat higher. For example, if there are a lot of soil clods on flat land, dots of salt will appear first on the clod surface, leading to salt accumulation on the land surface.

6.1.3 Soil parent materials and soil salinization

Soluble salts within soils originate from the weathering of rock materials. Therefore, the soil parent materials have a great influence on soil salinization.

6.1.3.1 Fluvio-lacustrine deposits

When rivers enter lowlands with slower flow velocities, sedimentation can occur in and around lakes. This leads to lakes become shallower and dryer with a smaller surface area, and finally fluvio-lacustrine deposits are formed. The texture of these deposits is relatively coarse at the estuary delta and finer at the original lake area. In inland lakes with uneven outflow and strong surface evaporation, soluble salts are continuously condensed, and saline soils with high salt contents are formed. Saline lakes are commonly formed such as some of the lakes in Qinghai and Xinjiang.

6.1.3.2 Marine deposits

Marine deposits formed by the uplift of coastal or estuary sediments out of the seawater cover a large area in the littoral region of southeast China and Bohai Bay and the littoral regions of northern Jiangsu Province. The components of marine deposits are different because, due to long term seawater inundation, the salt content is very high. Normally the salt content of marine deposits is 0.8–2.5%, and the main components are Cl^- and Na^+ ions. Marine deposits are the main soil parent materials of coastal salt-affected soils.

6.1.3.3 Fluvial deposits

Fluvial deposits are formed from the piedmont sedimentation of rock crumbs, sand particles, and silt particles carried by floods. The deposits develop as alluvial fans in the piedmont belt and fan ends at the outlet of valleys. Fluvial deposits vary in their components, textures and thicknesses in different geographical locations. At the valley outlets, the deposits are mainly gravels, boulders, and coarse sands, but on the edge of a fluvial fan, the deposits are mainly finer sand, powdery sand and loamy clayey particles. Various salts exist in fluvial deposits in arid areas, but no soil salinization occurs on these deposits, or soil developed on them due to leaching and the lower groundwater table. In some patches at the edge of fans with bad drainage, soil salinization may occur. However, if floods flow across saline strata, there may be many salts in the deposit, causing soil salinization on fluvial fans.

6.1.3.4 Aeolian deposits

Aeolian deposits can be classified into aeolian sand soil and aeolian loess. The former has no salt accumulation, while the latter has a higher powdery sand content, which is carbonate rich with few other soluble salts. There are more sulfates in the red ancient loess layer under the Malan loess. The majority of the Loess Plateau is covered with thick loess sediment, and no soil salinization appears. The only soil salinization on the Loess Plateau occurs in low valleys and along the rivers due to the high groundwater table.

6.1.3.5 Ancient salt-bearing strata

In some regions, soil salinization is related to ancient salt-bearing strata, for instance: (i) The distribution of soda salt-affected soils in Xinjiang coincides with albite-rich granite and gneiss. (ii) Northeast China is rich in sodium, hence soda salinization occurs broadly; igneous rocks occur around Da Xing'anling, Heilongjiang Province. (iii) The northern part of the Yuncheng Basin, Shanxi Province has an underlying stratum of saline soil in the first and second terraces of the river. The soil is formed by buried lacustrine sediments from the last phase of the Tertiary and a potential risk of soil salinization exists.

6.1.4 Hydrogeological conditions

The hydrogeological conditions that influence soil salinization are surface runoff, underground flow and the corresponding watertable change. The effects of surface runoff on soil salinization are two-fold: one is a direct impact where salts are transported into soil by flooding or irrigation; and the other is an indirect impact, whereby the surface runoff into groundwater leads to a raised groundwater table, from which evaporation will bring salts onto the soil surface. Field surveys on the Huang-Huai-Hai Plain have shown that brackish water should be used as irrigation water due to serious water shortages in some areas. When irrigation is undertaken twice each season with water containing more than 3 $g{\cdot}L^{-1}$ mineralization, obvious soil salinization occurred and crop yields decreased significantly.

Shallow groundwater drainage is one of main driving forces of salt transportation within soil bodies, leading to horizontal differentiation of soil salts.

The depth to the groundwater table is closely related to soil salt accumulation. Soluble salts in groundwater accumulate on the soil surface through evaporation and soil salinization occurs. Research shows that following the lowering of the groundwater table, surface evaporation and plant transpiration are also reduced. When the watertable was reduced to a critical depth, evaporation from the soil surface and the corresponding soil salinization process will stop. Different soil textures and different groundwater mineralization levels result in different critical depths. Table 6.1 lists critical groundwater depths in the North China Plain.

Table 6.1 Critical groundwater depth in the North China Plain (m)

Groundwater mineralization($g{\cdot}L^{-1}$)	Light textured soils	Medium textured soils	Clay textured soils
<2	1.6–1.9	1.4–1.7	1.0–1.2
<5	1.9–2.2	1.7–2.0	1.2–1.4

6.1.5 Human activities and soil salinization

6.1.5.1 Main human influences on soil salinization

(i) Irrigation

Secondary soil salinization resulting from inappropriate irrigation is very severe. It has been estimated by UNESCO that about a half of irrigated farmland globally is affected by secondary soil salinization and waterlogging, and about 10 million ha of irrigated farmland have been abandoned due to inappropriate irrigation.

Irrigation, in effect, is a soil water supply process under human control, and strict management can reduce the disadvantages to a minimum. The impacts of irrigation on soil salt change are as follows.

i) Impact of irrigated water quality on soil salts

Limitations caused by regional water resources, especially the shortage of freshwater resources, mean that mineralized brackish water has to be used for irrigation in some regions. For example, the Yellow River is the largest irrigated water source for the Huang-Huai-Hai Plain, and it is estimated that the amount of salt coming into the plain may be as much as 3 million tons per year based on 7.6 billion m^3 of water channeled in with a salt content of 0.04% (Shi et al., 1983).

ii) Impact of irrigated water amount on regional groundwater

In channel irrigated areas, a great deal of channeled water results in a rising groundwater table and soil salinization. In the Renmin Shengli Channel Irrigated Area of the Huang-Huai-Hai Plain, due to unplanned rice sowing in 1958, and more rainfall in 1957–1958, the groundwater table in the following four years rose to less than 1.5 m below ground level, and the area of soil salinization increased from 6,400 ha in 1957 to 11,300 ha in 1959.

iii) Salt leaching effect of irrigation

The main goal of irrigation is to meet the water requirements for crop growth. In salt-affected soils, appropriate irrigation can also leach salts from the soil layer, which has a positive effect on soil improvement.

(ii) Fertilization

The addition of manure and chemical fertilizers has an important role in increasing crop yield. However, many salts will be taken into soil during fertilization. For example, if 300 $kg \cdot ha^{-1} \cdot a^{-1}$ of chemical fertilizer was added, the salt content within the cultivated soil layer would increase by 0.13%, which cannot be neglected in severe salinized land.

A case study on soil water-salt movement in one year and three year planted greenhouses was conducted in Shouguang County, Shandong Province. The results showed that soil salts came mainly from fertilizer addition, and irrigated water was the main driving force of salt transportation. When the groundwater table is relatively low, the movement of soil water within the cultivated layer is upward one day after irrigation, resulting in salt accumulation on the soil surface. The application rate of fertilizers in the greenhouse was several times than that in an open field situation, and much more than the requirement of the plants. Therefore, the soil salt content in the one year and three year planted greenhouse trials are significant and show very substantial differences from field situations.

6.1.5.2 Example of human influence on soil salinization

The Renmin Shengli Channel Irrigated Area (RSCIA), located in the northern part of Henan Province (E 113°31′–114°25′, N 35°0′–35°30′) and covering a total area 1,183 km^2, is an example demonstrating the human influences on soil salinization. This was the first irrigation project using channeled water from the lower reaches of the Yellow River since 1949, and irrigation began in 1952.

RSCIA has a warm temperate continental monsoon climate, the mean annual temperature is 14 °C, the frost-free period is about 220 days, annual precipitation is 620 mm, and annual evaporation is 1,800 mm. The precipitation that occurs from June to September is about 70–80% of annual amount, and the climate is characterized by drought in the winter and spring, and rains in the summer and autumn, which is typical on the Huang-Huai-Hai

Plain.

RSCIA consists of the terraces and the lowlands of ancient Yellow River floodplains, and a recent Weihe River sedimented area. The terraces of the ancient Yellow River floodplains have a higher elevation with a groundwater depth of 6 m and 1 $g \cdot L^{-1}$ soil mineralization. The lowlands of the ancient Yellow River are 3–4 m lower than the current river level, the groundwater depth is about 3–4 m, soil mineralization is 2 $g \cdot L^{-1}$, and the majority of ancient salinized land from historical times is located in this area.

The relationship between the salinized land area and water conditions in the RSCIA over the past 40 years is given in Table 6.2. In the RSCIA, the salinized land area increased from 6,800 ha in 1953 to 9,000 ha in 1955, due to the large amount of water supplied by channels from the Yellow River. Following the establishment of the drainage system, the salinized land area decreased to 6,400 ha in 1957. By the end of the 1950s, due to over-impoundments of water, unrestricted paddy field development and too much rainfall in 1957–1958, the groundwater depth was less than 1.5 m for four subsequent years, and salinized land area increased to 11,300 ha in 1959. After the severe drought in 1959–1960, the salinized land area peaked at 18,800 ha in 1961. In 1962, many irrigated areas in the lower reaches of the Yellow River were abandoned,

Table 6.2 Relationship between salinized land area and water conditions in RSCIA

Year	Groundwater depth (m)	Irrigation amount (million m^3)	Precipitation (mm)	Salinized land area (ha)
1953	2.76	139.4	673.82	6,800
1955	1.89	101.8	574.10	9,000
1957	1.80	187.1	676.55	6,400
1959	1.48	491.7	430.00	11,300
1961	1.40	363.8	678.80	18,800
1963	1.82	20.5	779.70	11,600
1964	1.85	9.1	1,027.80	8,700
1965	2.54	214.6	346.20	7,200
1966	2.85	399.1	394.00	6,900
1967	2.49	237.4	606.00	9,000
1968	2.60	230.6	529.00	8,500
1971	2.29	344.0	546.90	8,800
1973	2.08	297.5	564.50	6,600
1974	2.05	457.6	669.30	4,500
1976	1.79	616.7	455.50	3,900
1977	1.91	475.0	771.60	5,700
1979	2.30	470.7	474.70	4,200
1980	2.53	513.3	445.70	4,400
1983	2.73	373.0	689.30	5,300
1986	3.09	478.0	331.90	1,700
1990	–	–	–	1,300
1994	3.25	–	–	700

and only 16,000 ha irrigated area was usable. Strict water controls aimed at reducing the soil salinization problem were introduced, the drainage system was perfected, paddy sowing was forbidden, and well managed irrigation was extended. These measures led to a reduction in the area of salinized land to 6,900 ha in 1966, near equal to the amount before irrigation. Since 1978, the integration of well and channel irrigation has reduced the groundwater table, and the salinized land area has reduced from 4,400 ha in 1980 to 1,700 ha in 1986. To date, salinized land has almost disappeared in this irrigated area.

The following methods are used to evaluate the human influences on soil salinization (Li et al., 1993). First, the functions of groundwater fluctuations and soil salt accumulation are calculated as:

$$G = M_1 f_1(R) \tag{6.1}$$

$$S = M_2 f_2(G) \tag{6.2}$$

Where G is the groundwater table depth (m), R is the rainfall amount (mm), S is the salinized land area (ha), and M_1 and M_2 are the intensities of human influences on groundwater fluctuation and soil salt accumulation respectively. Two equations can be derived from the above equations as:

$$\frac{\Delta G}{G} = \frac{\Delta M_1}{M_1} + a_1 \cdot \frac{\Delta R}{R} \tag{6.3}$$

$$\frac{\Delta S}{S} = \frac{\Delta M_2}{M_2} + a_2 \cdot \frac{\Delta G}{G} \tag{6.4}$$

Where $a_1$and a_2 are resilience coefficients of the rainfall impact on the groundwater table and the groundwater table impact on soil salt accumulation, respectively.

The contribution rates of human activities to the groundwater table (m_G) and soil salt accumulation (m_S) are calculated from:

$$m_G = (\frac{\Delta M_1}{M_1} / \frac{\Delta G}{G}) \cdot 100\% \tag{6.5}$$

$$m_S = (\frac{\Delta M_2}{M_2} / \frac{\Delta S}{S}) \cdot 100\% \tag{6.6}$$

During the natural process of soil salt accumulation, when the watertable is relatively high, change in the groundwater table is almost synchronous with rainfall, i.e., a higher rainfall results in a higher watertable; and the watertable change is also almost synchronous with the salt accumulation, i.e., a rising watertable results in more severe soil salt accumulation. Therefore, we assume that $a_1 = a_2 = -1$. The contribution rates of human activities on the groundwater table and salt accumulation are calculated in Table 6.3.

Table 6.3 Contribution rates of human activities on ground watertable fluctuation and soil salt accumulation

Period	$\Delta M_1/M_1$	m_G	$\Delta M_2/M_2$	m_S
1953–1955	–46.32	146.95	0.83	2.57
1955–1957	13.08	–274.75	–33.65	116.48
1957–1963	16.36	1,472.18	82.57	101.36
1963–1964	33.47	2,030.41	–22.06	93.05
1964–1965	–29.02	–77.80	18.71	–100.68
1965–1966	26.01	213.13	8.42	–222.09
1966–1967	41.18	–325.97	17.15	57.58
1967–1968	–8.29	–187.62	–1.28	22.49
1968–1971	–8.54	71.62	–8.47	–245.23
1971–1973	–5.95	64.91	–34.06	136.85
1973–1974	17.12	–1,187.18	–33.87	104.45
1974–1976	–44.63	351.86	–24.79	204.75
1976–1977	76.10	1,135.16	51.60	114.93
1977–1979	–18.06	–88.45	–6.22	23.36
1979–1980	3.89	38.91	16.08	264.47
1980–1983	62.56	791.39	27.66	140.01
1983–1986	–38.66	–293.19	–54.19	80.43

The results show that the average contribution rate of human activities to the groundwater table is 514.8%, while on the contribution rate to soil salt accumulation is 119.5%. Due to greater effects of irrigation and drainage on the groundwater table, the variability of the former is relatively greater (Fig. 6.2).

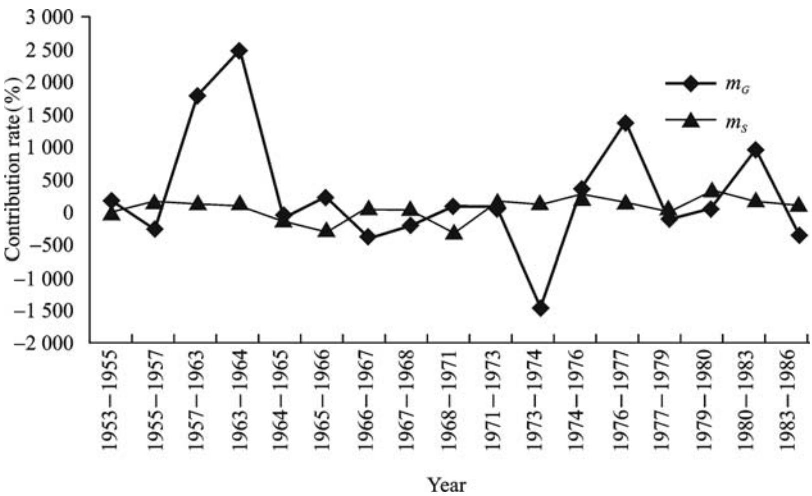

Fig. 6.2 The contribution rates of human activities on ground watertable and salt accumulation

6.1.6 Biological salt accumulation

Many halophytes with vigorous root systems, such as *Halogeton arachnoideus*, *Populus euphratica*, *Suaeda salsa* and *Tamarix* spp., can absorb salts from deeper soil layers, store them in stalks and leaves, and excrete salts through stomata to modify the salt balance within the plant. The salt content in these plants can be up to 57.8%, and these salts will return to the soil surface as litter and other plant dead residues which will be decomposed, can leach into soil and may result in soil surface salinization. In general, the biological salt accumulation process is significant during steppe soil formation. Halophytes in desert areas have little salt accumulation ability due to their low biomass and low vegetation coverage.

6.2 Distribution of salt-affected soils

Salt-affected soils in China are distributed mainly in inland basins and alluvial plains in the arid and semi-arid areas of northern China, and along the coastal plains in humid and semi-humid monsoon areas. Salt-affected soils are found in 17 provinces from 32°–48°N to 78°–130°E, within seven zones determined by formation characteristics, salt component and geological distribution (Fig. 6.3).

6.2.1 Salt-affected soil zone in extremely arid desert

This zone includes mainly the Tarim Basin in northern Xinjiang, the Turpan Basin in eastern Xinjiang and the Qaidam Basin in Qinghai. The precipitation in this zone is less than 100 mm, evaporation is more than 2,500 mm, and the bioclimatic zone is classified as an extremely arid area. As closed basins, runoff carrying salt flows into the basin center from the peripheral areas and accumulates in the soil. The soil surface in many areas may be covered with a thick salt crust and the salt content may exceed 20%. Many kinds of salt accumulation processes occur in this zone including accumulation resulting from groundwater, relic salt accumulation, diluvial salt accumulation processes and formation of lakeside salt crust and salt mud.

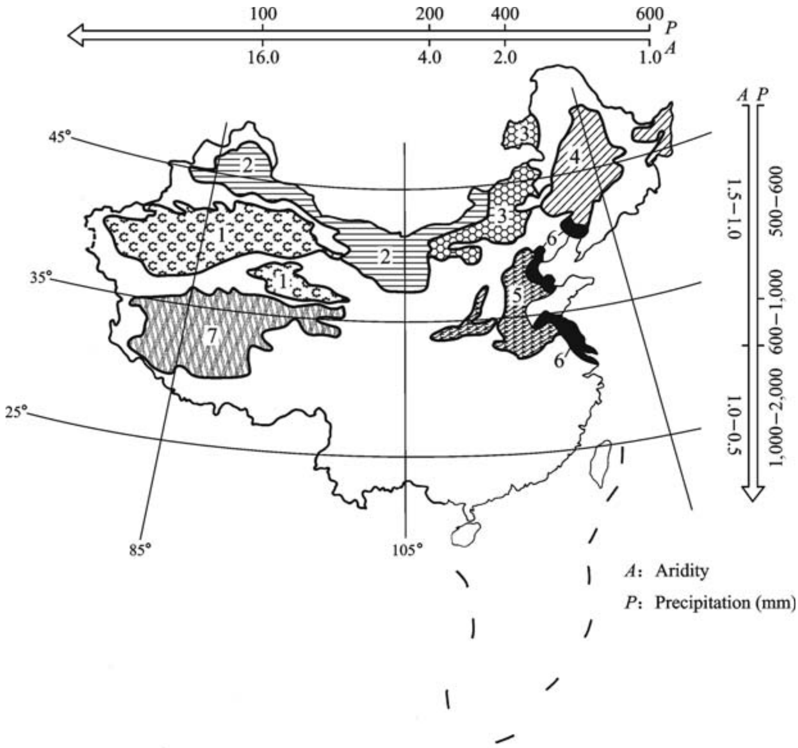

Fig. 6.3 Salt-affected soil zone in China (Shi, 1986, with permission from author)

1, salt-affected soil zone in extremely arid desert; 2, salt-affected soil zone in arid desert and desert steppe; 3, salt-affected soil zone in arid and semi-arid steppe region; 4, soda salt-affected soil zone in semi-arid and semi-humid climates; 5, salinized soda alkalized salt-affected soil zone in semi-humid monsoon climates; 6, coastal salt-affected soil zone in semi-humid and humid monsoon climate; 7, salt-affected soil zone in high altitude cold deserts, lakes and basins

6.2.2 Salt-affected soil zone in arid desert and desert steppe

6.2.2.1 Salt-affected soil sub-zone in semi-arid and semi-desert of upper and middle reaches of the Yellow River

This sub-zone covers parts of Shaanxi, Gansu, Qinghai and Inner Mongolia and majority of Ningxia. The main climate characteristics are aridity and low precipitation. Annual precipitation is 150–500 mm, evaporation is 1,800–2,400 mm and the soils in the zone are dark loessial soil, chestnut soil and gray calcium soil. In addition to sulfate-chloride or chloride-sulfate salt-affected soils formed by modern salt accumulation process, there are also albic soils and partial relic salt-affected soils.

This sub-zone consists mainly of two famous Hetao Plains (the Qiantao and Houtao plains) along the Yellow River and two Plateaus (Loess Plateau and Ordos Plateau), with the Yellow River flowing through across this area. In the semi-arid area of the Loess Plateau, there are thick sulfate sediment materials in the soil substrate, which comes from some branches of the Weihe and Jinghe Rivers which originated in the Liupan Mountains. For example, the mineralization in the Hulu River, a branch of Weihe River, is 0.6–2.0 $g \cdot L^{-1}$, and in the Xianma River, a branch of Jinghe River, mineralization is up to 7 $g \cdot L^{-1}$, which leads to salt accumulation in soil substrate. Salt content in clay soils in Guyuan County, Ningxia is up to 0.33%, and in clay subsoil of Haiyuan County, Ningxia is 0.35–0.66%. Gypsum can also be found in some substrates, and hence there exists a potential risk of salinization.

In the middle reaches of the Yellow River, modern salt accumulation occurs mainly in the Hetao Irrigated Area (the Qiantao and Houtao plains). This region was irrigated for a long time with water channeled from the Yellow River, and the large amount of irrigated water caused the watertable to rise. This, coupled with low precipitation (200–300 mm) and high evaporation (more than 2,000 mm), causes serious salt accumulation in the topsoil layer of the whole region. Based on incomplete statistics, it appears that the land area with the water table less than 2 m below ground level accounts for 80% of the whole irrigated area. Therefore, under arid climate circumstances, it is difficult to control soil salinization in the long term. If the mineralization in the Yellow River is taken as 0.3 $g \cdot L^{-1}$, it is calculated that 13.82 million tons of salt each year enter the Houtao Irrigated Area. The salinized area in 1954 was 11–15% of cultivated land area, in 1963 it was 22% of the cultivated land area, and in 1973 salinization affected 58% of the cultivated land area. Soil salinization has yet to be controlled effectively.

In addition, salt-affected soil patches are distributed along some intermittent or seasonal rivers and valleys in middle of the Ordos Plateau, eastern area of Qinghai and southern are of Gansu in the upper reaches of the Yellow River.

6.2.2.2 Salt-affected soil sub-zone in the arid desert of Gansu, Inner Mongolia and Xinjiang

This sub-zone covers the Hexi Corridor of Gansu, the Alxas region of Inner Mongolia and the northern region around the Tianshan Mountains of Xinjiang. These areas are closed inland areas, and surface runoff flows from melted alpine snow and precipitation disappear via infiltration into Gobi and sandy deserts, or flow into inland lakes. Salts accumulate in the slow flow areas, and inland salt-affected soils with a high salt content are formed over large areas. The soil types in this sub-zone are grey desert soils, gray-brown desert soils and gray calcium soils, in which there are moderately soluble salts characterized by gypsum ($CaSO_4$) and $MgCO_3$. In addition to a large area of modern crusty chloride-sulfate salt-affected soils, there are also relic salt-affected soils, gypsi-salipan relic salt-affected soils, takyri-alkalic salt-affected soils and other salt-affected soils. Based on the bioclimatic condition and soil salinization features, this sub-zone can be classified into two parts: the Hexi Corridor-Alxas Desert area with alkalic-Gobi chloride-sulfate salt-affected soils, and the Junggar Basin area with alkalic-gypis-Gobi chloride-sulfate salt-affected soils.

6.2.3 Salt-affected soil zone in arid and semi-arid steppe region

This zone is distributed mainly in the high plains of eastern Inner Mongolia, including the Hulun Buir high plain and the eastern part of the Inner Mongolian grassland. Here the altitude is 700–1,500 m, the accumulated temperature more than 10 °C is 2,000–3,000 °C, the annual evaporation is 1,500–2,000 mm, the annual precipitation is 200–350 mm with more than 70% of annual precipitation falling in July, August and September, aridity is 1.25–1.50, the ratio of evaporation to precipitation is 5–10, and the bioclimatic zone is classified as temperate steppe. The groundwater table depth changes following the landform position: on high terraces, the groundwater table depth is about 6–8 m below ground level and mineralization is normally 1–2 $g \cdot L^{-1}$ while in valley or lakeside lowlands, the groundwater table depth is mostly 1–2 m, mineralization is up to 2–3 $g \cdot L^{-1}$, salt components include sodium bicarbonate, sodium chloride-bicarbonate and sodium sulfate-bicarbonate.

Two soil types, saline soil and alkaline soil, are formed from soil salinization. In the undulating Hulun Buir high plain, the altitude of the valley is several tens meters lower than that of the high plain. The height difference results in water and salt redistribution, and salt-affected soil formation with a distinct spatial pattern. In the *Leymus chinensis* community, the humus layer is relatively thick, and there is a slow soil desalination process which follows the steppe soil formation process. Steppe tectonic alkaline soil can be found in many areas. In lower positions, meadow tectonic alkaline soil is formed following meadow formation, and in the lowlands along the valleys, some aquatic and salt-tolerant vegetation such as *Carex* spp., can be found among the *Leymus chinensis* community, where soda salt-affected soils or soda-sulfate salt-affected soils are formed.

6.2.4 Soda salt-affected soil zone in semi-arid and semi-humid climates

Soda salt-affected soils are concentrated in the SongLiao, Songnen and Sanjiang plains in northeast China and the eastern part of Inner Mongolia. The temperature in this zone is relatively low, with an obvious freeze-thaw process in the soil, and annual precipitation is 500–700 mm, mostly from May to October. Spring droughts are very serious, and hence soil salt accumulation is very significant. Although there are some outflowing rivers such as the Nenjiang, Songhuajiang and Liaohe Rivers in this zone, many short course or seasonal rivers do not join these. Instead, these seasonal rivers form little lakes or bogs at the end. In the northeast China, small and large shallow lakes dot the plains and collect runoff but most of the water soon evaporates, resulting in higher mineralization in these lake areas (normally 1–3 $g{\cdot}L^{-1}$, but up to a maximum of 5–7 $g{\cdot}L^{-1}$). In this zone, the main chemical component of groundwater with low mineralization (< 1 $g{\cdot}L^{-1}$) is calcium bicarbonate, in groundwater with moderate mineralization (1–5 $g{\cdot}L^{-1}$) is sodium bicarbonate, and in groundwater with high mineralization (3–7 $g{\cdot}L^{-1}$ or more) is sodium chloride.

Due to special climatic and geographical conditions, soil salinization is related closely to meadow forming processes, and develops mainly from meadow marsh soils, dark meadow soils, black calcium meadow soils and black soils. Soda salt-affected soils are mostly distributed as patches, and sodium accumulation is often associated with salt shortage and soil alkalization. Based on the geomorphology and river systems in northeast China, the soda salt-affected soil zone can be divided into two sub-zones, being the semi-humid meadow alkalization-patchy soda salt-affected soils sub-zone in the SongLiao Plain and the semi-humid meadow bog dotted with soda salt-affected soils sub-zone in Sanjiang Plain.

6.2.5 Salinized soda alkalized salt-affected soil zone in semi-humid monsoon climates

This zone is the largest area covered with salt-affected soils in China, and includes the North China Plain, the Fenhe River watershed in Shanxi Province, and Jinghe River-Weihe River watershed in Shaanxi Province.

6.2.5.1 Steppe salt-affected soil sub-zone on the Huang-Huai-Hai Plain

The Huang-Huai-Hai Plain, covering 310,000 km^2, is one of main agriculture zones in China. This zone is characterized by severe drought, flooding, and soil salinization. Crop yield has been low and unstable in the past but recently, through large scale land reclamation, the agricultural environment has been improved and soil salinization is effectively controlled. However, soil salinization and its secondary processes cannot be eradicated, and salt affected soil covers about 3.33 million ha, with other sites also threatened by secondary salinization to a greater or lesser degree. There are two tasks for soil salinization improvement in this zone, one is the use and improvement of existing salt-affected soils and the other is the prevention of potential secondary soil salinization.

(i) Low plains area along Bohai Bay

This area is located within a 150 km stretch of coastline on Bohai Bay. The altitude is about 2–5 m above sea level, and the area includes a large part of Tianjin, and parts of Hebei and Shandong provinces. The soil salt is mainly sodium chloride. The salty landscape in this coastal area exists only within 10–15 km of the coastline. Rice paddy development with freshwater channeling is a successful method for improving coastal salt-affected soils. For example, in the northern part of Bohai Bay and the southern part of Luannan County, paddy fields are being reclaimed by channeling water from the Luanhe River and rice yield has increased to 7,500–9,000 $kg \cdot ha^{-1}$. Soil salinization has been alleviated recently.

Soil management in this area should be focused on the use of the soil, and soil improvement measures. Fresh water from the rivers can be used for agricultural development. Due to seawater inundation and the negative effect of groundwater on salt leaching, soil desalinization is very difficult. Therefore, controlling surface salt accumulation is an effective method for salt-affected soil improvement. Even if a great deal of freshwater is channeled in from other regions, the groundwater table will not rise much. The key question here is how to use wisely the freshwater resources from rivers that flow into the sea. If there is no freshwater there is no agriculture, and few alternative land uses. One main problem is that there is surplus freshwater in the rainy seasons but little in the dry seasons. This means that, assuming that there are no changes to drainage and flood prevention in the upper reaches, freshwater storage infrastructure should be developed downstream for the benefit agricultural use in this area, to change passive condition of agriculture and land use.

(ii) Salt-affected soils area in the middle reaches of the Heilonggang River

This area includes Shenxian, Wuyi, Zaoqiang, Jixian and Xinhe counties in Hengshui region, Hebei Province. The formation of salt-affected soils is related to the semi-humid monsoon climate and shallow salty underground water. Salt-affected soils have been improved effectively with a series of controlling measures such as ditch drainage, well irrigation and drainage and replacement of salty water with freshwater since the 1960s. Recently, due to a shortage of surface water, well irrigation has been one of primary methods of agricultural development, and a lowering of the groundwater table has also decreased the degree of soil salinization. However, the groundwater depth in spring averages about 2.5 m in this area, and is only 1.6 m in Shenxian County, so the natural salt accumulation process at the soil surface is relatively serious. Irrigation and drainage infrastructure needs to be further enhanced, and irrigation with water containing more than 3 $g \cdot L^{-1}$ total soluble salts should be forbidden.

According to field investigations, soil management, and especially soil fertility, plays an important role in increasing soil productivity. For example, in Qianbao Village, Xinhe County in Hebei Province, the groundwater depth is 2.5 m. When channel irrigation methods were applied, the soil salt accumulation was very serious, with the salt content in the 0 –10 cm soil layer increasing to 0.235%, the soil organic matter content was 1.10%, and the wheat yield was about 7,500–9,000 kg · ha^{-1}. In Zhaojiaquanfeng Village, Taocheng District in Hengshui region (which has similar conditions to Qianbao Village), thanks to intensive soil management, the salt content in 0 –10 cm soil layer is only 0.066%, the soil organic matter content is 1.23%, and the wheat yield is about 10,500–12,000 kg · ha^{-1}.

(iii) Salt-affected soil area in southwest Shandong Province

This area includes the western part of Nansi Lake and Liangshan, Jiaxiang, Jinxiang, Yutai, Yuncheng, Juancheng and Heze counties on the right bank of the Yellow River, in southwest Shandong Province. In this area, the main soil salt component is sulfate, and the salt content in the whole soil layer is very high. This area is irrigated with water channeled from the Yellow River, the groundwater depth is about 1 m, and the natural salt accumulation in the soil is very strong. Here, improvement of the salt-affected soil is different from the situation in Heilonggang. When salt accumulation has a significant influence on crop production, water with high sediment content is channeled from the Yellow River, creating a new sediment soil layer about 30 cm thick on which cultivation and cropping proceeds.

The water level in Nansi Lake has risen due to the rising groundwater table and lateral (horizontal) infiltration from the Yellow River. Drainage is very bad, and it is very difficult to lower the watertable below the critical value in the short term. Soil salinization control will be a long term task in this area. In addition, if the proposed east line project to transfer water from south to north is implemented, soil salinization will become more severe. Therefore, the only method for improvement of the salt-affected soils in this area is salt leaching with flood water. In the lakeshore area, rice is sown with channeled water, which is a cost effective method for salt-affected soils utilization.

6.2.5.2 Patchy chloride-sulfate salt-affected soil sub-zone in semi-arid Fenhe River-Weihe River Valley

This sub-zone includes the Fenhe River valley plain and the Weihe River valley plain. The area is more arid than the North China Plain, and relies more on channel irrigation. Because of a poor drainage system, soil salinization is on the increase. In 1957, salt-affected soils covered about 50% of the cultivated land. The area of salt-affected soil has decreased drastically due to drought and water shortage in recent years, but there are two severe salt accumulation areas in the Jinzhong Basin: one is the Jinyuan Lowland and the other is the end of the Jinzhong Basin. In the Weihe River watershed, salt-affected soils are mainly distributed on floodplain terraces and ancient riverbed terraces. The salt component is mostly sulfate.

In addition, in the Shanxi-Hebei inter-mountain basins such as Datong, Xinding and Changzhi basins, there are a few patches of chloride-sulfate salt-affected soils.

6.2.6 Coastal salt-affected soil zone in semi-humid and humid monsoon climate

This zone is mainly located in low plains along the coastline in the eastern part of China and the delta areas of large river basins. Due to long term seawater inundation, there is a high salt content in the soil and groundwater.

6.2.6.1 Chloride salt-affected soil sub-zone around the Bohai Sea

This sub-zone is located at 35°–41°N, from Liaodong Bay in the north to Laizhou Bay in the south, and includes the Liaoning Province, Hebei Province, Tianjin Muncipality and Shandong Province. The climate is classified as a warm-temperate monsoon climate, the annual precipitation is 500–700 mm, mainly falling from July to September, and the climate is characterized by alternating spring droughts, autumn flooding and late autumn drought. Seasonal salt accumulation and desalinization processes alternate. The altitude is 2–10 m above sea level, the groundwater depth is 1–2 m, and in reclaimed farmland, the soil salt content is about 0.1–0.3% and the salt components are mainly Cl^- and Na^+ ions.

6.2.6.2 Chloride salt-affected soil sub-zone around the East Sea and the Yellow Sea

This sub-zone is located at 26°–35°N, from Haizhou Bay in the north to the estuary of the Mingjiang River in the south. The annual precipitation is 1,000–1,800 mm, annual mean temperature is 13 –18 °C, and the main soil salt component is chloride. Salt-affected soils form in bands parallel to coastline. From east to west, the soil salt content and groundwater mineralization decrease, and dominant soil salt type changes from chloride, to sulfate-chloride, to bicarbonate-chloride. Vegetation communities change from *Artemisia halodendron*, *Aeluropus littoralis* and *Imperata cylindrica* to farmland.

6.2.7 Salt-affected soil zone in high altitude cold deserts, lakes and basins

This zone is part of the Tibetan Plateau in the south of the Kunlun Mountains and west of the Hengduan Mountains. There are few outflowing rivers, as most of the rivers on the plateau are short course and dispersing rivers that terminate in isolated lakes, forming the large lake group in the highest altitude part of China. Lake water mineralization is mostly above 1 $g{\cdot}L^{-1}$, due to strong evaporation, and some lakes have become saline. Many water bodies have gradually shrunk, and some lakes have dried up and disappeared. Diverse salt-affected soils are formed in lakeshore terraces. Due to weaker salt accumulation and stronger steppe-bog processes, geochemical differentiation of the salt types is not obvious. The soil salt component is mainly soda-sulfate-chloride in the Qiangtang Plateau, and sulfate in the alpine valleys in the northwest of the Tibetan Plateau. In addition, there are patches of sulfate salt-affected soils in the Yarlung Zangbo Valley.

6.3 Soil salinization damage and control

Soil salinization not only harms plants directly, but indirectly influences plant growth and development through changing soil physico-chemical properties. Due to the complicated impacts of salinization on plants and soil, pedologists and plant physiologists have paid great attention to their researches since the start of the 21st century. The research focus is as follows.

6.3.1 Impact of salts on plant germination and establishment

The physiological drought hypothesis was put forward at the end of 19th century. This theory hypothesized that plants absorb water from soil through the high osmotic pressure of root cells. Normally, the osmotic pressure of root cells is 1 –2.5 MPa, while that of soil solution is only 0.1–0.2 MPa, so plants can absorb water and nutrients from soil through root cells. If the osmotic pressure of soil solution increases to 0.4 MPa, plant water absorption from soil will become difficult and plant growth is restrained, and if the osmotic pressure of soil solution is increased to 1 MPa, most plants will not grow normally. Finally, if the osmotic pressure of soil solution is 1.5 MPa, most plants will wilt and die.

As the soluble salt concentration of the soil increases, the osmotic pressure of the soil solution also increases. When the osmotic pressure is $0.5-1.5$ MPa or higher, plants cannot get water from soil, and even if there is sufficient water in the soil, plants show water deficit symptom, i.e., physiological drought occurs. During the crop sowing period (usually spring), salts in salt-affected soils accumulate mainly on the soil surface and at sowing depth. This means that higher salt concentrations in the soil will impede germination and result in poor plant establishment. During the seedling period, crops with shallow roots and weak resistance are easily harmed by soil salinization. After germination and establishment, the root elongates into deeper soil layers. Soil salinization can be alleviated to some extent. Different salt components in soil will cause different intensities of damage. Normally single salt components cause greater harm than combinations of salt.

6.3.2 Effect of salts on plant photosynthesis and metabolization

Research into plant physiology shows that the stomatic diameter will become smaller when the soil salt concentration increases, and this influences CO_2 diffusion within the plant and affects plant photosynthesis. The main reason for this phenomenon is that plant hormones are affected by salts, so that when the soil salt content is too high, the concentrations of hormones that enhance stomata opening are reduced and the concentration of abscisic acid that checks stomata opening is increased. The change in stomata openness influences plant growth directly.

Higher soluble salt concentrations will also weaken plant metabolism. Scientists from the former Soviet Union identified that soil salts will result in some poisonous intermediate materials during N metabolism. The direct harm of these poisonous metabolites is sometimes several times of that the harm from NaCl.

6.3.3 Effect of salts on ion poison and nutrient absorption maladjustment

If plants absorb too much Na^+ from salt-affected soil, their absorption of Ca^{2+} and Mg^{2+} will be reduced, leading to Ca^{2+} deficits within the plant. Too much SO_4^{2-} in soil will also result in a Ca^{2+} deficit in plants. This is seen when the leaves on the lower position of the stems become red and fall off. Over-accumulation of Na^+ within the leaves leads to withering at the leaf tips and margins. Similar effects are also seen with Cl^- over-accumulation within leaves because this also leads to leaf edge withering and chloroplasts decrease influencing photosynthesis and starch composition. In recent years, some experts identified that a high soil salt content damages the selective absorption capacity of root cells to nutrient ions: when too many non-nutrient ions and poisonous ions are absorbed, plant nutrition maladjustment and nutrition deficit symptom appear.

6.3.4 Effect of salts on soil physico-chemical properties and biological properties

When soluble salt concentrations in soil are too high, these salts often accumulate on the soil surface, resulting in a reduction in surface temperature and slower plant growth. If the salt is mainly $MgCl_2$ and $CaCl_2$, due to their strong moisture absorption capacity, the soil surface becomes wetter and the soil surface temperature increases slowly during the spring. In addition, salt-affected soil, especially alkalinized soil, may form a hard salt layer which reduces root penetration and restricts plant growth. Meanwhile, high soil alkalinity makes nutrients such as phosphate, Fe, Zn and Mn unavailable to plants which results in plant nutrition deficit symptom.

Soil salinization can limit soil microorganism activity. When the concentration of NaCl and Na_2SO_4 is 0.2% or more, nitrogen mineralization reactions decrease significantly, and when the salt concentration is more than 1%, these reactions effectively stop, which directly influences the absorption of available N by the crop.

6.3.5 Effect of salts on crop quality

Soil salinization not only reduces crop yields, but seriously influences the quality of the crops. It has been reported that high Cl^- content in soil reduces the igniting feature of tobacco, while moderate Cl^- content could increase grape yield and quality. At higher Cl^- concentrations, however, grape yield and quality are reduced.

6.4 Improvement of salt-affected soils

Since the foundation of the People's Republic of China, great achievements of improvement of salt-affected soils have been gotten. Here, we introduce these achievements from researches to practices.

6.4.1 Progress in salt-affected soil improvement research in China

6.4.1.1 Geographical and genetic classification of salt-affected soils

Salt-affected soils in China have a broad distribution and a rich variety of types. Large scale integrated investigation of natural resources in the 1950s laid a good foundation for research into the geographical and genetic classification of salt-affected soils. Xiong (1957) initially classified salt-affected soils into four zones: a coastal salt-affected soil zone; a floodplain salt-affected soil zone; a desert and desert steppe salt-affected soil zone; and a steppe salt-affected soil zone. Later, regional salt-affected soils research in Xinjiang, the North China Plain, Ningxia, Inner Mongolia and the Northeast Plain was undertaken. The salt-affected soils group of the Nanjing Institute of Soil Science, Chinese Academy of Sciences (1978) and Wang (1993) classified the whole national territory into eight salt-affected soil zones and 27 salt-affected soil sub-zones based on a comprehensive analysis of existing data and documents. Shi (1986) suggested at the 13th International Conference on Soil that seven salt-affected soil zones should be categorized based on bioclimatic zones and soil salinization types. The salt-affected soil zone in the semi-humid monsoon climate was singled out and the salt-affected soil formation, characteristics, geographical distribution, water-salt movement and improvement in this zone was described in detail (Shi, 1986).

In the 1950s and 1960s, China applied the salt-affected soil classification system from the former Soviet Union. The Nanjing Institute of Soil Science, in 1978 suggested the Chinese Salt-affected Soils Category System, whereby salt-affected soils were classified into two soil types — saline salt-affected soils and alkali salt-affected soils. Saline salt-affected soils were further classified into six sub-types and alkali salt-affected soils into four sub-types. The sub-types were classified based on the differences of formation conditions and processes, and integrated the previous classification system. The principles, methods and nominations of this categorization system are relatively clear and logical, but lower categories have no consistent classification criteria and system.

Compared to research on saline salt-affected soils, research on alkali salt-affected soils is relatively weak. In the 1950s and 1960s, the research emphasis was on steppe and meadow alkali salt-affected soils with B horizons in the chestnut soil belt and black soil belt. Takyr alkali salt-affected soils in Xinjiang and Ningxia also received some attention. In the 1970s, and especially since the 1980s, Yu et al. (1984) published their series of papers on tile-like crust-solonetz. From field surveys and indoor simulation experiments, they hypothesized that as long as dissociative sodium bicarbonate and sodium carbonate exist in low mineralization groundwater, alkalization processes cannot be halted even in calcareous soil and other neutral soils. They also concluded that irrigation with low alkaline mineralization groundwater can also result in secondary soil alkalization. They established a classification indicator system for alkali salt-affected soils in the Huang-Huai-Hai Plain with relic sodium carbonate and exchangeable sodium (ESP) as the main indicators.

6.4.1.2 Water-salt movement in salt-affected soils

The occurrence and evolution of salt-affected soils and any amelioration are closely related to the movement of soil water and soluble salts, making it necessary that the studies on salt-affected soils and their improvement focus on water-salt movement.

The improvement of salt-affected soils involves influencing and improving water-salt movement by means of human measures. This means that water-salt dynamics in salt-affected soils can be used to validate the effects of any improvements. In large areas of salt-affected soils where improvement is attempted using water conservancy in 1950s, some experts suggested that the rising height of capillary water and the moisture of capillary bond disruption can be used as determining indices for the critical groundwater table. This then provides a valuable reference for drainage engineering design and secondary soil salinization control.

The book *Saline Land Improvement* edited by Huang and Wei (1962) provided an overview of the determination of critical watertable depth, salt-washing standards with irrigation, and technical indices of irrigation and drainage systems for salt-affected soils improvement with water conservancy. Some researchers have used agronomic techniques such as gutter-sowing, ridge culture and making soil clods to improve the water-salt condition within the salt-affected soil surface layer so that crop germination and survival rate could be significantly increased. In addition, water-salt dynamics in paddy fields and brackish water irrigation of seasonally freezing soil also provide scientific data for measuring salt-affected soil improvement and utility.

Over time, studies on water-salt movement of salt-affected soils progressed. For example, Shi and Xin (1983) and Shi (1986) classified salt-affected soil zones in the semi-humid monsoon climate and explained the seasonal dynamics of water-salt movement in salt-affected soils and the transfer of soluble salts and their re-distribution features in soil and groundwater. Yu et al. (1984), through field observations and lab simulations, validated the viewpoint of Xiong (1965), that tile-like crust-solonetz formation is related to low mineralization alkalic groundwater evaporation and seasonal transfer of neutral salts. Jia (1985), using trace isotope and numerical simulation methods, built a numerical simulation model of water-salt movement processes and the characteristics of a loose sand soil column under various evaporation conditions.

In the early 1980s, water-salt movement in salt-affected soils was studied by applying an energy viewpoint, using principles of soil hydrodynamics and solute transportation, and computer numerical simulations and modern testing methods. For instance, Liu (1985b) modified the equation for the critical depth of sub-water for salt accumulation, and the estimation method of soil salt with subwater evaporation using multi-scenarios with a soil water-salt movement model under steady evaporation conditions. Zhu et al. (1986) studied the water-salt movement of soil with a clay layer during the rainy season. Yang (1986) made progress in understanding saturated and unsaturated soil water-salt movement, and established a mathematical model for soil water-salt movement using water and solute transportation dynamics. He also provided methods for determination of model parameters. Huang's (1988) results on the salt dispersion coefficient of unsaturated soil under field conditions provided a valuable reference for soil water-salt movement. The spatial heterogeneity of soil properties also drew attention from Chinese scientists, for example, Hu et al. (1995) analyzed the spatial variation of soluble salts in soil under field conditions. Li and Li (1998), using a hydrodynamic model, studied the water-salt movement in soil with a clay layer under non steady state evaporation conditions, and identified that the hydraulic conductivities of different soil layers and the position and thickness of the clay layer all play important roles in water-salt movement. They also identified that the potential risk of soil salinization can be predicted with mathematical models and numerical simulations (Li et al., 2003).

6.4.1.3 Regional water-salt movement in salt-affected soil zones and its control

It is well-known that soil water-salt movement should be studied and controlled systematically in large scale salt-affected soil zones. For example, to channel water from the Nenjiang River to the northern part of Heilongjiang Province in late 1970s, the water-salt balance in a 24,000 km^2 area was analyzed, and it was estimated that 26% of the irrigated water would infiltrate into groundwater and the groundwater table would be raised by 0.32 m after the project implementation. In the Urumqi River watershed in Xinjiang, a system comprising mountainous reservoirs, groundwater exploitation in the outflow belt of fluvial fan edges, and irrigation and drainage in the alluvial plain was integrated for scientific management of regional water-salt movement. Huang et al. (1985) established optimized models of salt-affected soils for the integrated improvement of Yanqi Basin of Xinjiang, in which concrete measures and objectives for reducing the groundwater table, improving groundwater quality and lessening salt accumulation in soil surface under different irrigation and drainage conditions were included. The examples above are attempts at integrated planning and improvement of salt-affected soils on a large scale using advanced techniques.

In regional water-salt movement studies, the water-salt balance is a basic and important method. Shi and Xin (1983) and Shi (1986) established the water-salt balance equations and models for the Huang-Huai-Hai Plain, discussed methods for water-salt control for salinized land improvement in this region, and suggested classification principles and methods for small watershed or counties based on water-salt movement types and corresponding water-salt control modes. Wei (1990) also achieved good results calculating the water-salt balance in salt-affected soils in a lowland area of the ancient Yellow River course, Ling County, Shandong Province.

Regional and watershed scale water-salt movement and the effects of its control should be monitored and predicted. Shi et al. (1991) established a complete regional water-salt monitoring and prediction system named RWS. A generalized model for regional water-salt movement can be derived with this system, which elucidates the water-salt condition in a certain subsystem at a certain point based on environmental factors, spatial locations, and internal factors within the system.

$$
\begin{aligned}
&RWS(x,y)_i(t) = \{[C(x,y)_{i\tau} + L(x,y)_{i\tau}] \cdot G(x,y)_i + 1\} + \\
&RWS(x,y)_i(t-1) + A_{ei} \cdot RWS(x_e,y_e)_i(t-1) + \sum_{\substack{j=1 \\ j\neq i}}^{4} r_{ji} RWS(x,y)_j(t) \\
&[i = 1,2,3,4 \,|\, (x,y) \in D] \qquad (6.7)
\end{aligned}
$$

Where RWS is the regional water-salt condition, $(x,\ y)$ is the location of a point; i is the i-th water-salt sub-system, including the groundwater table, groundwater quality, soil water and soil salt; t is time; τ is period from t-1 to t, C is the climatic factor; L is the land use factor; G is the geological and geomorphological factor; A_{ei} is influence of conditions at the neighbor point (x_e, y_e) on the water-salt condition at point (x, y); r_{ji} is influencing parameter of other sub-systems to the i-th sub-system; and D is the study region.

Based on equation 6.7, above, an integrated model was built into RWS to predict the regional groundwater table, water quality and soil water-salt movement. Aided by GIS, a series of thematic maps and tables for regional water-salt movement can be generated. The RWS establishment processes and functions are demonstrated in Fig. 6.4.

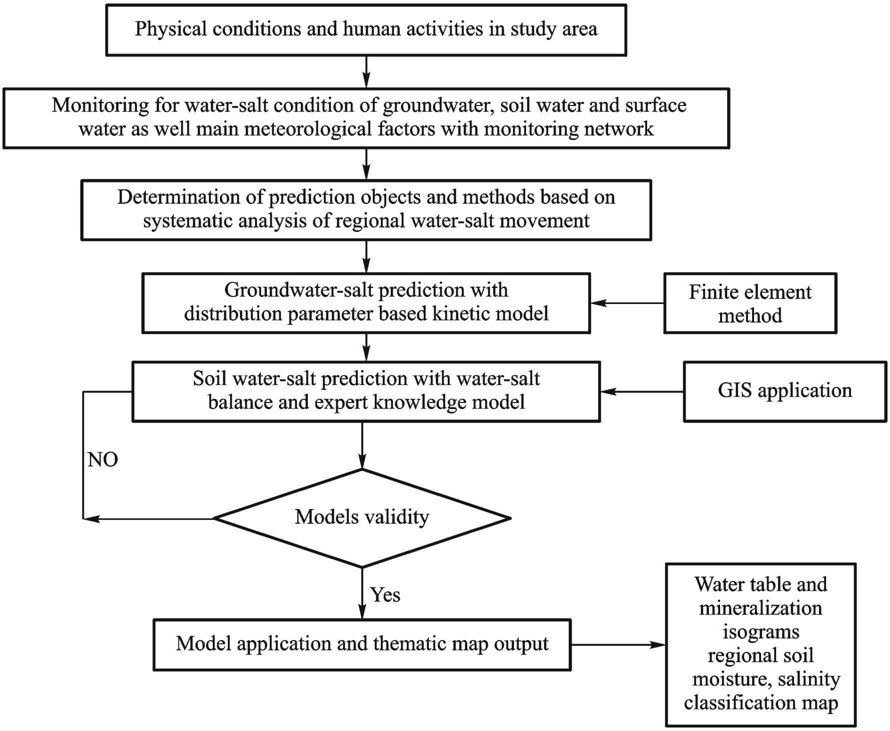

Fig. 6.4 RWS establishment processes and its functions

6.4.1.4 Salt-affected soil improvement and increase in soil fertility

The goal of soil improvement is to allow better land use, so different land-use types require different soil improvement methods. Land-use types are limited by natural conditions and economic and technical feasibility on one hand, and determined by market needs on the other hand. In the salt-affected soil zone of Xinjiang, agroforestry systems integrating salt-tolerant trees or shrubs such as *Populus euphratica*, *Hippophae rhamnoides* and *Tamarix chinensis* with salt-tolerant herbaceous plants have been developed in some salt-affected soils. Some salt-tolerant crops such as sugarbeets, sunflowers, *Carthamus tinctorius* and rape are also sown and processed in some salt-affected soil types.

In the Huang-Huai-Hai Plain, cotton plants with drought and salt tolerance, high rainwater use efficiency and high economic benefit are sown over a large area. Highly salt-tolerant plants such as *Amaranthus hypochondriacus* are sown in coastal salinized soils, where reeds are planted using surface runoff in rainy seasons and river water in winter and aquaculture has been developed on low beaches. The selection of appropriate land-use types can reduce the difficulty and required inputs for salt-affected soils improvement, and increase integrated benefits. For instance, Yin et al. (1993) integrated agriculture, salt industry and animal husbandry in salt-affected soil zones with highly mineralized groundwater (60–100 $g \cdot L^{-1}$) in Laizhou Bay, Shandong Province, and achieved good ecological and economic benefits.

Rice sowing is a good example of salt-affected soil improvement and utility. Some successful pilot studies in Xinjiang, the Yichuan Plain and Liaohe River Delta irrigation area using water from the Yellow River in Shandong and Henan provinces proved that rice sowing and rain-fed rice rotation cropping are good alternatives for salt-affected soil improvement and use with the support of a good irrigation and drainage system (Lei et al., 2006). In addition, following the development of animal husbandry, large areas of salt-tolerant grasses can be sown to raise livestock in salt-affected soil zones.

Salt-affected soil improvement with addition of soil organic matter is one of the traditional methods for soil improvement in China, and farmers are experienced in this technique. Many scientists also conducted related research into this method of improvement. For example, Chen et al. (1985) analyzed improvement caused by soil microorganisms, enzyme activity and organic acids on sodium salts after the addition of organic matter to soda salt-affected soils in Jilin Province. Zhao (1980) conducted a long term study on salt-affected soil improvement using green manure crops and the addition of organic manure in northern Jiangsu Province, and found improvements in increasing biological cover, improvement in soil physico-chemical properties and an increase in soil fertility. He identified that soil improvement must be integrated with building soil fertility and balancing land conservation and land use. Important aspects are the ratio of organic manure and chemical fertilizer, and to the ratio of N and P within the fertilizer mix. The Institute of Soil Science, Chinese Academy of Sciences conducted an on-site study for stabilizing and desalinizing surface soil in coastal regions of northern Jiangsu Province, and provided some soil stabilizing indices such as soil organic matter content, water stable aggregation content, soil bulk density and soil porosity.

For more than 40 years great progress and achievement have been made in salt-affected soil improvement and utilization, successful techniques have been developed and rich experience has been gained. However, due to the large area of salt-affected soils, the complicated physical conditions, and low financial and technical input, secondary soil salinization has reoccurred in some regions and the potential risk of soil salinization exists in other regions. Simultaneously, some progresses in scientific research has also been made. However, some research aspects such as salt-affected soil chemistry, the intrinsic interaction of salt-affected soils with plants, and water-salt movement models need further development (Li et al., 2003).

6.4.2 Achievements in salt-affected soil improvement in the past 60 years

Salt-affected soils are a low production soil with a wide distribution, multiple types and a significant impact on agriculture. In China, there is about 6.7 million ha of agricultural land. Salt-affected soils are an important land resource in northern China and have high potential productivity. Crop yields could double through soil improvement and appropriate use of salt-affected soils. It is expected that land reclamation and expansion in the future will occur in salt-affected soil zones. In addition, following the development of agricultural irrigation technology, secondary soil salinization control has also become a major task for salt-affected soil improvement. In the past 60 years, governments and institutions in China have made substantial effort to foster research into salt-affected soil improvement and utility and significant progress and achievements have been made.

6.4.2.1 Survey, reclamation and improvement with water conservation(1950s)

In the early stage of the establishment of the People's Republic of China, a large group of experts was organized by central government to survey the land resources in the northeast, Qinghai, Tibet, Xinjiang, Ningxia, Inner Mongolia and the North China Plain, and to complete a nationwide soil survey which laid the foundation for salt-affected soil reclamation. At the same time, salt-affected soil reclamation and use were undertaken in many of the regions. For example, a large area of salinized wasteland was reclaimed in Xinjiang and this has become an important food and cotton base. Salt control measures such as a good drainage and irrigation system, artificial salt-washing, paddy rice sowing, and fodder rotation were used.

On the Yinchuan Plain, Ningxia Hui Autonomous Region, salt-affected soils were improved through paddy rice sowing using water from the Yellow River which has resulted in about 0.5 million ha of salinized wasteland becoming highly productive farmland. In addition, successful examples of salt-affected soil improvement were also implemented in the Hetao Plain, Inner Mongolia, the Songnen Plain and the Liaohe River Delta.

In the 1950s, research on salt-affected soils and their improvement was influenced by pedology and measures of soil improvement from the former

Soviet Union. Surveys of salt-affected soil distribution and their classification were done according to the view of soil genetic theory.

These ideas were broadly applied in land reclamation, and more than 20 experimental stations for salt-affected soil improvement were established in northeast, northwest and northern China. These stations played an important role in research on salt-affected soils and their improvement and laid a foundation for modern research into salt-affected soil use and improvement in China.

6.4.2.2 Secondary soil salinization control combined with agricultural measures and water conservation (early 1960s to early 1970s)

The reclamation of large areas of land and the establishment of large irrigation system promoted agricultural development in salt-affected soil zones in the 1950s. However, imperfect irrigation and drainage systems, the use of sloping land and primitive irrigation techniques resulted in rising of groundwater tables, and the development of secondary soil salinization. For example, the area of salt-affected soils on the Huang-Huai-Hai Plain in Hebei, Shandong and Henan Provinces in the mid-1950s was about 1.867 million ha, but this increased drastically to 3.2 million ha by the early 1960s. In the Hetao irrigated region of Inner Mongolia, about one third of land suffered from secondary soil salinization due to the scarcity of channels and drainage systems.

Control of secondary soil salinization was a major task for salt-affected soil improvement in the 1960s. It became known that the reclamation and improvement of salt-affected soils was a difficult and complicated task. This led to some technical research on water conservation, including groundwater critical depth control, irrigation channel arrangement and leakage prevention methods, open ditch drainage, pipe drainage and well drainage methods. Some agricultural measures such as drainage, filling and leveling, flooding sedimentation, green manure planting, salt-tolerant crop selection, and biological measures were also developed and used. Salt-affected soils improvement began to control secondary soil salinization by combining agricultural measures with water conservation.

In the early 1970s, salt-affected soil improvement had achieved significant effects in the main irrigated regions as areas of salt-affected soils decreased markedly. Salt-affected soils in the Huang-Huai-Hai Plain area of Hebei, Shandong and Henan Provinces decreased to 1.4 million ha, from a peak of 3.2 million ha in the early 1960s. In the Xinxiang region of Henan Province, a combination of agricultural measures and water conservation lowered the groundwater table, which totally controlled secondary soil salinization leading to significant increases in crop and cotton yields.

6.4.2.3 Integrated improvement and strengthening stage (mid-1970s to now)

In the early 1970s, there were several million hectares of salt-affected soils in cultivated land, which seriously limited agricultural development. Focused on the lasting drought, an anti-drought conference which covered the 19 northern provinces, identified an experimental zone for the sound use of groundwater and integrated control of drought, waterlogging and soil salinization over 37 counties in the Heilonggang region, Hebei Province. Following from that conference, the integrated control of drought, waterlogging and soil salinization were listed as key state projects in the "Sixth Five-Year Plan" (1980–1985) and the "Seventh Five-Year Plan" (1986–1990). Twelve experimental stations were established, involving dozens of research institutes and more than one thousand scientists. These projects provided great technical contributions to salt-affected soil improvement in the Huang-Huai-Hai Plain and across northern China. During this period significant improvement to salt-affected soils was achieved by: rice sowing in Xinjiang and Ningxia; soda salt-affected soils improvement in Jilin Province; low beach reclamation in coastal provinces; and well drainage systems in Inner Mongolia. Following the reform process in China and opening up to the international community, more and more international exchanges in science and technology have strengthened the salt-affected soil improvement projects. Understanding of salt-affected soils and their improvement has entered a new century.

6.4.3 Integrated management of soil salinization

The occurrence and evolution of soil salinization are related closely to climate, geological and geomorphological conditions, and irrigation and drainage conditions. In agricultural areas, especially, irrigation and drainage influences the regional water-salt condition, and therefore soil salinization. In the early 1950s, the Jinmenqu and Shuiyuesi irrigated areas were setup in northern Hebei, but irrigation was stopped within a short time due to secondary soil salinization from bad drainage. In Hebei, Shandong and Henan Provinces, the area of salinized land increased from 1.87 million ha to 3.24 million ha in the late 1950s due to inappropriate irrigation channeled from the Yellow River and the large amount of water storage on the Huang-Huai-Hai Plain. The integrated management of water resources was implemented and after more than 10 years of integrated management, the area of salinized land decreased to 1.81 million ha in the mid-1970s. By the late 1980s this area had increased again to 1.92 million ha due to inappropriate channeling of water from the Yellow River and too many diversions built in the drainage rivers. In the Hetao region, Inner Mongolia, water had been channeled from the Yellow River for agricultural irrigation since 1963 at a rate of more than 4 billion $m^{-3}\cdot a^{-1}$, but only 0.13 billion $m^{-3}\cdot a^{-1}$ of water was drained. Therefore, a large amount of irrigated water infiltrated into the groundwater, which resulted in a raised groundwater table and the area of salinized land increased from 0.02 million ha in 1962 to 0.23 million ha in the late 1980s.

Sound irrigation and drainage can improve the regional water-salt condition and reduce the area of salinized land. An unbalanced relationship between irrigation, drainage and water storage can worsen the regional water-salt condition and result in the expansion of soil salinization. In a broad sense, the focus of salinized land reclamation and secondary soil salinization control is the control of regional water-salt movement. For instance, whether the south to north water channeling project leads to secondary soil salinization on the North China Plain will be determined by the water-salt movement control measures.

6.4.3.1 Salinized land management in the eastern monsoon zone

Salinized land in the eastern monsoon zone is characterized by complex water-salt movement. Controlled by monsoon climate, 60–70% of the precipitation occurs in summer, resulting in a cycle of summer waterlogging and spring drought, where seasonal salt accumulation and desalinization processes in soil occur alternately, and salts are frequently exchanged between the soil and groundwater, resulting in soil salinization and groundwater mineralization. Therefore, drought and waterlogging are concomitant to soil salinization and water mineralization under monsoon climate and specific geological and geomorphological conditions. The drought accelerates soil evaporation, while waterlogging raises the water table, both of which are important causes of soil salinization and water mineralization. Salt-affected soil also absorbs more soil water, exacerbating drought conditions and influencing crop growth, while high water mineralization can accelerate salt accumulation and weaken the anti-drought capacity. In a summary, drought, waterlogging, soil salinization and water mineralization are closely related and salinized land management must be planned and implemented in an integrated way.

The focus of salinized land management in the eastern monsoon zone is on shallow groundwater exploitation, including saline water with less than 7 $g \cdot L^{-1}$ mineralization. The research results from the integrated experimental area for land salinization management in Quzhou County, Hebei Province showed that reasonable use of shallow groundwater could augment the irrigation water source. It can increase the soil water storage capacity and anti-waterlogging capacity by reducing the groundwater table. In addition, using groundwater helped to restrict the soil salt accumulation in the dry season and accelerated soil desalinization in the rainy season. In regions with saline water, saline water can be drawn out and supplemented or diluted with fresh water, which can gradually reduce the salt concentration in the groundwater. For example, in the east and north of Henan Province, due to inappropriate irrigation with water channeled from the Yellow River, the area of salinized land increased from 0.38 million ha in the early 1950s to 0.8 million ha in the late 1950s. Following the expansion of groundwater based irrigation, the watertable was lowered gradually each year, and the area of salinized land decreased to less than 0.27 million ha. There are many salinized land management models with groundwater irrigation in the northwestern part of

Shandong Province.

Water balance calculations show that, with the current irrigation methods, shallow groundwater cannot meet water requirements for higher crop yield in the eastern monsoon zone. Groundwater irrigation often leads to well drawdown cones due to over-exploitation of deep groundwater. Hence, with the effective use of precipitation, water from the rivers and deep fresh groundwater should be used to supplement inadequate water sources. In conclusion, to repair river courses and manage salinized land shallow groundwater should be used for irrigation supplemented with water from rivers and channel irrigation (Hu et al., 2007). This provides a feasible and generally accepted strategy for salinized land management of the Huang-Huai-Hai Plain in the eastern monsoon zone.

Compared to the Huang-Huai-Hai Plain, the Northeast Plain is characterized by low groundwater mineralization which is suitable for irrigation. However, soda salinization and alkalization are common, so in addition to water conservation measures, soil amendments with organic manure addition and green manure planting can be undertaken. Alkaline soil also can be replaced with new soil or improved with sand cover and some chemical measures such as addition of gypsum, phosphogypsum, calcium sulfite ($CaSO_3$) and ferrous sulfate ($FeSO_4$) and other can also reduce soil alkalinity.

6.4.3.2 Salinized land management in inland zone

Salinized land in the northwest arid and semi-arid inland areas is mainly distributed in closed and semi-closed basins, where underground runoff and salt have no discharge path. Controlled by an arid climate with low precipitation and high evaporation rates, the salt accumulation process is accelerated at the soil surface. Compared to the eastern monsoon zone, natural soil desalinization is very weak and crop growth is totally dependent on irrigation. However, inappropriate irrigation methods and channel construction, without appropriate leakage-proof technology result in rising watertables, commonly leading to secondary soil salinization in cultivated land.

The degree of salinization and the salt components in the salinized land of this zone are distinct due to characteristics such as precipitation, landform, soil texture and water sources. Improvement measures also need to be specific to the region, and here, the key point is management of the groundwater table, i.e., groundwater table depth must be lower than the critical depth at which soil becomes salinized and crops suffer from salt damage.

The basic method for salinized land improvement in this region is to establish drainage systems for lowering of the groundwater table and discharging water with high mineralization after salt-washing. The establishment of the drainage system must include a good outlet, a suitable distance between ditches and a suitable ditch depth, and also deal with the relationship between upper and lower reaches. To allow for smooth discharge in those places without artesian conditions, pumping stations should be set up.

The most common drainage method in these areas is open ditch drainage. Open ditch drainage is a simple and easy method, but when used on more cultivated land they silt up easily due to soil collapse, so other drainage methods such as well drainage or pipe drainage are also applied. Wells can be used for irrigation and drainage in regions with low mineralization groundwater, and in closed and poor drainage areas. Well drainage has a significant potential for salinized land improvement, and the distribution pattern of wells should be arranged according to local conditions. Pipe drainage, using ceramic or concrete pipes, has an advantage over ditch drainage, but the one-off input cost is considerably higher, so it is often applied first in richer regions or where high value crops are grown.

Scientific irrigation methods also play an important role in improving water-salt conditions. Flood irrigation not only wastes precious water resources, but raises the watertable and increases the drainage pressure. Therefore, water-saving irrigation methods should be advocated and extended. In addition, leak-proofing measures should be also strengthened for irrigation channels to avoid the formation of a salt-affected soil belt along the channels.

6.4.3.3 Reclamation of saline and alkaline land in coastal areas

Land in coastal areas had been formed within a short term, the elevation is below 10 m and the land surface is relatively flat with a slope gradient of about 1/7,000–1/10,000. Due to tidal inundation and the reversing flow of seawater, drainage is very difficult. In these areas, the groundwater table depth is 0.5–2 m, mineralization is typically 10–50 $g \cdot L^{-1}$ with a maximum of 120–150 $g \cdot L^{-1}$, salt distribution within the soil is relatively homogenous, and the salt content is typically 2–3% with a maximum of 5–8%.

Salty and acid soils in south China have a low salt content, normally less than 2%. In these areas, banks and watergates should be built to prevent tidal inundation, and the drainage rivers, field irrigation and drainage measures must be optimized to discharge flooding and waterlogging separately. Irrigation channels should be distinguished from drainage channels. Normally, salt is drained out using deep ditches, and pumping equipment is required for those deep ditches that do not drain into the sea with artesian discharge. In areas with clayey soil, shallow dense ditches can be used. According to the experimental results from the Agricultural Experimental Station of Xinyang County, Jiangsu Province, a combination of shallow dense ditches (1.2–1.5 m deep) with perennial green manure planting can halt soil resalinization. In addition, more water should be channeled in or stored, where possible, to wash salt or sow rice. Thanks to plentiful rainfall in these areas, rainwater can be collected in the summer to leach salt from soil, which will accelerate the soil desalinization.

6.4.3.4 Ecological measures and control of soil salinization

Salinized land management involves soil amendment, but this must be combined with basic farmland construction. Establishment of shelterbelt, land leveling, increasing soil fertility and an appropriate crop planting system will develop a good farmland ecosystem.

Farmland protection forest networks can enhance drainage, improve farmland microclimate and reduce soil evaporation and salt accumulation. Forestation in salinized land should use endemic salt-tolerant plant species. Tree species suitable for the eastern monsoon zone and coastal salinized land are *Robinia pseudoacacia*, *Melia azedarach*, *Sapium sebiferum*, *Morus alba*, *Ulmus pumila*, *Salix matsudana*, *Populus canadensis*, *Populus simonii*, *Populus tomentosa*, *Populus dekuanensis*, *Paulownia fortunei* and *Platycladus orientalis*. Suitable shrub species for this zone are *Tamarix chinensis*, *Amorpha fruticosa*, and *Salix purpurea*.

Plant species suitable for the northwestern inland salinized area are *Tamarix chinensis*, *Elaeagnus angustifolia*, *Salix matsudana*, *Populus simonii*, *Ulmus pumila*, and *Robinia pseudoacacia*. In heavy saline and alkaline land, forestation has to be implemented after desalinization, and some measures such as: ditches for salt drainage; blocking up lowlands; land preparation with ditch ridges, terraces, and small rectangular patches; and new soil replacement within planting holes should be applied. The landscape layout of ditches, canals, forest belts and roads should be arranged sensibly.

In arid and semi-arid areas, the micro-topology will influence the horizontal movement of salt. Salt will accumulate in higher locations under the influence of capillary action and evaporation and form patchy saline or alkaline soil. In monsoon areas, irrigation makes this phenomenon more obvious. If land is undulating and irrigation is uneven, salt patches will appear. Therefore, leveling is a key measure for salinized land reclamation and should be undertaken for each land area.

Soil salinization and soil fertility are closely related and the addition of organic manure can improve soil fertility conditions, enhance the capacity to crop salt-tolerant species and increase crop yields significantly.

From a long term view, changes to soil fertility and soil physical-chemical properties can improve water-salt movement conditions within cultivated soil layers. Consequently, the integration of the two measures is a key focus for salinized or alkalized land reclamation on basic farmland with a high and stable yield. As well as the addition of farmhouse manure and the return of crop stalks to the field, green manure should be developed, and raising livestock with green manure crops is also advocated to increase the development of animal husbandry. Sowing of green manure crops not only increases field fertility, but directly improves salt-affected soil. For instance, in Fengqiu County, Henan Province, *Medicago sativa* was planted to improve tile-like alkali patches, and the results showed a decrease in pH value by 0.5–1.4 units, and a reduction in the degree of alkalization by 7–23%, with a disappearance of soda.

Suitable green manure (or fodder) planting systems should be established, and the species of green manure plants should be selected in accordance with local climate and soil conditions, especially considering the intensity of soil salinization. For instance, on the Huang-Huai-Hai Plain, highly salt-tolerant plant species such as *Sesbania cannabina*, *Amorpha fruticosa* and *Vallisneria natans* can be planted in heavy salinized land, moderately salt-tolerant plant species such as *Melilotus suaveolens*, *Medicago sativa*, *Vicia villosa*, *Lolium perenne* and *Festuca elata* can be planted in slightly or moderately salinized land, and low salt-tolerant plant species such as horsebean, pea, *Medica gohispida* and *Astragalus sinicus* can only be planted in desalinized land. Salt-affected soils are normally phosphorus poor, so phosphorus based fertilizer must be used with green manure planting, and "nitrogen fertilizer increasing with phosphorus fertilizer addition" is a key measure of green manure planting (Xu, 2004).

Salinized land management should also include appropriate land use and crop sowing patterns. Based on various physical conditions, rainfed cropland, paddy fields, grassland, forestland and reed fields should be arranged for the best use of soil and water resources. However, it should be noted that although paddy fields are useful for improving salinized land, the area and pattern of paddy fields should be planned taking water sources, drainage capacity, soil, landform, labor force and fertilizers into consideration. Paddy fields should be developed on low-lying salinized land, such as coastal areas, low-lying regions along the rivers and closed lowlands in the interior of the plains, but good irrigation and drainage systems must first be established.

In summary, salinized land management should be implemented combining biological measures with agricultural practices such as forest plantation, land leveling, fertilizer addition and crop sowing. High yield farmland ecosystems characterized by salt-affected soil improvement, secondary soil salinization control and soil fertility amendment should be established where possible.

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7 Steppe Degradation and Rehabilitation in Northern China

Zhongling Liu and Xinshi Zhang

Steppe is the natural grassland in temperate semi-arid areas of the northern Asia, with the potential for desertification. Although the desertification of the steppe is not as strong or rapid as earthquakes and floods, it has become the most extensive and serious ecological event. The main objectives and basic measure to combat the steppe desertification is developing a high-quality and high-yielding and eco-friendly intensive modernized husbandry to gradually supersede the traditional low productivity and eco-unfriendly backward mode of husbandry production that had characterized grazing practices in natural grassland for thousands of years.

7.1 Territorial distribution of steppe and natural geographic conditions

China's steppe is a part of the temperate grassland and the eastern half of the Eurasian steppe zone. The special geographical position of China's steppe decided it's significant position in ecological function and economy-cultural impact in East Asia and Northern China, but, also gave it a strong potential and trends of desertification; China's grassland might (actually) develop varying degrees of desertification, it is also available through reasonable conservation and ecological restoration for an effective front edge and barrier for combating desertification, conservation field for biodiversity, as well as the sustainable production base of grassland agriculture.

7.1.1 Evolution and territorial location of steppe in northern China

Steppes in northern China are found in the sub-humid zone, semi-arid zone and arid zone in a temperate climate zone that stretches for thousands of kilometers from east to west. Vast steppe areas occur in the semi-arid zone of the Inner Mongolian Plateau. As the largest area of steppe, they are linked to the steppe in the Republic of Mongolia to the north; join with the Nenjiang Plain grassland in western Heilongjiang Province and Jilin Province to the east; extend east to the steppes in northern Hebei Province, northern Shanxi Province, northern Shaanxi Province, eastern Ningxia Hui Autonomous Region and eastern Gansu Province in the south; and have the Helan Mountains as their western boundary.

The steppe in temperate zone in Northern China has experienced a long geological and environmental evolution. Since the Oligocene epoch of the Tertiary period, the once vast Tetisi Sea in western China has retreated and disappeared due to the Himalayan uplift. The continental dry warm-cold climate has gradually accelerated and the forest vegetation evolved and turned into sparsely forested grassland and steppe. Various angiosperm genera displayed good adaptability and, malleability during the plant evolution and gradually became the main components of the plant communities. In particular, *Stipa* spp., which first appeared during the Oligocene epoch and dissociated and developed in the later Tertiary period, becoming the dominant species in steppe evolution until the Pliocene Epoch and eventually forming various different *Stipa* spp. which dominate the steppes.

There are a total of 970,000 km^2 of steppe in Northern China representing more than 10% of the total land area of China. The north part of the steppe zone is the grazing area of the Mongolian ethnic minority, while the eastern and southern parts of the steppe zone are transitional areas of agriculture and animal husbandry. The population is made up of multi-ethnic minorities in these transitional areas. With the East Asia monsoon climate circulation system, steppes in Northern China are situated at the frontlines of the Siberia-Mongolia cold fronts and winter winds, and these steppes become source regions for blown sand disasters and harsh climate conditions, which move southeast toward Beijing and the coastal cities of China.

Before the 1960s, steppe vegetation was well conserved, delivering a range of ecological services such as providing a natural ecological protective belt in Northern China. During the 1970s, because of the rapid growth of livestock populations, inappropriately cultivated steppes and ruthlessly exploited plant resources, steppe vegetation and soils became degraded and damaged by shifting sands, and the ecological environment deteriorated. At present, these steppes are under the threat of severe desertification and the productivity of the agriculture and animal husbandry sectors is critically limited.

7.1.2 Geological and geomorphologic conditions in steppe areas

The geological structure of the steppe areas in Northern China is controlled by the Cathaysian structural system and parallel structures. The orientation is northeast–southwest with an arc-belt shaped distribution. Geologically, the steppe zone starts from the Helan Mountains in the west, links with the Yinshan Mountains and Da Xing'anling Mountains in the east and forms the peripheral mountains at the southeast of the Inner Mongolian Plateau. It is an important natural boundary line in Northern China and affects all the natural elements, including biogeographic distribution. The massive geomorphologic patterns, like plains, mountains and plateaus, in steppe areas run east-west or northeast-southwest and are distributed in belt shapes stripes that reflect the geotectonic forms of the underlying strata.

The vast Inner Mongolian Plateau lies to the north of the Da Xing'anling Mountains, the Yinshan Mountains and the Helan Mountains, which are linked and form an uplift belt. The elevation of the plateau is 700–1,400 m and its topography is gradually inclined and declined from south to north and from west to east. Geomorphologically, it generally alternates successively from peripheral mountains to full round low and gentle hills and uplands.

The Hulun Buir Plateau in the northeastern part of the Inner Mongolian Plateau consists of piedmont hills and uplands along the western foothills of the Da Xing'anling Mountains with an elevation of 700–900 m above sea level. There are vast sediment deposits of loess materials and moraines on the piedmont hills belts and is characterized by forest grassland landscapes. In the middle of the upland, zonal grassland vegetation is widely distributed. The sediments are composed of sand layers and sand-gravel layers of different thicknesses. Sparse forests, bush communities and semi-bush vegetation are well developed on parts of the sandlands. Both Hulun Lake and Buir Lake are low lying centers in the upland and there are some salinized lowlands surrounded by various types of meadows. Along both sides of several rivers, there are some areas of wider riverbank swamps, flood-land, bush communities and meadows.

From the Hulun Buir Plateau towards the south, the Inner Mongolian Plateau stretches across the east part of Mongolia into the Xilin Gol Plateau of Inner Mongolia and with an elevation varying from 900 m to 1,300 m above sea level. In the eastern area, mountains from the southern section of the Da Xing'anling Mountains close in with an arc-shape and in the southern area, low hills rise along base of the Yinshan Mountains. Some inland rivers and depressions are distributed in this vast region and these are covered by various meadows. The eastern half of the Xilin Gol Plateau extends from the center of Ulagai River and forms the Uzhumuqin Basin, of which the central part is the Abaga lava tableland, the western part is the Erlian Basin, and the southern part is the vast Otindag Sandland.

The western neighbor of the Xilin Gol Plateau is the Ulan Chabu Plateau.

Its elevation is 1,000–1,500 m above sea level, the south area consists of vast piedmont foothills in the north of Yinshan Mountains, and the northern part of the foothills are level and consist of caved belts at 1,300 m elevation. This is a transitional belt of agriculture and animal husbandry. In the north part of this caved belt, an east–west rocky hill uplift belt, with an elevation of 1,500–1,600 m, has been severely denuded. Northward, it enters into an upland area where the landform is flat and elevation varies from 1,000 m to 1,200 m. The surface materials are mainly composed of Tertiary mudstones and sandstones, which are the natural landscape of the desert steppe. There are some areas of dried river courses and lake depressions on the upland terraces which originated from the Yinshan Mountains, and have developed into a salinized meadow habitat.

The Ordos Plateau is an ancient terrace with an elevation of 1,100–1,500 m. The bedrock is composed of loose Mesozoic sandstone which has formed various landform patterns due to the denudation and sedimentation in the Quaternary period. The middle part of the Ordos Plateau is seriously denuded and there are some denuded residual hills, gullies and lake depressions on the upland with significant carved topography. The western part of the Ordos Plateau is a piedmont alluvial plain of the Zhuozi Mountains and the eastern part is carved and broken loess hills eroded by flood waters that have exposed bedrock areas. The southern part is the Mu Us Sandland which is covered by aeolian sands from the Quaternary period and the northern part is the Qubqi Desert, which stretches from east to west. Accordingly, there is a wide distribution of psammophytes and semi-bushes which are adaptable to topsoil erosion and sedimentation on the Ordos Plateau.

The Loess Plateau area in northern Hebei, northern Shanxi, northern Shaanxi, eastern Ningxia and eastern Gansu provinces are Quaternary aeolian landform patterns and they consist of various geomorphological units of tablelands, ridge lands, terraces and mesa. Natural steppes have almost disappeared due to long term agricultural cultivation and as a consequence, serious soil erosion has occurred and this area has become an originating source of sediments to the Yellow River. At present, these regions are defined as the core region for implementing the national project of "rejecting crop farming for reforesting and revegetating degraded lands" (the Grain for Green Project). This national project will, in the context of ecological safeguards, form an integrated management area of natural and developed landscapes composed of agriculture, animal husbandry, forest plantations, plant breeding and processing industries.

7.1.3 Climate conditions of the steppe areas

Steppes in Northern China are situated inland or adjacent to inland regions at medium latitudes, and are characterized by a temperate continental climate. The climate on all steppes is controlled by the Mongolian high pressure air currents in the winter season as cold fronts from the continental center frequently move to the coastal areas. The influence of the southeast ocean monsoon becomes gradually weaker from the southeast to northwest and the monsoon is unable to influence climate in steppe areas. This is because of the encirclement by the Changbai, Yanshan, Taihang and Luliang Mountains, and inside the steppe areas, and because of the impediments formed by the Da Xing'anling and Yinshan Mountain ranges. The climate in the vast areas in the western part of the Helan Mountains is under the control of the continental air mass. Under the effects of ocean and continental distributions and topographic structure, the climate elements in the steppe areas in the arc-shaped belt that runs from northeast-southwest are determined by characteristics of atmospheric circulation.

The temperature in the steppe areas reduces gradually from northeast to southwest and both the southern periphery and the western region of the steppe have an annual accumulated temperature of greater than 3,200 – 3,300 °C. The zonal difference in temperature affects significantly the botanical composition of plant communities.

Long sunshine hours are also an important feature of the climate in steppe areas. The annual accumulated sunshine hours are 2,500–3,400 hours in various regions and the sunshine percentage is around 55–78%. The steppe area is one of the regions with the richest sunshine hours in China. This is particularly important in the areas with low temperature and a short frost-free period in Northern China. High levels of sunshine are a favorable condition for plant growth and agricultural production.

The geographic distribution of precipitation is determined by the effect of the southeast air currents. Due to the blocking effect of the high mountains, precipitation in the eastern part of the Da Xing'anling Mountains, and in the southern part of the Yinshan Mountains is higher than that of the Inner Mongolian Plateau. Precipitation declines gradually moving further inland. In the northern area and along the eastern foothills of the Da Xing'anling Mountains, the annual precipitation is 400–450 mm; along the Xiliao River valley, in the piedmont plain areas and hilly areas of the southern foothills of the Yinshan Mountains and in the east part of the Ordos Plateau, annual precipitation is as high as 350 mm. However, on the Hulun Buir and Xilin Gol Plateaus in the western part of the Da Xing'anling Mountains and the central part of the Ordos Plateau, the annual precipitation is about 300 mm. Annual precipitation declines in a westerly direction and varies from 200 mm to 250 mm. In the eastern Alxa Plateau in far west Inner Mongolia, the annual precipitation is less than 200 mm. Atmospheric precipitation, in this vast region, is the fundamental water source for plant growth and biological existence and almost all water supplies originate from atmospheric precipitation. The amount of precipitation is the important driver in this vast region.

The seasonal distribution of precipitation is also an important ecological element. The precipitation in the steppe areas is mostly distributed in the summer and autumn seasons, namely July, August and September and the precipitation during these seasons accounts 80–90% of the total annual precipitation. The daily mean temperature during the period with a daily maximum more than 10 °C is around 20 °C. This temperature is favorable for the growth of plants. However, in the spring season, frequent droughts are unfavorable for the re-greening of steppe.

The annual evaporation rate in steppe areas is typically three to five times the annual precipitation rate, but can be eightfold in some areas and in even as high as fifteen to twenty times in desert regions. The annual evaporation in different regions increases from the east to the west along with a decline in humidity, reduction in cloud cover and increase in sunshine. Beside the Da Xing'anling Mountains, the average evaporation varies from 1,200 to 3,000 mm while in some western regions, it can be as high as 4,600 $mm{\cdot}a^{-1}$.

Frequent wind is another important feature of the steppe climate. Under the control of the Mongolian high pressure systems in the winter and spring seasons, strong winds blow frequently in steppe areas. The prevailing wind in the winter season is from the north-west and the most frequent winds in the summer season are from south and southeast. In most regions, the mean annual wind speed is 3–4 $m{\cdot}s^{-1}$. In arid and semi-arid regions, wind force is always an important driving force in the creation of the natural landscape. The occurrence of deserts, sandlands and loess landforms are all closely related to the effects of the wind. The geomorphological structure in various deserts in the steppe regions is consistent with the dominant wind direction. Loess hills are often subject to long periods of wind denudation and accumulation, and the ground surface is unstable. Consequently, there is some redistribution of plant communities on sandland and eroded lands in steppe areas. Strong windstorms are one of serious natural disasters destroying the steppe landscape, threatening agriculture and animal husbandry production and worsening the habitats in the affected regions. In recent years, due to steppe degradation, sand encroachment and acceleration of land surface erosion, sand-dust storm weather often occurs in the steppe areas and also affects Beijing and adjacent regions and other districts in north China.

Climate elements cause variations in steppe types, steppe landscape structure and the material and energy conditions of steppe productivity. The temporal and spatial differences of temperature and humidity create different combinations of water and heat which are the leading factors affecting various biogeographic features of steppe. The differentiation of steppe landscape belts coincides with the distributions of climate belts. Table 7.1 shows climate elements in different districts of steppes in Northern China.

Table 7.1 Climate elements values in different districts of steppes in Northern China

Steppes	Temperature (°C)				Precipitation (mm)			H	GP(day)
	MAT	AT	HMMT	CMMT	MAP	MAM	MIM		
I	2.5–4.4	2,150–2,665	20.5–23.2	–17.2– –19.8	417–458	141–152	0.6–1.7	0.53–0.70	172–188
II	–2.8– –3.4	1,622–1,886	17.5–19.6	–27.8– –29.5	356–425	118–130	2.0–3.8	0.61–0.74	150–164
III	5.8–6.4	2,844–3,108	23.7–24.8	–13.8– –15.4	448–514	147–168	0.4–1.4	0.60–0.78	185–205
IV	–2.2–4.7	1,888–2,485	17.8–21.3	–17.8– –27.7	258–406	66–114	0.8–3.1	0.28–0.54	160–175
V	0.6–3.8	1,894–2,320	18.2–24.0	–13.9– –19.3	378–411	109–149	0.6–2.1	0.30–0.82	166–180
VI	5.2–6.0	2,665–3,022	19.8–24.8	–12.7– –16.1	352–424	98–137	0.7–1.7	0.34–0.49	188–210
VII	2.8–5.1	2,086–2,590	19.2–22.7	–15.4– –18.6	148–262	41–77	0.2–1.1	0.12–0.26	180–205
VIII	6.5–7.6	3,046–3,312	22.4–25.5	–10.6– –13.2	418–528	132–164	0.8–2.8	0.48–0.56	195–220
IX	4.8–7.5	2,658–3,266	21.2–23.8	–11.3– –15.1	344–446	90–145	0.5–2.5	0.31–0.47	205–228
X	6.6–7.9	2,653–3,257	22.2–24.5	–10.2– –13.6	246–315	68–102	0.3–1.2	0.19–0.25	205–232

I: Meadow grassland in the Nenjiang River valley; II: Meadow grassland in the west Xing'anling Mountains; III: Meadow grassland on the Liaohe River Plain; IV: Typical steppe on the Inner Mongolian Plateau; V: Typical steppe in the south Xing'anling Mountains; VI: Steppe of Horqin Sandland; VII: Sunite Desert steppe; VIII: Forest grassland on the Loess Plateau; IX: Typical steppe on the Loess Plateau; X: Desert steppe on the Loess Plateau; MAT: Mean annual temperature; AT: Accumulated temperature ≥ 10 °C; HMMT: Hottest month mean temperature; CMMT: Coldest month mean temperature; MAP: Mean annual precipitation; MAM: Maximum month; MIM: Minimum month; H: Humidity; GP: Growth period

7.1.4 Hydrological conditions of the steppe areas

The distribution of surface water systems is determined by geomorphological structure and atmospheric precipitation. Inside the steppe areas in Northern China, the mid-eastern part of the Hulun Buir Plateau, the eastern side of the Da Xing'anling Mountains and the southern part of the Yinshan Mountains are the outflow water systems, including the Ergun, Nenjiang, Xiliao and Yellow Rivers. The headwaters are sufficient and the river networks are densely developed. Along the banks of these rivers, wide river beaches or alluvial plains were formed and these are adaptable to the growth of meadows, swamp plants, riparian woodlands and other riverbank plant communities and halophytic vegetation. Most parts of the Inner Mongolian Plateau have inland rivers with few streams and rivers and low water discharge. The few permanent rivers are the Kelulun, Ulagai and Xilin rivers. The bends of these rivers are well developed and river beaches and riverbeds are colonized by meadows, salinized meadows and halophilous vegetation.

There are vast numbers of different sized lakes on the Inner Mongolian Plateau. However, because of arid climate and strong evaporation, most of the lakes are highly mineralized saline lakes. Fresh water lakes with low mineralization are mostly located in the eastern and middle parts of the Inner Mongolian Plateau, and include the Hulun Lake, Buir Lake, Dali Nur and Uliangsu Nor, which have large areas of water. Low wetlands and salinized lowlands are distributed around these lakes and nors and are dominated by intra-zonal vegetation types.

The distribution of groundwater varies significantly in response to the variation of stratum and regional climate. The regions with sufficient groundwater are mostly located in semi-closed basins, such as the Tumote Plain, the Xiliao River plain, the Uzhumuqin Basin, the Mu Us Sandland, the Otindag Sandland, the Horqin Sandland, and the Wuerson Lowland in the Hulun Buir Plateau. These regions are rich in shallow aquifers with low mineralization and have a large distribution of intra-zonal vegetation. In upland areas, due to the complex geological structure, aquifers are unstable and there is substantial regional variation in groundwater in terms of distribution, quality and accessibility. In general, these regions are short of groundwater. Other than lake basins and areas adjacent to river courses, the groundwater table is normally less than 30–50 m and there is a wide distribution of zonal plants which are indirectly impacted by groundwater, especially riverine forests like *Populus euphratica*.

7.1.5 Soil conditions of the steppe areas

The zonal soils formed under the bioclimatic conditions in steppe areas are complex types, mainly composed of black soil, black calcium soil, chestnut soil, brown calcium soil, gray-brown desert soil, drab soil, black loam soil, and grey calcium soil. In addition, under special conditions which exist in some regions, such as low wetlands with a high groundwater table, and some sandlands and gravel slopes, there are some areas of meadow soil, swamp soil, saline soil and low-fertility sandy loam and gravels. The soil belt, which typically coincides with the bioclimatic belt of steppe described above, mainly comprises a zonal soil type with some non-zonal soil types.

Black soil is mainly located on the piedmont plain areas on the eastern foothills of the northern Da Xing'anling Mountains and is combined with other types of soils to form the black soil belt. By analyzing the differences in black soil profiles, it can be classified into three sub-types as deep-thick black soil, normal black soil and meadow black soil.

Black calcium soil is largely distributed along both sides of the foothills of the Da Xing'anling Mountains in the form of a continuous but narrow belt of black calcium soil mainly found in the forest-grassland. The development of black calcium soil is closely related to meadow grassland vegetation under sub-humid climate conditions. *Stipa baicalensis* steppe, *Leymus chinensis* steppe and *Filifolium sibiricum* steppe are all commonly found on black calcium soil. Black calcium soil can be classified into sub-types of dark black calcium soil, normal black calcium soil, light black calcium soil, and meadow black calcium soil.

Chestnut soil is a typical steppe soil originated under semi-arid climate conditions, which coincides with the typical steppe belt to form a chestnut soil belt. This chestnut soil belt is widely distributed from the Hulun Buir Plateau and the Xiliao River valley in the east to the northern foothills of the Daqing Mountains and the Ordos Plateau in the west. As the climate aridization accelerated and the xerophilization of steppe vegetation increased, the chestnut soil formed different sub-types, including dark chestnut soil, normal chestnut soil and light chestnut soil. The depth, thickness, quantity and patterns of alluvial sediment layers vary depending on regional water and thermal conditions and soil parent materials. For instance, chestnut soils in the southeast foothills of the Da Xing'anling Mountains and the Ordos Plateau contain the highest calcium carbonate content and the thickest calcium sediment especially in topsoil layers. Different types of chestnut soil are all related to the steppe community.

Brown calcium soil is formed under the hottest and most arid steppe climate and is mainly found on the Inner Mongolian Plateau and the western part of the Ordos Plateau, which coincides with desert steppe to form the brown calcium soil belt. This belt is dominated by brown calcium soil with patchy saline desert soil, salinized meadow soil, salt soil, sandy soil and alpine chestnut soil. The bioclimatic conditions forming brown calcium soil are characterized by transitional features of steppe and desert and are the result of soil forming factors from both steppe and desert. These processes include humus accumulation and calcium carbonate sedimentation balanced by occurrences of rough gravel, sand shifting and crust formation. The sub-types of the brown calcium soil are dark brown calcium soil, light brown calcium soil and meadow brown calcium soil. Vegetation in this brown calcium soil belt is mainly composed of a *Stipa* spp. dominant desert steppe community and *Caragana tibetica* and *Reaumuria soongarica* dominant steppe desert community. *Stipa tianschanica* var. *klemenzii* steppe covers the majority of the area. In addition, the *Stipa breviflora* community can be found on dark brown calcium soil, the *Stipa glareosa* community on sandy brown soil, and *Caragana tibetica* and *Reaumuria soongorica* communities on sandy gravel brown calcium soil are also found on the brown calcium soil.

The black loam soil is found in the southern regions in the warm-temperate steppe area and is normally developed on loess parent material. The Loess Plateau is the original source of the black loam soil. Due to special structural features of loess soil, it is highly erodible and as a result, a limited amount of black loam soil has been preserved following long term erosion after the destruction of surface vegetation. The natural vegetation growing on residual black loam soil is dominated by *Stipa bungeana*.

The grey calcium soil is distributed from the southwestern part of the Ordos Plateau to the loess hills of Ningxia and Gansu in the southern and western areas of the steppe. This soil type is formed in warm-temperate desert steppe of the Loess Plateau and its parent material is mainly loess. The grey calcium soil has sub-types of light grey calcium soil and meadow grey calcium soil. The vegetation that is adapted to the grey calcium soil is a desert steppe community dominated by *Stipa breviflora*.

The soils described above are zonal soils distributed on steppe belts and are characterized by pedogenic features of steppe soils, which play an important role in the provision of ecological services by the various steppes.

Meadow soil, swamp soil, saline soil and aeolian soil are all azonal soils from different parts of the steppe areas and they interact significantly with eco-geographic nature of the intra-zonal plants.

7.2 Steppe types, landscape ecological structure, and its regional characteristics

The typical plant community of steppe vegetation type or biome is dominated by the xeric grasses and mixed with a few xeric forbs. Steppe is in the position of the Earth's ecological zones between the mesic forest and super-xeric desert. Because of this, differentiation of steppe types and species composition structure is happening. There were very close relationship between the types and species composition of steppe with desertification.

7.2.1 Botanical composition of steppe and the differentiation of steppe types

The steppe is an ecosystem pattern (biome) that evolved and formed under the various climate conditions found in arid, semi-arid and sub-humid zones in the temperate climate regions of the inland. The plant community of the steppe is a primary producer in the steppe ecosystem. Therefore, the differences of steppe type are principally manifested in the nature of the steppe plant communities they support. All steppe plant communities are composed of low-temperature tolerant and drought tolerant perennial species. Since the Oligocene epoch of the Tertiary period, various plant species have been differentiated and these plants are mainly drought-resistant and adaptable to extremely arid and cold climates and different soil conditions. Many are xerophytes including bunch grass, chamaephytes including rhizome grasses and axial root grasses, and geophytes. There are also some chamaephytic dwarf semi-bushes and semi-bushes.

According to the living form of the main steppe plants, the steppes can be classified into patterns of herbosa associated steppe, rhizoma herbosa steppe, axial root herbosa steppe and dwarf semi-bush steppe . Based on the eco-geographic environment of the steppe, it can be classified into three types, i.e., meadow steppe developed in the sub-humid zone, typical steppe in the semi-arid zone, and desert steppe in the arid zone.

The following sections briefly describe the features of the main representative plant communities (formations) of the various types of steppes.

7.2.2 Main types of steppes

7.2.2.1 *Stipa baicalensis* steppe, one of the main types of temperate meadow steppe

Stipa baicalensis steppe is a peculiar aboriginal type in the eastern part of the Asian steppe. Its distribution is centered on the Songhuajiang-Liaohe River Plain in northeast China, in the eastern part of the Inner Mongolian Plateau, in the northeastern part of the Mongolian Steppe and the Baikal Steppe in eastern Siberia of Russia. This type of steppe is widely distributed along the foothills of the two sides of the Da Xing'anling Mountains. It is a herbosa community steppe type of meadow steppe.

Stipa baicalensis steppe is located in low temperature regions of the semi-arid and sub-humid zones where the annual precipitation is 350–450 mm and the rainfall in July is generally over 100 mm. Annually, there is a 1–2 month semi-dry period and there is no absolutely dry period. There are about 70 (maximum 140) snowy days per year. Annual mean temperature is –2.3 °C to 5 °C and the accumulated temperature $\geqslant$10 °C varies from 1,500 to

2,700 °C. The growth period is 180–210 days and humidity is 0.4–0.7. The elevation is 700–1,700 m.

Stipa baicalensis formation can be classified into six association groups and eleven associations (Table 7.2).

Table 7.2 Classification of *Stipa baicalensis* association formation

Association classes	Association groups	Associations
Stipa baicalensis herbosa community	*Stipa baicalensis* – *Stipa grandis*	*Stipa baicalensis* + *Stipa grandis*
	Stipa baicalensis – *Cleistogenes polyphylla*	*Stipa baicalensis* + *Cleistogenes polyphylla* + *Lespedeza davurica* + *Artemisia gmelinii*
Stipa baicalensis – rhizoma herbosa	*Stipa baicalensis* – *Leymus chinensis*	*Stipa baicalensis* + *Leymus chinensis* + *Filifolium sibiricum*
		Stipa baicalensis + *Leymus chinensis* + *Stipa* spp.
		Stipa baicalensis + *Leymus chinensis*
		Stipa baicalensis + *Leymus chinensis* + weeds
		Stipa baicalensis+*Leymus chinensis*+*Cleistogenes squarrosa*+*Lespedeza davurica*
Stipa baicalensis – forbs	*Stipa baicalensis* – mesophilous weeds	*Stipa baicalensis* + *Melissitus ruthenica* + *Dyxtropis coerulea*
	Stipa baicalensis – *Filifolium sibiricum*	*Stipa baicalensis* + *Filifolium sibiricum* +*Stipa* spp.
		Stipa baicalensis + *Filifolium sibiricum* +*Melissitus ruthenica*
Stipa baicalensis – bush	*Prunus sibirica* – *Stipa baicalensis*	*Prunus sibirica* – *Stipa baicalensis* +*Cleistogenes polyphylla* + *Filifolium sibiricum*

7.2.2.2 *Stipa grandis* steppe, one of the main types of mesothermal typical steppe

Stipa grandis steppe is centrally distributed in steppe belt of the Mongolian Plateau and it is the primary steppe type within the typical steppe. It extends into southern part of Central Siberia, to the central part of the Songhuajiang-Nenjiang Plain and to the Loess Plateau of China. In Northern China, this type of steppe is also continuously distributed on the Xilin Gol Plateau (1,100–1,200 m above sea level) and to the Hulun Buir Plateau (700–1,200 m above sea level). The soil is a thick layer of typical loam and sandy loam chestnut soil and dark chestnut soil. Much of it has eroded in the last few decades.

Stipa grandis steppe is distributed in the semi-arid climate zone in the temperate zone. In this zone, the greatest temperature and rainfall are occured in the summer season, which provides the fundamental conditions for the formation of the *Stipa grandis* zonal steppe. When the habitat condition becomes drier, the *Stipa grandis* steppe will be replaced by xeromorphic *Stipa krylovii* steppe. Therefore, *Stipa grandis* steppe can be regarded as the typical representative steppe of mesothermal steppes of China. According to the classification of natural zones, *Stipa grandis* steppe is an important indicator for classification of the mesothermal forest-grassland sub-belt, typical steppe sub-belt and desert steppe sub-belt. As an original community group, *Stipa grandis* steppe forms an association with various herbosa.

Other plant species of *Stipa grandis* steppe are from Compositae, Gramineae, Leguminosae, Liliaceae, Rosaceae, Labiatae, Chenpodiaceae, and Ranunculaceae families. There are at least five species in each family. The main genus from Gramineae family include *Stipa* spp., *Cleistogenes* spp., *Leymus* spp., *Agropyron* spp; genus from Compositae family is *Artemisia* spp.; from the Leguminosae family is *Astragalus* spp., from the Rosaceae family is *Potentilla* spp. and from the Liliaceae family is *Allium* spp. These plants are indicative of typical steppe in the semi-arid zone.

Stipa grandis steppe is classified into five association classes, eight association groups and seventeen associations (Table 7.3).

Table 7.3 Classification of *Stipa grandis* association formation

Association class	Association groups	Associations
Stipa grandis – herbosa community	*Stipa grandis* – *Stipa baicalensis*	*Stipa grandis* + *Stipa baicalensis*
	Stipa grandis – *Cleistogenes squarrosa*	*Stipa grandis* + *Cleistogenes squarrosa* + *Agropyron cristatum*
		Stipa grandis + *Cleistogenes squarrosa* + *Lespedeza davurica*
		Stipa grandis + *Cleistogenes squarrosa*+ *Artemisia frigida*
	Stipa grandis – *Stipa krylovii*	*Stipa grandis* + *Stipa krylovii*
	Stipa grandis – *Achnatherum sibiricum*	*Stipa grandis* + *Achnatherum sibiricum* + *Leymus chinensis*
	Stipa grandis – *Stipa* spp.	*Stipa grandis* + *Stipa* spp. + *Leymus chinensis*
Stipa grandis – rhizoma herbosa	*Stipa grandis* – *Leymus chinensis*	*Stipa grandis* + *Leymus chinensis* +*Filifolium sibiricum*
		Stipa grandis + *Leymus chinensis* + *Achnatherum sibiricum*
		Stipa grandis + *Leymus chinensis* + *Stipa baicalensis*
		Stipa grandis + *Leymus chinensis* + *Cleistogenes squarrosa* + *Agropyron cristatum*
		Stipa grandis + *Leymus chinensis* + *Cleistogenes squarrosa*

Continued

Association class	Association groups	Associations
Stipa grandis – rhizoma herbosa	*Stipa grandis* – *Leymus chinensis*	*Stipa grandis* + *Leymus chinensis* + *Artemisia frigida*
Stipa grandis – weeds	*Stipa grandis* – *Filifolium sibiricum*	*Stipa grandis* + *Filifolium sibiricum* +*Leymus chinensis* + *Bupleurum scorzonerifolium*
Stipa grandis – semi-bush	*Stipa grandis* – *Artemisia frigida*	*Stipa grandis* + *Artemisia frigida*
Stipa grandis – bush	*Caragana microphylla* – *Stipa grandis*	*Caragana microphylla* – *Stipa grandis* + *Cleistogenes squarrosa* + *Agropyron cristatum*
		Caragana microphylla – *Stipa grandis* + *Leymus chinensis* + *Agropyron cristatum*+ *Serratula centauroides*

7.2.2.3 *Stipa krylovii* steppe, one of the main types of mesothermal typical steppe

The *Stipa krylovii* steppe is associated with herbosa steppe similar to the *Stipa grandis* steppe, and both are common steppe associations in Asian steppes. *Stipa krylovii* steppe is mainly distributed in typical steppe areas of the Mongolian Plateau, stretching northward and eastward to the boundary of the forest-grassland belts. In the south it is located in the semi-arid zone of the Loess Plateau in China, and to the west it is distributed in mountain areas in the arid zone, such as the Yinshan, Helan, Qilian and Tianshan Mountains.

In the Inner Mongolian Plateau areas, a large area of this type of steppe is distributed in a typical steppe belt alternating with *Stipa grandis* steppe. This alternating steppe belt is mainly distributed in the central and western parts of the Hulun Buir Plateau and the Xilin Gol Plateau. The climate is a mesothermic semi-arid climate and the topography is open with flat uplands and hilly slopes. The soils are mainly comprised of loamy soil, sandy loam or sandy chestnut soil.

Stipa krylovii is a xerophyte in the typical steppe and its associations are similar to those of *Stipa grandis* but the community is more restricted. However, in the western part of the typical steppe belt (adjacent to areas of desert steppe), the quantity and function of *Stipa krylovii* exceeds that of *Stipa grandis* and it becomes the dominant plant association. There are typically 15–20 species in one square meter of *Stipa krylovii* association.

Stipa krylovii steppe can be classified into ten association groups and eleven associations (Table 7.4).

Table 7.4 Classification of *Stipa krylovii* association

Association classes	Association groups	Associations
Stipa krylovii – Association of herbosa	*Stipa krylovii* + *Cleistogenes squarrosa*	*Stipa krylovii* + *Cleistogenes squarrosa*
		Stipa krylovii + *Cleistogenes squarrosa* + *Artemisia frigida*
	Stipa krylovii + *Stipa grandis*	*Stipa krylovii* +*Stipa grandis* + *Cleistogenes squarrosa* + *Artemisia frigida*
	Stipa krylovii + *Stipa tianschanica* var. *klemenzii*	*Stipa krylovii* +*Stipa tianschanica* var. *klemenzii* + *Cleistogenes squarrosa* + *Artemisia frigida*
	Stipa krylovii + *Stipa gobica*	*Stipa krylovii* + *Stipa gobica* +*Cleistogenes squarrosa* + *Artemisia frigida*
	Stipa krylovii + *Stipa breviflora*	*Stipa krylovii* + *Stipa breviflora* +*Cleistogenes squarrosa* + *Artemisia frigida*
	Stipa krylovii + *Stipa* spp.	*Stipa krylovii* + *Stipa* spp. +*Thymus vulgaris*
	Stipa krylovii + *Agropyron cristatum*	*Stipa krylovii* +*Agropyron cristatum* + *Artemisia frigida*
Stipa krylovii – rhizoma herbosa	*Stipa krylovii* + *Leymus chinensis*	*Stipa krylovii* + *Leymus chinensis* + *Cleistogenes squarrosa* + *Artemisia frigida*
Stipa krylovii – semi-bush	*Stipa krylovii* + *Artemisia frigida*	*Stipa krylovii* + *Artemisia frigida* + *Potentilla acaulis*
Stipa krylovii – bush	*Caragana* spp. – *Stipa krylovii*	*Caragana microphylla* – *Stipa krylovii* + *Cleistogenes squarrosa*

7.2.2.4 *Stipa tianschanica* var. *klemenzii* steppe, one of the main types of mesothermal desert steppe

Stipa tianschanica var. *klemenzii* steppe is one of the small types of herbosa associated steppe in the desert steppe zone and it is mainly distributed in the Ulan Qab Plateau at the northern and southern foothills of the Yinshan Mountains and the central-western parts of the Ordos Plateau. *Stipa tianschanica* var. k*lemenzii* is the dominant plant species in desert steppe in the Dorno Gobi Province of Mongolia and it is widely distributed in the Altai Mountains in Xinjiang.

Stipa tianschanica var. *klemenzii* steppe is the most drought-tolerant of the *Stipa* spp. steppes and its distribution is closely related to the location of the continental arid climate in the temperate zone. In spring and autumn seasons (particularly in spring), drought will occur for 4 to 6 months and seriously affects the stability of steppe productivity. *Stipa tianschanica* var. *klemenzii* is a typical component of the desert plant community in the Gobi-Mongolia area in Central Asia.

There are few species present in *Stipa tianschanica* var. *klemenzii* steppe and the dominant ones are: *Stipa tianschanica* var. *klemenzii*, *Cleistogenes soongorica*, *Allium polyrrhizum*, *Allium mongolicum*, *Lagochilus ilicifolius*, *Scorzonera divaricata*, *Gypsophila desertorum*, *Iris bungei*, *Hippolytia trifida*, *Ajania achilloidea* and *Caragana stenophylla.* These species are the most stable plants in *Stipa tianschanica* var. *klemenzii* steppe.

Based on differences in plant association groups and their habitats, eleven associations have been determined (Table 7.5).

Table 7.5 Classification of association of *Stipa tianschanica* var. *klemenzii*

Association classes	Associations	Ecological succession trend
Stipa tianschanica var. *klemenzii* – community herbosa	*Stipa tianschanica* var. *klemenzii* + *Cleistogenes squarrosa* + *Artemisia frigida*	Typical *Stipa tianschanica* var. *klemenzii* steppe community
	Stipa tianschanica var. *klemenzii*+ *Cleistogenes songorica*	Evolution to aridization
	Stipa tianschanica var. *klemenzii*+ *Stipa breviflora* + *Cleistogenes squarrosa*	Transition to warm desert steppe
	Stipa tianschanica var. *klemenzii*+ *Stipa krylovii* + *Cleistogenes squarrosa*	Transition to typical steppe
Stipa tianschanica var. *klemenzii* + *Allium* spp.	*Stipa tianschanica* var. *klemenzii*+ *Allium polyrrhizum*	Evolution to soil salinization
	Stipa tianschanica var. *klemenzii*+ *Allium mongolicum*	
Stipa tianschanica var. *klemenzii* + dwarf semi-bush	*Stipa tianschanica* var. *klemenzii*+ *Artemisia frigida*	Evolution to soil erosion and gravel surface
	Stipa tianschanica var. *klemenzii*+ *Hippolytia trifida*	
	Stipa tianschanica var. *klemenzii*+ *Ajania achilloidea*	
Stipa tianschanica var. *klemenzii* + bush	*Caragana intermedia* + *Stipa tianschanica* var. *klemenzii*	Evolution to sandy soil
	Caragana stenophylla + *Stipa tianschanica* var. *klemenzii*	

7.2.2.5 *Stipa bungeana* steppe, one of the main types of warm-temperate typical steppe

Stipa bungeana steppe is widely distributed in warm-temperate belts of the Asian Continent. It is mainly distributed in the Yellow River valley, and extends eastward to the North China Plain. The northern boundary of this type of steppe is the loess hills in the south part of the Xiliao River and in the south of the watersheds of the Yinshan Mountains. To the west, in Qinghai Province, it is distributed in the Qilian and Tianshan Mountains, and even into western Sichuan Province and the Tibet Autonomous Region. South, it is distributed along the Funiu Mountains in Henan Province. *Stipa bungeana* is widely distributed in the Loess Plateau areas of the warm-temperate zones of China including the provinces (or Autonomous Regions) of Shanxi, Shaanxi, Gansu, Ningxia and Inner Mongolia around the middle reaches of the Yellow River.

During a long history of crop farming, land was extensively cultivated and soil erosion has occurred frequently and consequently, very limited areas natural steppe were preserved. Based on research in residual natural vegetation and existing plants, analysis of spore and pollen and surveys of soil and climate conditions, the Loess Plateau has be classified as a sub-humid forest-grassland in its eastern area; a semi-arid steppe in its center; and a desert steppe zone in its western area. It is not easy to find a large piece of continuous original *Stipa bungeana* steppe. Some small pieces of secondary *Stipa bungeana* steppe can be found on abandoned cropland and grazing slopes.

Stipa bungeana is one of the thermophilic xerophytes and is distributed in dense communities to form herbosa community steppes. *Stipa bungeana* is adapted to the environment. Soils are composed of black loam soils with some carbonate brown soils and loess parent materials. There is also some growth of *Stipa bungeana* in mountain areas with thin soil layers.

The original community type of *Stipa bungeana* steppe was monomorphic and its main communities include *Stipa bungeana* + *Cleistogenes squarrosa* association groups, *Stipa bungeana* + *Stipa breviflora* association groups, *Stipa bungeana* + *Agropyron cristatum* association groups, *Stipa bungeana* + *Leymus chinensis* association groups, *Stipa bungeana* + *Lespedeza davurica* association groups, *Stipa bungeana* + *Thymus vulgaris* association groups, and *Stipa bungeana* + *Artemisia gmelinii* association groups (Table 7.6).

Table 7.6 Classification of associations of *Stipa bungeana* steppe

Association classes	Association groups	Associations
Stipa bungeana – herbosa association	*Stipa bungeana* + *Cleistogenes squarrosa*	*Stipa bungeana* + *Cleistogenes squarrosa* + *Artemisia frigida*
	Stipa bungeana + *Stipa breviflora*	*Stipa bungeana* + *Stipa breviflora* + *Cleistogenes squarrosa* + *Artemisia frigida*
	Stipa bungeana + *Agropyron cristatum*	*Stipa bungeana* + *Agropyron cristatum* + *Cleistogenes squarrosa* + *Lespedeza davurica*
	Stipa bungeana + *Leymus chinensis*	*Stipa bungeana* + *Leymus chinensis*+ *Lespedeza davurica*

Continued

Association classes	Association groups	Associations
	Stipa bungeana + Lespedeza davurica	*Stipa bungeana + Lespedeza davurica*
Stipa bungeana + dwarf semi-bush	*Stipa bungeana + Thymus vulgaris*	*Stipa bungeana + Thymus vulgaris + Cleistogenes squarrosa*
	Stipa bungeana + Artemisia gmelinii	*Stipa bungeana + Artemisia gmelinii + Cleistogenes squarrosa*

7.2.2.6 *Stipa breviflora* steppe, one of the main types of warm-temperate desert steppe

Stipa breviflora is widely distributed in warmer regions of desert steppe in the Asian steppes and it is also distributed in some mountain areas of desert regions. *Stipa breviflora* steppe is mainly located in the northwest part of the Loess Plateau, the northern part of the Yinshan Mountains and the southern part of the Inner Mongolian Plateau. This type of steppe stretches south to Lanzhou, Huining and Huanxian in Gansu Province, to Guyuan in the Ningxia Hui Autonomous Region, to Jingbian, Yulin and Suide in Shaanxi Province, and to Hequ and Pianguan in Shanxi Province. This type of steppe can be found in the east to the loess hills of Chifeng in the Inner Mongolia Autonomous Region, and to the north it is directly linked with the steppe area in the southern part of Mongolia (at 45° N latitude). To the west, it extends from Alxa in Inner Mongolia to the mountain areas in the deserts of the southern Xinjiang Uygur Autonomous Region. This species expands even into Kazakhstan. This species also can be found in loess hills in the southwest part of the Qinghai-Tibetan Plateau and in Cuomei and Longzi districts in southern parts of the Yarlung Zangbo River.

Stipa breviflora forms a permanent dense herbosa community belonging to the desert steppe classification. The associations of *Stipa breviflora* include few tall plants. The herbosa species are the most significant associated species including *Stipa* spp. and *Cleistogenes* spp., followed by legume species (predominantly *Caragana* spp.), *Ajania* species and herbaceous species including *Artemisia* spp.

Due to the wide geographic distribution, *Stipa breviflora* steppe has been divided into different community patterns which are manifested according to their individual eco-geographic features (Table 7.7).

Table 7.7 Classification of association of *Stipa breviflora* steppe

Association classes	Association groups	Associations
Stipa breviflora + herbosa community	*Stipa breviflora + Stipa bungeana*	*Stipa breviflora+ Stipa bungeana+ Cleistogenes squarrosa + Lespedeza davurica*

Continued

Association classes	Association groups	Associations
Stipa breviflora + herbosa community	*Stipa breviflora* + *Stipa krylovii*	*Stipa breviflora* + *Stipa krylovii* + *Cleistogenes squarrosa*
	Stipa breviflora + *Stipa tianschanica* var. *klemenzii*	*Stipa breviflora* + *Stipa tianschanica* var. *klemenzii* + *Cleistogenes songorica* + *Ajania achilloidea*
	Stipa breviflora + *Cleistogenes squarrosa*	*Stipa breviflora* + *Cleistogenes squarrosa* + *Artemisia frigida*
Stipa breviflora + dwarf semi-bush	*Stipa breviflora* + *Artemisia frigida*	*Stipa breviflora* + *Artemisia frigida* + *Cleistogenes squarrosa*
		Stipa breviflora + *Artemisia frigida* + *Cleistogenes squarrosa*
Stipa breviflora + dwarf bush	*Caragana intermedia* – *Stipa breviflora*	*Caragana intermedia* – *Stipa breviflora* + *Cleistogenes squarrosa*
	Caragana stenophylla – *Stipa breviflora*	*Caragana stenophylla* – *Stipa breviflora* + *Cleistogenes squarrosa* + *Ajania achilloidea*

7.2.2.7 *Leymus chinensis* steppe, one of the mesothermal rhizome herbosa steppe types

Leymus chinensis steppe is a special type of steppe found in the eastern part of the Euro-Asia continental steppe zone and it is distributed in the Baikal Steppe belt of Russia, in the Mongolian steppe belt, in the steppe belts on the Northeast China Plain, on the Inner Mongolian Plateau and the Loess Plateau of China. The *Leymus chinensis* steppe is distributed in sub-humid and semi-arid zones in the temperate zone of the middle and the eastern parts of Asia. This kind of steppe extends in the north to 62° N latitude and south to 36° N latitude and 92°–132° E longitude. Based on small to medium vegetation maps, it is roughly estimated that the total area of *Leymus chinensis* steppe in the middle and eastern parts of Asia is 420,000 km^2, of which, 220,000 km^2 are found inside China. These are the steppe types with the highest economic value for grazing purposes.

The natural distribution belt of *Leymus chinensis* steppe is wide and it is the largest steppe type in size in the forest-steppe belt. Among the typical steppes, the area of *Leymus chinensis* steppe is a little smaller than *Stipa* spp. steppe, but it still contains various steppe types.

The differences in moisture conditions and the soil salt regime are the important ecological elements differentiating the types of *Leymus chinensis* steppe communities. *Leymus chinensis* steppe is well developed in the zonal habitat and is the most developed steppe community in this habitat. In this ecological area, *Leymus chinensis* steppe often alternates with *Stipa* spp. steppe or *Filifolium sibiricum* + forbs steppe, *Leymus chinensis* + *Bromus* *inermis* steppe, *Leymus chinensis* + mesophilous weeds steppe and herbosa meadow.

Leymus chinensis steppe communities can be differentiated according to eco-geographic areas and botanical composition and can be divided into four sub-associations: (i) Typical steppe type of *Leymus chinensis* steppe; (ii) Mesophilous *Leymus chinensis* steppe; (iii) salinized wet *Leymus chinensis* steppe; and (iv) sandy and gravel *Leymus chinensis* steppe. These sub-associations are based on different plant associations.

7.2.2.8 *Filifolium sibiricum* steppe, one of the cold alpine axial root herbosa steppe types

Filifolium sibiricum steppe is a specific axial root herbosa steppe association found in mountain areas in the middle of Asia, where axial root herbosa is the dominant plant community. The geographic range of *Filifolium sibiricum* steppe formation is at 100°–132° E longitude and at 37°–54° N latitude and it is continuously distributed in the Hang'ai, Kente and Da Xing'anling mountains, the northern part of the Yanshan Mountains, the eastern part of the Yinshan Mountains and the low hills and uplands beyond these mountains.

In China, *Filifolium sibiricum* steppe is mainly distributed in the low hill districts along the eastern and western foothills of the Da Xing'anling Mountains, in the eastern periphery of the Hulun Buir-Xilin Gol Plateau and on the low mountain slopes of the Songhuajiang-Nenjiang River Plain in Northeast China, and it occupies the central part of the steppe area.

Due to the relatively low evaporation rate, the soil moisture conditions during the growth season are high and this provides good growing conditions for meso-xerophilous, xero-mesophilous and mesophilous forbs. Therefore, the *Filifolium sibiricum* steppe community is composed of a rich variety of plant species, with colorful shapes and forms in the community and is highly productive.

Filifolium sibiricum is classified as a cold-tolerant meso-xerophilous axial root herbosa. The *Filifolium sibiricum* steppe community is also characterized by a series of features that are similar to alpine steppe.

Due to the variations in eco-geographic conditions, *Filifolium sibiricum* steppe is differentiated into six association classes and twenty-one associations (Table 7.8).

Table 7.8 Classification systems of *Filifolium sibiricum* steppe associations

Association classes	Association groups	Associations
Filifolium sibiricum – mesothermal herbosa	*Filifolium sibiricum–Stipa baicalensis*	*Filifolium sibiricum + Stipa baicalensis+ Carex pediformis + Prunus sibirica + Hemerocallis citrina*
		Filifolium sibiricum + Stipa baicalensis + Potentilla betonicaefolia
		Filifolium sibiricum + Stipa baicalensis + Galium verum

Continued

Association classes	Association groups	Associations
Filifolium sibiricum – mesothermal herbosa	*Filifolium sibiricum–Stipa grandis*	*Filifolium sibiricum* + *Stipa grandis* + *Hedysarum gmelinii*
		Filifolium sibiricum + *Stipa grandis* + *Stipa davurica*
		Filifolium sibiricum + *Stipa grandis* + *Leymus chinensis*
		Filifolium sibiricum + *Stipa grandis* + *Artemisia frigida*
	Filifolium sibiricum–Stipa krylovii	*Filifolium sibiricum* + *Stipa krylovii* + *Chamaerhodos trifida*
Filifolium sibiricum – frigid-warm herbosa	*Filifolium sibiricum–Stipa* spp.	*Filifolium sibiricum* + *Stipa* spp. + *Aster alpinus*
	Filifolium sibiricum–Leucopoa albida	*Filifolium sibiricum* + *Leucopoa albida* + *Oxytropis filiformis*
Filifolium sibiricum – warm herbosa	*Filifolium sibiricum–Spodiopogon sibiricus*	*Filifolium sibiricum* + *Spodiopogon sibiricus* + *Atractylodes chinensis*
	Filifolium sibiricum–Cleistogenes polyphylla	*Filifolium sibiricum* + *Cleistogenes polyphylla* + *Lespedeza hedysaroides*
Filifolium sibiricum – *Carex* spp.	*Filifolium sibiricum–Carex pediformis*	*Filifolium sibiricum* + *Carex pediformis*+ *Sanguisorba officinalis*
Filifolium sibiricum – bushes	*Prunus sibirica – Filifolium sibiricum*	*Prunus sibirica – Filifolium sibiricum* + *Stipa* spp.+ *Potentilla betonicaefolia*
		Prunus sibirica – Filifolium sibiricum+ *Cleistogenes polyphylla* + *Lespedeza davurica*
	Caragana microphylla – Filifolium sibiricum	*Caragana microphylla – Filifolium sibiricum* +*Stipa baicalensis* + *Carex pediformis*
		Caragana microphylla – Filifolium sibiricum+ *Stipa grandis* + *Leymus chinensis*
		Caragana microphylla – Filifolium sibiricum + *Agropyron cristatum* + *Koeleria cristata*
Filifolium sibiricum – dwarf semi-bush	*Filifolium sibiricum–Thymus vulgaris*	*Filifolium sibiricum* + *Thymus vulgaris* + *Artemisia gmelinii*
		Filifolium sibiricum + *Thymus vulgaris* + *Lespedeza bicolor*
	Filifolium sibiricum–Artemisia gmelinii	*Filifolium sibiricum* + *Artemisia gmelinii*

7.2.2.9 *Artemisia frigida* steppe, one of main degraded steppe types

Artemisia frigida steppe is mainly vegetated by the dwarf-bush *Artemisia frigida* and its succession pattern has changed under the impacts of overgrazing and strong wind erosion in steppe areas.

Artemisia frigida steppe is distributed to the east in steppe districts along the Xiliao River valley in northeast China and to the west in the central and eastern parts of the Mongolian Plateau, the typical steppe of the Ordos Plateau and the desert steppe belt, and it extends into the territories of Mongolia and Kazakhstan.

Artemisia frigida steppe, which is distributed in the central and the eastern parts of the Mongolian Plateau, is classified as a semi-arid typical steppe, and its typical zonal plants are *Stipa grandis* steppe and *Stipa krylovii* steppe (Table 7.9). Due to long-term overgrazing and trampling, the herbosa growth was limited and the drought-tolerant *Artemisia frigida* replaced the original dominant plants and developed the steppe into an *Artemisia frigida* steppe.

Artemisia frigida steppe in the central and west parts of the Ordos sandy-gravel upland is classified as desert steppe when the climate is drier and annual precipitation is 150–250 mm and vegetation is composed of *Stipa breviflora* and *Stipa glareosa* steppe (Table 7.9). The growth of *Artemisia frigida* steppe is closely related to long-term wind erosion and sub-stratum conditions.

Table 7.9 Classification systems of *Artemisia frigida* steppe associations

Association classes	Association groups	Associations
Artemisia frigida typical steppe	*Artemisia frigida* – herbosa	*Artemisia frigida* + *Stipa krylovii* + *Cleistogenes squarrosa*
		Artemisia frigida + *Leymus chinensis*
		Artemisia frigida + *Stipa bungeana*
	Artemisia frigida – dwarf semi-bush	*Artemisia frigida* + *Thymus vulgaris*
	Artemisia frigida – shrubby	*Caragana microphylla* – *Artemisia frigida* + *Stipa krylovii* + *Cleistogenes squarrosa*
		Caragana microphylla – *Artemisia frigida* + *Leymus chinensis*
Artemisia frigida desert steppe	*Artemisia frigida* – *Stipa tianschanica* var. *klemenzii*	*Artemisia frigida* + *Stipa tianschanica* var. *klemenzii*
		Artemisia frigida + *Stipa glareosa*
	Artemisia frigida – dwarf semi-bush	*Artemisia frigida* + *Ajania achilloidea*
	Artemisia frigida – shrubby	*Caragana stenophylla* – *Artemisia frigida* + *Oxytropis aciphylla*

Artemisia frigida is a dwarf semi-bush and it is characterized by its extensive root system, high sprouting and root growth potential, tolerance to trampling and adaptability to soil erosion.

Artemisia frigida is a xerophyte that is distributed in areas from the sub-humid zone to the arid desert steppe and it is either the dominant plant, or in different steppe community, is co-dominant. *Artemisia frigida* steppe usually has rich species diversity.

Artemisia frigida steppe is normally distributed in temperate zone steppes and forms six association groups and ten associations.

7.2.3 Ecological structure and regional differentiation of steppe landscape

During the evolution of geological environment, climate gradients between regions were formed and as a result, different steppe types and regional differentiation have occurred. A complicated series was formed from sub-humid and semi-arid zones to the arid zone in the temperate steppe zone of Northern China based on the gradient of the humidity coefficient. According to the features of landscape structure and ecological services, the zones can be divided into several different regions, and the environment and resources status of each are briefly discussed in following paragraphs.

(i) The Nenjiang-Liaohe River Valley and the piedmont plains at the eastern foothills of the Da Xing'anling Mountains, include Qiqihaer and Daqing cities in Heilongjiang Province, Baicheng and Songyuan cities in Jilin Province, Xing'an Prefecture, the northern part of Tongliao and Chifeng City in Inner Mongolia. This is a region with rich biodiversity. Due to repeated cultivation and grazing, the existing steppe vegetation has been almost totally degraded and the sandy steppe has been desertified. In some low-lying areas with poor drainage systems, the steppe was alkalized.

(ii) The Horqin Sandland along the Xiliao River valley, includes Tongyu in Jilin Province, Zhanggutai in Liaoning Province, Xing'an Prefecture, the southern part of Tongliao, and the central part of Chifeng City in Inner Mongolia. This sandland is an aeolian landform developed on the alluvial plain of the Xiliao River during the Quaternary Period. However, due to population growth in past centuries, steppe and arable land have over-used with high carrying capacities and consequently, forest and grass vegetation has been destroyed, desertified lands have been rapidly spreading over the last three decades and new sand-dust storm sources are expanding.

(iii) The piedmont plain in the western foothills of the Da Xing'anling Mountains forms the forest-grassland belt of Inner Mongolia Plateau, and includes Eerguna City, Yakeshi City, Chenbaerhu banner, Ewenke banner, Ulagai Prefecture and Xiwuzhumuqin banner in Inner Mongolia. Since the 1970s, the steppe and grassland have been inappropriately cultivated resulting in a loss of land productivity as the soil has been turned into sand or covered by shifting sand.

(iv) The Hulun Buir Basin, the western part of the Wuzhumuqin Basin, and the typical steppe belts downstream of the Xilin River, including Chenbaerhu Banner, the western part of Ewenke Banner, Xinbaerhu Zuo Banner, Xinchenbaerhu Zuo Banner, Xinchenbaerhu You Banner, Dongwuzhumuqin Banner, Xiwuzhumuqin Banner and Abaga Banner and Xilinhot City in Inner Mongolia, form another important area where typical steppe is interspersed with hills and upland. The humidity index is 0.35–0.50 and due to over-loading and overgrazing, the steppe is generally degraded at present.

(v) Otindag Sandland, including Keshiketeng, Xiwuzhumuqin, Abaga, Sunite Zuo, Sunite You, Zhenglan, Zhengxiang Bai, Xianghuang and Duolun banners or counties and Xilinhot City in Inner Mongolia, is an aeolian sandland formed during the Tertiary Period on the synclinal structure base stratum at the north foothills of the Yinshan Mountains. The sandland has a total area of 40,000 km^2 and is characterized by alternating sand ridges, longitudinal dunes and inter-dune depressions and a mosaic of small lakes. At present, the vegetation in the west part of the Otindag Sandland is seriously degraded with mobile sand. It is now one of the main sand-dust storm source areas in Northern China.

(vi) The Saihan Tala Upland, Erlianhot Basin and Ulanqab Plateau, including Sunite Zuo banner, Sunite You banner, the northern part of Siziwang banner, Daerhan Maoming'an banner and Ulatezhongqi banner in Inner Mongolia, are vast desert steppes. The climate humidity index is 0.13–0.25 and it forms a transitional zone on the edge of the inland arid zone. The structure of the ecosystem is monotonous with a low level of biodiversity, and steppe productivity is less than 40% of typical steppe productivity. This region is completely affected by desertified land and is one of the main source areas for sand-dust storms. Counter measures must be taken to control the further degradation of this area caused by immigration of people and livestock. The steppe area must be entirely fenced and maintained to restore the steppe ecology.

(vii) The eastern part of the Ordos Plateau, northern Shanxi Province and the loess hills of northern Shaanxi Province, including Hohhot City and Ordos City in Inner Mongolia, Datong, Shuozhou and Xinzhou cities in Shanxi Province, and Fugun, Shenmu, Hengshan, Jingbian and Dingbian counties and Yulin City of Shaanxi Province, is in the warm-temperate zone. The climate humidity index in this region is 0.30–0.48. Due to severe soil erosion and steep cuts in the landform, the steppe has been denuded and cut into small pieces, and plant communities, residual woodlands and arable lands have been severely degraded as seen in large expanses of destroyed landscapes. This region is a large-scale coal mining base and improvement of the ecological environment is a burning issue at the moment.

(viii) The Mu Us Sandland includes Ordos City in Inner Mongolia and Yulin City in Shaanxi Province. This region is a warm-temperate type steppe sandland. The landscape includes sand-gravel hard ridges, sandy soft ridges and coastal landscapes. A high level of biodiversity forms an abundant resource combination, and the climate humidity index is 0.30–0.45. With the development of animal husbandry and rapid increase in livestock population, desertification occurred and currently, combating desertification is a priority task of the region.

(ix) The western parts of the Loess Plateau in Ningxia and Gansu are in the warm-temperate type desert steppe belt, and include Ordos City in Inner Mongolia, the entire Ningxia Hui Autonomous Region, and Baiyin City and Lanzhou City in Gansu Province. The climate humidity index is 0.20–0.30 and the landscape is mostly loess tablelands and loess hills with sparse desert steppe vegetation. Land productivity is low and wind and water erosion is severe. The measures and policies to restore the natural steppe vegetation by retiring cropland on slopes, revegetating degraded lands by growing grass and reforesting unproductive hilly areas should be encouraged.

7.3 Steppe degradation mechanisms

Reasons and mechanisms of steppe desertification are complex, and each other involved. The reasons for this are climate, geology, hydrology, biology, human, social, and so on. The mechanism are physical, chemical, economic (market), systems, chaos, customs, culture, and so on. It can be said, that the desertification is a non-conforming and inharmonious immingling of humanities and natural forces, which produces a deleterious effect on humanities and natural forces each other and resulted in a tragedy for both.

7.3.1 Causes of steppe degradation

Steppe degradation refers to the process of decline in steppe productivity and environment quality caused by inappropriate management and over-use of steppe under the effects of climate change. Steppe degradation is complicated by interactions of many different elements. Steppe degradation is seen in the degradation of the biological composition and vegetation of the steppe, soil deterioration, degradation of the hydrological circulation system and the worsening of the climatic environment. Overgrazing pressure and over-loading of the steppe have destroyed its regenerative ability and the community composition of the steppe vegetation resulting in a decline in steppe vegetation biomass and a change in the plant community to sparse and dwarf plantings. Some grasses with high value are reduced and poor quality grass species have increased. Along with vegetation degradation, some animal species (such as rodents, insects and earthworms) have disappeared. In general, steppe degradation is one of important effects of desertification which has led to the deterioration of the ecological health of the steppe ecosystem.

The causes of steppe degradation are summarized below and each should be further analyzed.

- Climate variation, drought and frequent winds
- Growth in both human and livestock populations
- Over-loading and inappropriate use of the steppe
- Rodent and insect disasters on the steppe
- Insufficient investment in steppe infrastructure, particularly the construction of water conservation projects

By analyzing the degradation process on the steppe in the Xilin Gol Prefecture, it can be seen that by the end of 1980s, the area of degraded typical steppe in the prefecture was 35% and there were a total of nine million head of livestock in the prefecture. By the 1990s, the total livestock population had increased to over 15 million head and the total area of degraded steppe had also increased to over 60%. The growth in livestock population coincided with the accelerated degradation of the steppe.

Steppe degradation is closely related to insufficient investment in steppe infrastructure, particularly for water conservation projects in steppe areas. Through detailed analysis of the relationship between steppe degradation and insufficient investment, it can be seen that there are two main aims behind the implementation of water conservation projects in steppe areas. The first aim is to meet the needs of human and livestock drinking water. Second, projects are aimed at increasing forage/fodder by developing fodder farms and artificial grassland by pumping water from river and digging wells in depressions. There has been too little effort and investment in increasing fodder/forage production even though the livestock population has increased rapidly and consequently, steppe degradation has accelerated. The increase in livestock population and the over-use of the steppe are the leading causes of steppe degradation. The low level of awareness and lack of attention to the ecological and environmental services of steppe are the underlying causes of steppe degradation.

The immediate concern of farmers involved in animal husbandry is to increase income by raising livestock population, and there are less concerned with maintaining the ecological environment of steppe. Consequently, the limited steppe or grassland areas were inappropriately used and mismanaged on a large scale. Outcomes of this unsustainable use of the steppe lead to a breakdown of steppe ecosystems because the pressure exceeds the capacity for regeneration. Steppe degradation is a continuing and worsening process. The condition of the steppe can be improved only by combining scientific analysis, sound planning and optimum design to determine a viable steppe management system and make the use of the steppe resource sustainable.

7.3.2 Imbalance in material and energy flows in the steppe ecosystem

Steppe vegetation is a fixed source of energy in the steppe system. Soil is the nutrient bank for material circulation. When the steppe ecosystem is in its original state, the unit material energy storage inside the ecosystem is assumed to be a constant, so that the instantaneous change value for each unit is:

$$dv/dt = dl/dt = dm/dt = ds/dt = 0 \tag{7.1}$$

Where v is the vegetation in the steppe; (represented by plant biomass); l is the amount of livestock; m is the microbial community; s is the soil nutrition bank; and t is time.

When the element of economic income is incorporated into a steppe ecosystem and the livestock population increases incrementally, $dl/dt > 0$, vegetation will also be changed and the velocity of energy flow will be increased, in other words $dv/dt < 0$, namely, plant biomass will be decreased. As the plant biomass is reduced, so is the photosynthesis area which reduces the energy flow from solar energy into the vegetation. Due to the increase in dwarf plants and the alterations to the dominant plant community, the energy flow is not able to support the increase of dl/dt, in other words, livestock are hungry. Under these circumstances without disturbance of the soil bank, the degraded steppe vegetation has a certain recovery potential (CR). When $dv/dt = dl/dt$, i.e., when livestock intake is equal to the regrowth of steppe vegetation, a new balanced relationship between forage and livestock is established. When this occurs, v in the system becomes v', l becomes l', and m and s are respectively become m' and s'. In other words, a new, balanced system, which is different to the original system, is established.

$$dv'/dt = dl'/dt = dm'/dt = ds'/dt = 0 \tag{7.2}$$

This kind of system occurs in degraded steppe ecosystems. When the steppe becomes degraded, and the new system is established, the materials and energy storage of the various biological units within the ecosystem are less than those of the original system and the flow rates of energy, water and nutrients have decreased. Therefore, the energy level of the ecosystem for self-maintenance and self-control will be reduced. It is therefore clear that differences in use patterns (such as harvesting of forage and grazing of steppe) determine the feedback regulation effect and this will result in different changes to steppe vegetation. The final regime of the ecosystem varies depending on the use patterns and there are also different degradation patterns. With similar land use models, the change dl/dt of domestic animal units is different, so the feedback flow intensity, dl/dt, is different and the energy level, when the system is in a stable state, will also be different. These balanced regimes at different energy levels are seen with different degradation intensities.

It can be concluded from the analysis above that the imbalance in the steppe ecosystem caused by over-use is a leading cause of steppe degradation. Under low energy conditions, the realization of balance in the ecosystem is limited by the conditions of utilization intensity and restoration capacity underpinned by well preserved soil. However, this new relative balance can also be broken.

The structure, texture and nutrient contents of soil resources can be seen as either the nutrient source for the supply of moisture and nutrients, or the environmental elements of a steppe ecosystem. For instance, when the saline and alkali ion storage is high and the groundwater depth is shallow, steppe ecosystems with a potential salinization risk will be frequently become salinized due to the reduction of vegetative coverage. Soil salinization increases unfavorable ecological elements and reduces the absorptivity of mineral nutrients by plants. On a sandy steppe, for example, any reduction of vegetative coverage will make the land surface more susceptible to wind erosion, which can damage soil structure, and result in the development of shifting sands and/or mobile dunes. In a worst case scenario, the steppe may become a lifeless physical system, as the ecosystem completely collapses.

7.3.3 Deterioration of primary productivity in degraded steppes

In normal years, the existing above ground biomass of undegraded typical steppe in Inner Mongolia can be as high as 300 $g{\cdot}m^{-2}$ while in poor years with harsh conditions, the biomass can be as low as 200 $g{\cdot}m^{-2}$. The average yield of typical steppe biomass is 250 $g{\cdot}m^{-2}$. After 8–10 years of restoration of degraded steppe communities, the productivity approaches 30% of the non-degraded community productivity.

Plants of poor palatability and low preference cover a large percentage of the degraded steppe community. In the summer season, the existing plants, which livestock dislike browsing on, such as *Artemisia frigida* and *Artemisia pubescens*, comprise 38% of the existing community. *Cleistogenes squarrosa*, which has a low forage value covers 12%, *Caragana microphylla* covers 4%, while *Leymus chinensis*, *Stipa grandis* and *Agropyron cristatum* which have good palatability cover only 15%. Among the dominant plant associations, at least 50% of the above ground biomass is composed of low palatability plants mainly *Artemisia frigida*. However, these same plant species cover only 4% of the area in non-degraded steppe communities. When the steppe is degraded and covered mainly by *Artemisia frigida*, the productive potential is approximately 16.7% of the non-degraded community. With continuous grazing of the degraded steppe, a relative stable degraded community can be maintained provided the land use intensity remains constant. Of course, a reduction of grazing or steppe utilization intensity can lead to the restoration of the plant community. Animals grazed at low stocking rates on degraded steppe can keep the intake and restoration processes in a dynamic balance so that the community can be maintained in a relatively stable state.

The decline in primary productivity is a basic feature of steppe degradation, and it is also a regulating mechanism to readjust the over-use of the steppe ecosystem through a feedback pattern. The decrease in productivity refers to both the decline in plant biomass and a worsening of plant forage quality. These two factors interact, and a lower availability of poor quality forage provides poor animal nutrition.

The original cause of decline in primary productivity is over-use but more particularly, the impact of selective grazing on the higher value plants. At present, the utilization pattern of steppe resources leads to the almost continuous harvest of high quality plants. During earlier times, the processes of synergistic evolution between steppe and livestock meant that there were sufficient forage sources with good palatability for livestock. However, overgrazing led to a decline of tall herbosa that were the main contributors to primary productivity of steppe communities. In non-degraded steppe communities, the above-ground utilization rate per unit area of tall herbosa plants is high and below ground, the resources of deeper soil layers will be exploited by tall herbosa plants with their extensive root systems. For instance, in the non-degraded communities of *Leymus chinensis* and *Stipa grandis*, the biomass of *Leymus chinensis*, *Stipa grandis* and *Achnatherum sibiricum* account for 75% of the biomass of community. Therefore, the decline of tall herbosa plants causes a significant change to the available resources of the community. The tall herbosa species are replaced by low plants which mainly consume water and nutrient resources from shallow soil layers and are unable to explore the deeper soil layers. This is one of the mechanisms leading to decline in primary productivity of steppe.

The changes to the micro-environment and soil regime that have occurred along with the degradation of the steppe are also relevant controlling factors for the decline in primary productivity. These changes are particularly obvious on the sandy steppe and salinized steppe. Changes to the micro-environment and soil regime threaten the disappearance of some species and cause a decline in overall productivity.

7.3.4 Rehabilitation of degraded steppe

The process of restoration and transformation of degraded steppe begins with a reduction in grazing pressure. Over-utilization must be eliminated if degraded steppe is to be restored. However, some restoration processes require a long time. For instance, the stabilization of shifting sandlands and the desalinization and de-alkalization of salinized steppe are slow interactive processes between biology and the environment. Furthermore, during the restoration process, fluctuations in various elements lead to changes to the restoration process and an uneven rate of progress. The primary condition to restore the degraded steppe is to remove pressure of over-loading or overgrazing of steppe to reach the threshold that leads to restoration of steppe. Once grazing pressure is relieved, the factors that will favor restoration of the degraded steppe are: (i) the fact that on a local scale the temperature, sunshine and atmosphere precipitation do not alter significantly; and (ii) where soil retains its basic structure, there is still a resource in the soil bank of the ecosystem. The soil bank contains seeds and other disseminules, nutrients and water as well as soil biota and micro flora. Even where the soil structure has been partially destroyed, biological processes will allow for the soil structure to be rebuilt over time.

7.4 Successional pattern and diagnosis of steppe degradation

There are different types of steppe vegetation and steppe ecosystems, due to different characteristics in the eco-environment, and the utilization and management patterns and utilization intensity are different. Therefore, the successional patterns, botanical composition and degradation intensities are also quite different. The types of degraded steppe and the degradation series can be differentiated based on eco-environment and land use patterns.

7.4.1 Series and types of meadow steppe degradation

The main community types of meadow steppe are *Stipa baicalensis* steppe and *Leymus chinensis* steppe + forbs steppe. The steppe degradation sequences include:

Stipa baicalensis → *Stipa baicalensis* + *Stipa krylovii* +*Artemisia frigida* → *Artemisia frigida* + *Cleistogenes squarrosa*,

Stipa baicalensis → *Stipa baicalensis* + *Carex duriuscula* → *Carex duriuscula*,

Leymus chinensis + forbs → *Leymus chinensis* + *Carex duriuscula* → *Carex duriuscula*.

The above three degradation sequences indicate different degradation processes but a tendency towards similarity in the degradation results. All processes occur due to overgrazing and over-use, although different steppe types have been manifested. *Artemisia frigida* is a chamaephyta, which is well adapted to steppe, highly tolerant to grazing, and is often a winner in the process of steppe degradation succession (Liu et al., 2002).

7.4.2 Series and types of typical steppe degradation

Typical steppes include *Stipa grandis* steppe, *Stipa krylovii* steppe, and *Leymus chinensis* steppe. With intensive grazing and utilization, different degradation successional sequences have appeared which are similar to the steppe types dominated by *Artemisia frigida*. They can be briefly described as follows:

Stipa grandis → *Stipa grandis* + *Stipa krylovii* + *Artemisia frigida* → *Artemisia frigida* + *Cleistogenes squarrosa*,

Stipa krylovii → *Stipa krylovii* + *Artemisia frigida* → *Artemisia frigida* + *Cleistogenes squarrosa*,

Leymus chinensis → *Leymus chinensis* + *Stipa krylovii* + *Artemisia frigida* → *Artemisia frigida* + *Cleistogenes squarrosa*.

Under long-term intensive grazing and over-use of steppe, the *Artemisia frigida* community is eventually succeeded by *Potentilla acaulis* or *Steellera chamaejasme* which are the dominant species in totally degraded steppe — a steppe type that is completely degraded and useless.

7.4.3 Series and types of desert steppe degradation

The main types of desert steppe include *Stipa tianschanica* var. *klemenzii* steppe and *Stipa breviflora* steppe. Under impacts of continuous intensive grazing, *Ajania achilloidea* and *Artemisia frigida* species groups are increased. The degradation successional orders are:

Stipa tianschanica var. *klemenzii* → *Stipa tianschanica* var. *klemenzii* + *Ajania achilloidea* → *Ajania achilloidea* + *Cleistogenes songorica*,

Stipa tianschanica var. *klemenzii* → *Stipa tianschanica* var. *klemenzii* + *Artemisia frigida* → *Artemisia frigida* + *Cleistogenes songorica*,

Stipa breviflora → *Stipa breviflora* + *Artemisia frigida* → *Artemisia frigida* + *Cleistogenes songorica*.

Under intensive grazing, the *Ajania achilloidea* and *Artemisia frigida* communities are eventually succeeded by *Convolvulus ammanni* communities.

7.4.4 Distribution of degraded steppe

The area occupied by degraded desert steppe (located in the western part of the Xilin Gol Prefecture, the northern part of the Wulanqab Prefecture, the northern part of the Bayan Nor Prefecture and the central part of Ordos City) is the highest percentage of degraded land. The typical steppe belt provides the second highest percentage of degraded area, and the forest-grassland belt has the least degraded land. This indicates that the harsh natural conditions in the desert steppe make this more vulnerable to degradation. The Table 7.10 shows the areas and distribution of steppe degradation between the three different degradation grades. The area of degraded desert steppe is more than 82% of the total area of desert steppe.

According to satellite images, remote sensing survey results and ground survey data of steppe and grassland resources conducted during 1994–1996, steppe degradation is widespread in all steppe regions of Northern China. Table 7.11 shows the areas of steppe degradation in the provinces, prefectures and cities of Northern China calculated based on the administrative divisions present in 1995.

It can be seen from Table 7.11 that the area of steppe degradation covers more than 50% of the total steppe area. The area of degraded steppe in Hohhot City, Baotou City, and Chifeng City, where crop farming is well developed, and in Ordos City, where natural erosion (soil and water losses and wind erosion and sand encroachment) is worst, is more than 50%. In Xilin Gol Prefecture, where animal husbandry and steppe management are well developed, the area of steppe degradation covers 32.85% of the total steppe area.

7.4.5 Diagnosis of steppe degradation

With appropriate grazing, the plant compositions of the various steppes remain stable but the annual biomass is highly variable due to variations in annual precipitation and the seasonal distribution of precipitation. The process of steppe degradation caused by overgrazing results in an obvious decline of total forage biomass, but also changes of the plant community structure and botanical composition. Some plant species disappear and other plant species gradually increase. According to the changes in quantity and type of plant species, the degradation processes on the steppe can be diagnosed.

7.4.5.1 Classification of steppe degradation intensity grade

Monitoring of steppe degradation was conducted continuously from 1983 in the middle reaches of the Xilin River in the central part of the typical steppe of Inner Mongolia. Based on the survey and the determination of steppe degradation in the northern China, the grading criteria of steppe degradation intensity were outlined as shown in Table 7.12.

7.4.5.2 Diagnosis of decline and succession of dominant plant populations

Using *Leymus chinensis* steppe, *Stipa grandis* steppe and *Stipa tianschanica* var. *klemenzii* steppe as examples, when the steppe is subjected to overgrazing pressure, these three species and other dominant plant species will gradually decline. At the Grade I degradation intensity stage the rate of steppe degradation is less than 30%; at the Grade II stage the steppe degradation

Table 7.10 Areas of degraded steppes in three steppe belts (1996) (10^4ha)

Steppe belts	Total area of steppe	Area of degraded steppe	% of degraded steppe in total steppe areas	Grade I degradation		Grade II degradation		Grade III degradation	
				Area	% of degraded steppe	Area	% of degraded steppe	Area	% of degraded steppe
Forest grassland	1,066.4	329.3	30.88	106.8	32.4	130.6	39.7	91.9	27.9
Typical steppe	3,228.3	1,847.3	57.22	262.5	14.2	780.0	42.2	804.8	43.6
Desert steppe	2,317.9	1,925.6	83.08	495.2	25.7	849.8	44.1	580.6	30.2
Total	6,612.6	4,102.2	62.04	864.5	21.1	1,760.4	42.9	1,477.3	36.0

Table 7.11 Areas of degraded steppe in provinces, prefectures and cities of Northern China (10^4 ha)

Provinces(Autonomous Regions)/Cities(Prefectures)	Available steppe	Total area of degraded steppe	% of available steppe	Grade I degraded steppe	% of degraded steppe	Grade II degraded steppe	% of degraded steppe	Grade III degraded steppe	% of degraded steppe
Heilongjiang	7,442,510	358,7450	48.20						
Jilin	2,837,430	1,528,225	53.86						
Hebei	1,525,200	814,440	53.40						
Shanxi	1,464,250	782,050	53.41						
Shaanxi	1,582,630	744,770	47.06						
Ningxia	1,248,500	683,255	54.73						
Gansu	2,012,480	1,016,820	50.53						
Inner Mongolia	45,632,587	22,258,764	48.37	10,046,966	47.28	8,305,404	35.32	3,906,394	17.40
Hohhot City	149,315	91,239	61.10	26,768	30.00	29,911	32.78	33,960	37.22
Baotou City	424,392	252,553	59.31	136,213	52.93	38,711	15.33	77,630	30.74
Chifeng City	4,565,010	2,885,325	63.17	964,307	33.43	1,086,607	37.65	834,410	28.92
Hulun Buir City	7,233,775	2,330,402	41.52	813,193	56.58	491,862	34.26	125,342	9.16
Xing'an Prefecture	2,612,174	968,748	34.08	305,628	40.28	194,712	25.66	258,409	34.06
Tongliao City	3,715,396	2,414,293	65.01	807,558	33.45	673,052	27.88	933,582	38.67
Xilin Gol Prefecture	17,660,962	91,882,945	32.85	3,472,446	47.66	2,994,256	41.01	819,072	11.24
Ulanqab Prefecture	5,084,420	261,775	51.43	1,515,678	57.96	625,926	23.94	473,481	18.44
Ordos City	2,175,689	1,415,106	64.35	514,937	37.26	608,069	42.45	292,100	20.29
Bayan Nir Prefecture	2,010,282	800,414	40.37	613,812	3.94	160,258	22.51	28,010	3.55

rate is less than 50%; and at the Grade III steppe degradation level the rate of steppe degradation is about 70%. Table 7.13 shows the results from survey estimations of sampling sites on different steppes.

Table 7.12 Classification of steppe degradation grade

Degradation indicators	Degradation intensity			
	I	II	III	IV
% of decrease of biomass productivity of plant community	20–35	36–60	61–90	>90
% of decline of dominant plant population	15–30	31–50	51–75	>75
% of productivity reduction of palatable grass population	30–45	46–70	71–90	>90
% of increase of productivity of unpalatable plants	10–25	26–40	41–60	>60
% of increase of plants indicative of degradation succession	10–20	21–45	46–65	>65
% of the decline in plant height (dwarf)	20–30	31–50	51–70	>70
% of the decline of vegetative coverage	20–30	31–45	46–60	>60
Degree of erosion of light texture soils	10–20	21–30	31–40	>40
% of increase in bulk density and compaction of medium and heavy texture soils	5–10	11–15	16–20	>20
Duration of reversibility and rehabilitation (year)	2–5	5–10	10–15	>15

I: Grade I degradation; II: Grade II degradation; III: Grade III degradation; IV: Grade IV degradation

Table 7.13 Decline and growth rates of dominant species during the processes of plant community degradation of different steppes

Steppe community	Dominant plants	I	II	III	IV
Leymus chinensis steppe	*Leymus chinensis*	–28.3	–48.2	–68.6	–94.5
	Stipa grandis	–32.2	–55.0	–77.6	–96.0
	Cleistogenes songorica	+ 5.5	+6.3	+1.8	+2.6
	Artemisia frigida	+21.5	+37.2	+66.4	+68.7
Stipa grandis steppe	*Stipa grandis*	–30.55	–52.6	–75.8	–95.4
	Cleistogenes songorica	+ 8.8	+10.5	+6.2	–5.4
	Artemisia frigida	+22.8	+33.3	+61.4	+67.1
Stipa tianschanica var. *klemenzii* steppe	*Stipa tianschanica* var. *klemenzii*	–31.0	–49.6	–49.6	–81.7
	Cleistogenes songorica	+10.6	+8.2	+8.2	–20.4
	Ajania pallasiana	+24.0	+41.4	+41.4	+68.2

Numbers refer to proportion of biomass loss relative to non-degraded plant community. I: Grade I degradation (population %); II: Grade II degradation (population %); III: Grade III degradation (population %); IV: Grade IV degradation (population %).

7.4.5.3 Diagnosis of the growth rate of plants indicative of degraded steppe

In the process of typical steppe degradation, *Artemisia frigida*, *Potentilla acaulis* and *Steellera chamaejasme* often increase as the steppe becomes more degraded, due to their specific adaptation of grazing-tolerance. Therefore, they are plant species that are indicative of the degradation process. In the process of desert steppe degradation, the plant species indicative of degradation include *Ajania achilloidea*, *Hippolytia trifida*, *Artemisia frigida*, *Cleistogenes soongorica*, *Allium polyrrhizum*, *Convolvulus ammanni*, and *Peganum harmala*. In the degraded plant communities of meadow steppe, *Carex duriuscula* is a very good grazing-tolerant indicator plant. The intensity of steppe degradation can be determined according to proportion of these plants. Table 7.14 shows the proportion of indicative plants at different levels of degradation series of the steppe (Wang et al., 1996a,b,c; Wang et al., 2000a,b).

7.4.5.4 Diagnosis of grazing forage composition of grass community

Livestock grazing causes variable degradation to different plant species according to the palatability and quality of steppe plants. Due to intensive and selective grazing, the ratio of good quality grasses in plant communities will gradually decrease and the ratio of poor quality grasses increases along with other non-edible and poisonous plants. Depending on the quality of forage grasses, steppe plant communities with different degradation intensities can be classified as good, fair, poor and non-edible, and this classification is an effective measure for diagnosing and assessing steppe degradation. Using *Leymus chinensis* steppe as an example of a degradation series, an assessment of plant forage edibility can be seen in Table 7.15.

7.4.6 Moisture and nutrient regime of degraded steppe

Based on dynamic monitoring of *Leymus chinensis* steppe degradation types with an *Artemisia frigida* community, the status of plant resources of degraded steppe can be defined.

The moisture regime of the steppe is reflected in the composition of plant moisture ecotypes. Normally, under relatively humid conditions, mesophilous plants form a high percentage of plant species. In drier habitats, the proportion of xerophytes is higher. The plant communities discussed in this chapter come from four moisture ecotypes, namely, xerophytes, meso-xerophytes, xero-mesophytes and mesophytes. The process of restoration succession can be measured from the proportion of plants representative of different moisture ecotypes. Xerophytic and meso-xerophytic plants are the dominant plant species in degraded steppes. Perennial mesophytes make up a low proportion of the total plant species during the process of restoring the normal succession. However, a high proportion of mesophilous annual and biennial plants is present during the initial stage of restoration but after six years, they comprise a very low proportion of the plant species. This shows that, due to the low biological productivity of degraded communities, perennial plants were unable to fully use the available water thus allowing annuals and biennials to flourish in the absence of grazing and make full use of remaining water,

Table 7.14 Survival rates of indicative plants in degradation series of steppe

Indicative plants	Typical steppe				Desert steppe				Meadow steppe			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
Artemisia frigida	+	++	+++	++	+	++	++	+	+	+	++	+
Potentilla acaulis	+	++	++	+++					+	++	+	
Cleistogenes squarrosa	+	++	++	+								
Heteropapus altaicus	+	+	+						+	+	+	
Thymus vulgaris	+	++	+++	++								
Steellera chamaejasme	+	++	++	++								
Ajania achilloidea					+	++	+++	+++				
Hippolytia trifida					+	++	+++	+++				
Cleistogenes songorica					+	++	++	+				
Allium polyrrhizum					+	++	+++	++				
Convolvulus ammanni			+	+	+	++	+++	+++				
Peganum harmala					+	+	++	+++				
Carex duriuscula									+	++	+++	++

Note: +++ for dominant species, ++ for sub-dominant species, and + for normal species; I: Grade I degradation; II: Grade II degradation; III: Grade III degradation; IV: Grade IV degradation.

Table 7.15 Diagnosis of forage plants community of degraded *Leymus chinensis* steppe (biomass unit: $g \cdot m^{-3}$)

Grass community patterns		I		II		III		IV	
		Biomass	%	Biomass	%	Biomass	%	Biomass	%
Good quality forage plants	Rhizoma herbosa	71.2	26.6	58.8	26.1	20.2	14.2	7.6	11.5
	Tall herbosa community	55.5	20.7	45.5	20.2	21.6	15.1	8.2	12.4
	Allium spp.	14.4	5.3	7.7	3.4	3.6	2.5	1.8	2.7
	Legume plants	12.2	4.6	8.2	3.7	3.1	2.2	1.2	1.8
	Total	153.3	57.2	120.2	53.4	48.5	34.0	18.8	28.4
Medium quality forage plants	Small herbs	15.0	5.6	12.6	5.6	11.5	8.1	8.5	12.8
	Carex spp.	10.6	4.0	7.5	3.3	4.2	3.0	0.5	0.8
	Small bushes	12.5	4.8	11.5	5.0	10.8	7.6	4.1	6.2
	Total	38.1	14.4	31.6	14.1	26.5	18.0	13.1	19.9
Inferior weeds	*Artemisia* plants	30.6	11.9	34.4	15.3	32.5	22.7	28.2	42.7
	Weeds	36.5	13.6	31.4	14.0	28.5	20.0	2.2	3.3
	Non-edible plants	9.0	3.3	7.8	3.5	6.6	4.7	3.8	5.7
	Total biomass	267.5	100.0	225.4	100.0	142.6	100.0	66.1	100.0

I: Grade I degradation; II: Grade II degradation; III: Grade III degradation; IV: Grade IV degradation.

occupying survival space in the degraded community.

Measurement of soil nutrients (Table 7.16) from sampling sites on the degraded steppe (He and Kang, 1994) shows that the concentrations of soil nutrients in the degraded community are not obviously reduced. The biomass productivity of the degraded steppe community is only one third of the biomass productivity of the community after fifteen years of restoration succession, and soil nutrients in the degraded community are not fully utilized (Hao et al., 2004; Wang et al., 2008). When the steppe is degraded and covered by *Artemisia frigida* communities, the soil fertility does not decline immediately. This indicates that soil deterioration is slower than vegetation degradation and that is why there are some nutrients still remaining in the degraded steppe. Moisture, nitrogen and phosphorus are the limiting elements that control the productivity of the steppe community. The remaining nutrients and moisture provide the basis for the restoration succession of the degraded community.

Table 7.16 Concentrations of soil nutrients in degraded (*Artemisia frigida*) steppe and revegetated steppe (He and Kang, 1994)

Sampling sites	Organic matter (%)	Total Nitrogen (%)	Total Phosphorus (%)	NO_3–N ($mg \cdot 100g^{-1}$)	NH_4^+–N ($mg \cdot 100g^{-1}$)	Available P ($mg \cdot 100g^{-1}$)
During restoration (1993)	1.7478	0.1491	0.1155	0.4399	0.1569	0.1863
Degraded without restoration	1.5163	0.1224	0.1076	0.4469	0.2056	0.1820
Restored after ploughing treatment	1.2604	0.1248	0.0964	0.3231	0.1135	0.1861
Site reseeding with *Leymus chinensis*	1.1406	0.1319	0.1208	0.5250	0.1297	0.1861
Restored after scarification treatment	1.8371	0.1594	0.1121	0.4018	0.2163	0.1741

7.5 Restoration and rehabilitation of degraded steppe

When the steppe degradation is too serious to self-recover with resilience, some artificial measures to assist the recovery succession must be applied. The ecological restoration of degraded steppe must follow the rules and principles of ecology and economy, so as not to create new degradation and destruction on steppe.

7.5.1 Restoration and succession of degraded steppe

The structure and appearance of the steppe plant communities are characterized by the dominant species and the botanical composition. Therefore, an alteration to the dominant species can be a signal as to the succession stage of the community. The above ground biomass is the indicator for judging and determining the dominant species. This is because there is functional relationship between the quantitative criteria of height, density, coverage, frequency of plant community and the biomass of the plants. The change in dominant species during the restoration succession is reflected in the biomass production of each species in the plant community. By analyzing the restoration succession of a degraded community of typical steppe, different successional stages can be classified according to the changes in the dominant species (Hao et al., 1997; Liu et al., 1998).

7.5.1.1 Dominant plant is *Artemisia frigida*

The plant community on a typical degraded steppe is dominated by *Artemisia frigida*, *Artemisia pubescens*, and *Cleistogenes squarrosa*. These species are representative of the final successional pattern in degraded typical steppe and can therefore be considered as a starting point for the study restoration succession. The dominant effect of *Artemisia frigida* is significant in this type of degraded community, and during the growing season the community is grey green in color, while the *Caragana microphylla* community is a dark green color that forms a mosaic of small bush layers.

Plants in such communities are dwarf sized and when the above ground biomass production is as high as possible, the mean heights of *Artemisia frigida*, *Artemisia pubescens*, and *Cleistogenes squarrosa* are respectively 13.0 cm, 16.7 cm and 12.3 cm, and the mean height of *Caragana microphylla* is 18.5 cm. The average dried weight of each individual *Artemisia frigida* plant is 0.25 g per bush. In comparison with the height of the original grass, this plant is very small and short. Thus, the exposed surfaces (bare ground) in the degraded communities are bigger. Due to the limitation of nutrients, the generation and growth of various communities are slow and therefore their seasonal changes are non-significant. Thus, this degraded community is a community that is maintaining itself on a lower energy level.

7.5.1.2 Growth stage of *Artemisia frigida* + *Agropyron cristatum*

During the initial phase (year 1–3) of the restoration succession, *Artemisia frigida* is the dominant species but *Cleistogenes squarrosa* is replaced by *Agropyron cristatum* which gradually exceeds the coverage of *Artemisia pubescens* becoming the second dominant species. During this stage, exploitation of various residual resources enables rapid generation and above ground biomass increases quickly during the growing season. The height of plant community increases and the biomass of each individual plant also gradually increases. This means that the remaining resources are transformed into a productive of plant community. Interactions between different species also take place, with the exception of *Cleistogenes squarrosa* which, at a lower layer of the community, continues to decline. *Artemisia frigida* and *Artemisia pubescens*, due to their capture of a large share of the nutrients, become the dominant plants. At the initial stage of restoration, *Artemisia frigida*, *Artemisia pubescens* and other dominant species did not fully use the resources (moisture and nutrients) available to the plant community; therefore, pioneer annual and biennial plants with a strong regeneration potential flourished.

7.5.1.3 Dominant plant — *Agropyron cristatum*

Agropyron cristatum is further developed from the previous stage and is one of the main contributors to the biomass of the plant community. *Leymus chinensis* is slowly increasing while *Artemisia frigida* and *Artemisia pubescens* decline, and the annual and biennial weeds also increase. The succession of community species is one of gradual replacement. The replacement of dominant species shows that a redistribution of community resources has taken place and it also indicates that the restoration succession is developing processes where inter-specific competition for remaining resources is a key factor in the redistribution of resources. During the early stages, the productivity level of the community is not obviously increased and the remaining resources are inefficiently used. Because both *Agropyron cristatum* and *Artemisia frigida* are densely crowded, some plant species are overshadowed and struggle for light. The appearance of the different patches of plant populations results in an unevenness in the plant community. The dominant plants have a dull color during the growing season, but *Allium bidentatum* and other *Allium* spp. flower in July.

7.5.1.4 Dominant plant — *Leymus chinensis*

Five years after the closure of the degraded steppe, *Leymus chinensis* becomes a co-dominant plant species with *Agropyron cristatum*, while *Artemisia frigida*, *Artemisia pubescens* and *Cleistogenes squarrosa* form a low proportion of the plant community. Along with the increase in *Leymus chinensis*, the plant community productivity rises to a high level and the maximum annual biomass of individual plants are approximately 200 $g \cdot m^{-2}$. Thus, the plant community is now able to fully utilize any residual resources from the previous stages of the succession. However, the redistribution of resources is not yet complete and the patches of different populations within the community structure become more pronounced. These patches of different populations enable different species occupy their own spaces among the community, forming a confrontational or competitive situation in the interspecies relationships. Because *Leymus chinensis* occupies the dominant position in the plant community, the height and density of plants increases and the accumulation of withered and dead vegetation (plant litter) also increases.

7.5.1.5 Dominant plant — *Stipa grandis*

During the succession stage from degraded steppe to typical steppe, *Stipa grandis* slowly increases to become the dominant plant species and it competes and grows and declines with *Leymus chinensis* in a spot-like pattern. As a perennial species, the population of *Agropyron cristatum* is stabilized, and other plant species in the community are redistributed. For example, *Achnatherum sibiricum*, *Serratula centauroides*, *Adenophora* spp., *Allium* spp. and other species increase. Thus, the process forming the spatial structure of the plant community is initiated by the gradual changes in the spatial distribution of various species and the patchy occupation of sites by other species.

7.5.2 Changes in primary productivity of plant communities during restoration

By measuring the time taken to achieve maximum above ground biomass of the plant community in the growing seasons during the restoration succession we can track changes in the productivity level of the main plant species during the restoration succession.

7.5.2.1 Step changes and metastable levels of plant community productivity during the restoration succession

The maximum above ground biomass of the degraded community increases, on average, to 250 $g \cdot m^{-2}$ and during the increase there are two step changes between three levels. The initial productivity level is the biomass of the degraded community which reflects productivity level of the degraded community under grazing pressure. The first step change occurs as the biomass of the community increases from 70 $g \cdot m^{-2}$ to 160 $g \cdot m^{-2}$ and then gradually increases to the second productivity level. The recovering degraded community remains at this productivity level for several years and its biomass is about 160–170 $g \cdot m^{-2}$. After 4–5 years, the second step change occurs as the community reached the third level of productivity with a mean biomass value of 240 $g \cdot m^{-2}$ which is similar to the productivity level of an undegraded community (Ren et al., 2001; Shi et al., 2001).

Following the two step changes, the annual change in productivity of the community is relatively small. Along with the replacement of the main species during the restoration succession, a metastable community is formed at two productivity levels.

7.5.2.2 Causes of step changes in primary productivity and the appearance of metastable states during the restoration succession

Based on the analysis above, it can be seen that the increases in primary productivity of the community during the restoration succession occur in the form of alternating step changes and metastable states.

7.5.3 Relationship between primary productivity of the community and water resources during the restoration succession

Water (moisture) is a factor limiting the primary productivity of the steppe community. For the plant community of the zonal typical steppe, atmosphere precipitation is the only method for harvesting the water resource. Based on the precipitation and the maximum existing above ground biomass from May 1st through the growing season every year (Table 7.17), the following paragraphs discuss the significance of precipitation on restoration succession, metastable states and the step changes in primary productivity of the degraded community.

It is useful to study the dynamic process of restoration and succession over time. The ratio of precipitation during the growing season to the existing above ground biomass is a useful criterion for measuring the utilization efficiency of water resource of the plant community.

It can be seen from Table 7.17 that the availability of water resources in the steppe community is not a direct factor governing the change in dominant species during the restoration succession.

7.5.3.1 Analysis of dominant species of *Artemisia frigida* community at degradation stage

It can be seen from Table 7.17 that the water volume consumed for biomass production by the degraded community is 2.55 $mm{\cdot}g^{-1}$ but this is reduced to only 1.09 $mm{\cdot}g^{-1}$ in second year of succession. This shows that available water resources in degraded community are sufficient. If the minimum value of water volume required per unit of dried material is 1.09 $mm{\cdot}g^{-1}$, the most effective ratio of water use in the community is as high as 1.10 $mm{\cdot}g^{-1}$. Using this ratio, the production of 74.13 $g{\cdot}m^{-2}$ of dried material by the degraded community requires only 81.5 mm of precipitation. Under pressure from overgrazing, plant growth and regeneration in the degraded community will be limited and even an increase in precipitation cannot significantly increase biomass production by the community. Accordingly, the productivity of the community at the degraded stage is primarily controlled by grazing pressure and it is not significantly related to precipitation.

Table 7.17 Dynamics of plant community biomass and precipitation during restoration succession

Testing date (month/day/yr)	Direct effective rainfall (mm)	Survival biomass of community ($g \cdot m^{-2}$)	Ratio* ($mm \cdot g^{-1}$)
08/03/1983	188.7	74.13	2.55
07/25/1984	175.5	161.60	1.09
08/15/1985	237.3	164.20	1.45
08/29/1986	275.0	171.92	1.60
08/30/1987	221.7	164.92	1.34
08/29/1988	247.6	166.01	1.49
08/30/1989	158.6	131.54	1.20
09/01/1990	401.2	250.90	1.60
09/01/1991	256.0	182.99	1.40
08/04/1992	303.8	246.39	1.23
08/14/1993	243.8	217.01	1.12

*Ratio = Effective precipitation/plant community biomass

7.5.3.2 Analysis of first meta-stable state

During the first meta-stable state, the maximum difference in precipitation during the growing season is 99.5 mm and the maximum difference in community biomass is 10.32 $g \cdot m^{-2}$. (Table 7.17). For instance, the precipitation during the growing seasons of 1988 and 1993 were almost similar, but the difference in biomass produced by the community was as high as 51 $g \cdot m^{-2}$. The average biomass was 166 $g \cdot m^{-2}$ (± 3.82) during the first meta-stable state when precipitation in the growing season was over 175 mm. When the precipitation increased, the change in the biomass of the community was remarkable.

The biomass of community at this stage of the succession is mainly determined by productive potential and resource utilization by the dominant species of community. Even when the precipitation is higher, the dominant plant species during the early stages of the succession (*Artemisia frigida*, *Agropyron cristatum* and *Artemisia pubescens*) will not be able to fully utilize the moisture. This is because these dominant plants are dwarfs with good drought-tolerance and they have a relatively low efficiency of biological accumulation and low water consumption. Therefore, the oversupply of water resources occurs during this stage and this is one of the factors leading to further succession. In general, the correlation between the biomass of community and higher precipitation at this stage in the succession is also unremarkable. The minimum water usage for the production of dry matter can be estimated at 1.10 $mm \cdot g^{-1}$ and thus the mean biomass of the community at 166 $g \cdot m^{-2}$ during this stage needs only 183 mm of precipitation. At this stage, precipitation during the growing season in most years exceeds the requirement.

7.5.3.3 Analysis of second meta-stable state

There is a significant interrelationship between the community biomass and precipitation during this stage. When there is an increase in precipitation during the growing season, the biomass of plant community will also be significantly increased. When the precipitation is very high during the growing season (if the rainfall is higher than 300 mm), the biomass of community will slowly increase. For instance, in 1989, precipitation was 158.6 mm and the water usage volume for the production of dry matter was 1.20 mm·g^{-1} (Table 7.17), which was a little more than the estimated 1.10 mm·g^{-1}. In 1993, precipitation was 243.8 mm and the use efficiency of the water resource was the highest. In 1990, the precipitation during the growing season was 401.2 mm and biomass was very high at 250.9 g·m^{-2}. If the precipitation during growing season is particularly high (more than 400 mm), the rate of increase of biomass would slow down or cease. Accordingly, the relationship between precipitation during the growing season and community biomass during this metastable state can be interpreted as a logarithmic curve with the mean precipitation at approximately 400 mm and the community biomass around 250g·m^{-2}. After 1990, the volume of water used for the production of dry matter by the community gradually decreased and this shows that the water resource use efficiency of the community with increased each year becoming more suited to the habitat conditions of the community.

To summarize, the step change in community productivity and the occurrence of meta-stable states are part of the process of restoration succession and are not directly related to precipitation.

7.5.4 Changes in community density during restoration succession

The resource ratio hypothesis of succession emphasizes only one area occupied by mature individuals and does not take into account the spatial variations and different life stages (Tilman, 1985; 1994). The method of calculating plant individuals is different to calculating plant species (calculations should be conducted on the basis of individual plants, communities and branches of different species); therefore, community densities are not comparable during the restoration succession process. To obtain comparable data, the community densities should be standardized, by converting the existing biomass of various communities above ground into a unit of density related to a single individual plant of *Leymus chinensis*, identified as the "*Leymus chinensis* Unit". Thus, the standardized community density (SCD) is calculated by:

$$SCD = \sum_{i=1}^{n} \frac{d_1}{W_1} W_i \quad (i = 1, 2, \cdots, n) \tag{7.3}$$

Where d_1 refers to the density of *Leymus chinensis*, W_1 refers to the dried above ground biomass weight of *Leymus chinensis*, W_i refers to dried biomass weight of species i, and n refers to the number of different species. Because d_1 and W_1 are data collected from similar sampling times the standardized community density is different from a comparison of the community biomass. Annuals and biennials are pioneer plants and as they are only temporarily dominant they are not calculated.

7.5.5 Improvement in herbosa composition after the enclosure of degraded steppe

The enclosure of degraded steppe eased the impacts of livestock trampling and selective grazing and allowed the severely degraded steppe community to be restored and improved. Through the survival, competition and interaction within and between species, the community composition gradually changed. For example, *Artemisia frigida* + small herbosa plant communities gradually evolved into *Leymus chinensis* + *Stipa grandis* communities which are adapted to the local climatic conditions. The structure and function of the community changed. Community succession patterns can be classified into three categories, namely:

- the growing community;
- the declining community; and
- the perennial associated community.

The growing community refers to plant species which are sparse and poorly represented in the degraded community but whose density and function increase each year during the restoration succession. These plants include *Leymus chinensis*, *Stipa grandis*, *Agropyron cristatum*, *Achnatherum sibiricum*, *Allium* spp. and others. In particular, *Leymus chinensis* increased significantly during the eighth year following the steppe enclosure and became the dominant plant species in the community with a high importance value. The density and function of other species such as *Stipa grandis*, *Agropyron cristatum* and *Koeleria cristata* gradually increased during the restoration succession. This is because these plants species have a high competitive potential under natural conditions, although their community functions fluctuate due to annual changes in atmosphere precipitation and stored soil moisture.

The declining community includes plants that decreased in number and function as the succession developed. They include *Artemisia frigida*, *Artemisia pubescens*, *Cleistogenes squarrosa*, *Allium tenuissimum*, *Potentilla acaulis* and *Heteropapus altaicus*. These declining plant species lost their dominance and became the associated plant species in the community.

The role and function of the perennial species of xeric dwarf semi-bushes, such as *Artemisia frigida*, *Artemisia pubescens*, *Cleistogenes squarrosa*, fluctuate during the restoration succession but many remain as associated species. Other associated species include *Carex korshinski*, *Allium bidentatum*, *Allium ramosum*, *Potentilla bifurca*, *Melandrium apricum*, *Saposhnikovia divaricata*, *Thalictrum petaloideum*, *Potentilla verticillaris* and *Cymbarria davurica.*

According to the living forms and eco-biological features of the various plant species, they can be divided into nine categories, including: bush plants, semi-bush plants, tall herb plants, dwarf herb plants, rhizoma herb plants, rhizoma *Carex* spp., bulb weeds, axial root herbosa, and annual and biennial plants (Table 7.18).

Table 7.18 Changes of important values (%) of plant layers during the restoration succession of degraded steppe

Plant layers	1983	1984	1985	1986	1987
Bush plants	8.2389	8.5652	5.6438	6.0096	6.6583
Semi-bush plants	4.4388	13.3171	15.3832	14.533	13.2631
Tall herbs	6.8338	10.0137	10.0226	11.6864	9.1432
Dwarf herbs	10.9618	7.9078	7.4366	7.7779	9.0655
Axial root herbosa layers	27.5846	20.6495	23.4866	20.3821	30.7006
Rhizoma herbs	14.5933	18.4435	18.6421	17.7213	17.8191
Rhizoma *Carex* spp.	0.6746	1.4265	0.8257	1.1481	1.0715
Bulb weeds	12.5054	11.8629	11.2094	12.0152	9.4052
Annual and biennial plants	7.1971	7.9138	7.35	8.7364	5.8736

Plant layers	1988	1989	1990	1991
Bush plants	6.8864	6.2914	6.8536	6.8707
Semi-bush plants	11.1231	9.577	9.1694	6.2874
Tall herbs	8.9905	14.6043	16.4742	16.959
Dwarf herbs	10.3198	9.7679	11.9528	11.734
Axial root herbosa layers	16.0262	23.0311	17.8812	17.777
Rhizoma herbs	21.3900	20.6193	23.6143	24.067
Rhizoma *Carex* spp.	0.8795	1.2157	0.8476	0.8715
Bulb weeds	12.6915	12.6915	12.3070	14.0276
Annual and biennial plants	4.3488	5.3018	4.8999	5.4047

The bush plants are mainly composed of *Caragana microphylla* which has a height of 20–30 cm. It is a dominant layer of the community and plays an important role in stabilizing degrading communities, because it is a grazing-tolerant plant.

The semi-bush plants are composed of *Artemisia frigida* and *Kochia scoparia* which have heights of 13–18 cm. At the initial stage of steppe enclosure, they hold an important position in community. Later, their function is significantly reduced and they can be regarded as slowly declining species.

The tall herb plants are composed of *Stipa grandis* and *Achnatherum sibiricum* which have heights of 30–50 cm. Their growth is slow prior to the closure of the steppe and but as restoration progresses they became the dominant layer in the community.

The dwarf herb plants are composed of *Cleistogenes squarrosa*, and *Koeleria cristata* and their heights vary from 10 to 15 cm. At the initial stage of closure of the steppe, these plants are dominant in the degraded community. At the later stage of community succession, the function of *Cleistogenes squar-*

rosa was reduced and the function of *Koeleria cristata* was increased. They are associated components of the plant association.

The rhizoma herb layer is composed of *Leymus chinensis*. After enclosure of the steppe, this layer gradually replaced the function of semi-bush plants of *Artemisia frigida* and became the dominant layer of the community.

The rhizoma *Carex* spp. layer is composed of *Carex korshinski* which is one of the perennial associated plants in the community.

The bulb plant layer is composed of several *Allium* spp. plants and their heights vary from 15 to 30 cm. This layer is also one of the perennial associated plant layers in the steppe community.

The axial root herbosa layers have important functions in community structure and function. They are mainly composed of *Ajania* spp., and species from the Leguminosae, Rosaceae, Umbellifereae, and Ranunculaceae families. These plants increased gradually after the enclosure of the steppe and are characterized by their colorful flowers, thus making an important contribution to seasonal changes of the natural scenery in the community.

The annual and biennial plants are mainly composed of *Artemisia scoparia*, *Salsola collina*, *Dontostemon micranthus* and several other hellebore plants. There is a trend of a gradual decrease in the function of these plants during the community restoration succession, related to competition for survival space, moisture and nutrients among annual/biennial plants and perennial plants.

After enclosure of the steppe, the changes of community structure described above enable the degraded steppes to improve from poor steppes or grazing lands with low utilization values to useful rangelands (Chen and Wang, 1998).

7.5.6 Amelioration of loose soil on the degraded steppe

When the soil of degraded steppe is raked and loosened (scarified), the change in community composition and structure was accelerated (Table 7.19). The height of *Leymus chinensis* doubled to 40–50 cm, plant density increased from 44 plants·m^{-2} to 185 plants ·m^{-2} and the above ground biomass increased by 49%. Additionally, the proportion of above ground biomass from herbosa plants increased from 43.5% to 57.2%. The proportion of above ground biomass from leguminous plants increased from 6.2% to 12.3% and the proportion of above ground biomass of *Ajania* spp. decreased from 41.14% to 16.6% (Chen et al., 2008).

After soil amelioration of the degraded steppe, 98% of the below ground biomass of the steppe community is concentrated in the top 40 cm of soil. The ratio of above ground to below ground biomass in the steppe community is normally 0.6, but this increased to 1.15 after soil amelioration, as the above ground biomass was greatly increased. It is thus clear that soil scarification in semi-arid climate conditions in the steppe zone is an effective solution to increase the community biomass.

Table 7.19 Comparison of quantitative nature of main plant community after eight years of soil raking and loosening

Plant species	Comparison(CK)			Loosen soil and light rake		
	H	DP	DW	H	DP	DW
Leymus chinensis	31	49.0	42.23	50	185.0	60.47
Agropyron cristatum	33	10.0	33.55	39	21.0	48.37
Cleistogenes squarrosa	8	2.0	4.08	11	8.0	1.54
Koeleria cristata	17	8.0	10.80	12	6.0	2.27
Stipa grandis	30	6.0	11.80	68	6.0	28.30
Artemisia pubescens	44	2.0	0.92	34	8.0	7.47
Artemisia scoparia	30	3.5	3.66	4	9.0	9.63
Artemisia frigida	17	3.0	4.81	11	4.0	4.22
Heteropapus altaicus	23	6.3	6.60	16	3.0	0.80
Allium bidentatum	25	3.8	0.80	21	12.0	5.53
Allium ramosum	26	2.0	0.67			
Allium tenuissimum	25	1.7	0.87			
Caragana microphylla	28.5	10.5	23.46	34	1.0	1.47
Melissitus ruthenica	32.2	20.0	9.37	20	5.0	5.66
Astagalus acaulis	6	1.0	0.11	13	3.0	9.23
Potentilla acaulis	4	1.0	4.02	3	1.0	1.50
Potentilla tanacetifolia	23	1.3	4.42	30	3.0	5.75
Potentilla bifurca	14.5	5.5	2.54	19	3.0	2.10
Others	33.2	2.4	5.95	27	9.0	3.05
Total		139.0			287.0	197.36

H: Height (cm); DP: Plant density (plants$\cdot$m^{-2}); DW: Dry weight (g$\cdot$m^{-2})

The evenness criteria (H) and the diversity criteria (D) of the community of degraded steppe were showed a general declining trend before soil amelioration. This trend can be expressed by the following equations:

$$H = 2.61 - 0.28t \text{ } (t = \text{years after soil treatment, where } t \leqslant 8 \text{ and } r = 0.99) \text{ and}$$
$$D = 3.76 - \ln t \text{ (where } t \leqslant 8 \text{ and } r = 0.99).$$

More than eight years after soil scarification, the trend in evenness criteria and the diversity criteria increased, and can be expressed with the following equations:

$$H = 0.97 \exp(0.06t) \text{ (where } t \geqslant 8; r = 0.99)\text{and}$$
$$D = 1.14 \exp(0.08t) \text{ (where } t \geqslant 8; r = 0.97)$$

It is thus clear that the increase or decrease in the diversity criteria is not related to a change in plant species richness, but is related to the plant species evenness and changes in the two criteria are consistent.

Both *Leymus chinensis* and *Stipa grandis* are poorly represented in the degraded steppe where *Artemisia frigida* and *Cleistogenes squarrosa* are dominant. Through soil amelioration, the growth of *Leymus chinensis* species was promoted, the evenness of community decreased and as result, community diversity also decreased. From the ninth year, the functions of the dominant plants of the hellebore and Ajania families were gradually replaced by herbosa plants, which are adapted to the zonal climate conditions so that evenness criteria and diversity criteria of the community increased (Hao et al., 2004).

7.5.7 Effect of burning on steppe degradation

Wild fires are an ecological phenomenon on the steppe that often occur during the winter and spring seasons. Fire has different effects on different species, so it can promote or control the generation and growth of plant species and affect the steppe quality and utilization value. Research has been conducted internationally on the effects of fire on the regeneration of forest and bush vegetation. Fire is used as one of the tools for managing the steppe, including for specific goals of bush clearance, insect control, grassland improvement, and the promotion of animal husbandry and its development.

Little research has been conducted in China on the effects of fire on the ecological and economic efficiency of typical steppe. However, some recent experiments on the effect of fire on *Leymus chinensis* steppe have been carried out. Experimental sites were established on enclosed and restored steppes of *Leymus chinensis* + *Stipa grandis* + *Achnatherum* spp. The enclosed steppe is an original steppe type which has been adapted to the local climate and soil conditions, while the restored steppe is a community type which mainly comprises *Artemisia frigida* + small herbosa following the enclosure of an over-grazed *Leymus chinensis* steppe. The soils of the two experimental sites are light loams and thick layer dark chestnut soils (Bao et al., 2000a).

The study examined the effects of fire on the composition, quality and utilization efficiency of *Leymus chinensis* steppe. The biomass, soil moisture and other parameters were measured every fifteen days during the growing season from May 15 to September 15.

Fire did not cause any obvious effects on the total production of the two experimental sites of the *Leymus chinensis* steppe. The maximum productivity value during the whole year occurred at the end of August and the maximum productivity was typically in the range of 180–200 $g{\cdot}m^{-2}$.

Fire promoted the growth of *Leymus chinensis* as a dominant plant in the community. During the maximum production period of the growing season, the production of *Leymus chinensis* inside the non-burned site was 30–50 $g{\cdot}m^{-2}$, which accounted for 70–80% of herb plants in the community. The effect of fire on the increase in production of *Leymus chinensis* is related to changes in the physical and chemical properties of the burned soil. *Leymus chinensis* is a nitrophilous rhizome geophyte and its newly generated sprouts grow under the topsoil so fire will not damage the growth of regenerating sprouts. In addition, fire can improve nutrient regime of the topsoil and can effectively control the growth of *Stipa grandis*, another dominant plant on the *Leymus chinensis* steppe (Bao et al., 2000b).

The yield of burned *Stipa grandis* steppe is lower than the yield of unburned *Stipa grandis* steppe. The yield of *Stipa grandis* in unburned steppe is similar to the yield of *Leymus chinensis* (peak biomass above ground is 30–50 g·m^{-2}). However, the biomass of the burnt *Stipa grandis* is only 10–30 g·m^{-2}. Burning in autumn has an obvious controlling effect on *Stipa grandis*. *Stipa grandis* is a chamaephyta and its generating sprouts are grown on the topsoil where they are damaged by fire.

In the burned community, herbosa plants maintain vigorous photosynthesis and the increase and accumulation of organic matter lasts to the end of growing season. At the end of the growing season, the yield of herbs on the burned steppe is higher than on the unburned steppe and the difference can be as high as 30–40 g·m^{-2}. During the second half of August and early September (harvest and forage storage season), the total yield of herbs from *Leymus chinensis* steppe is 300–375 kg·ha^{-1}. The increased production of these nutritious herbs improves the quality of steppe community. It can also be seen from the experiments, burning in spring has more beneficial effects on the production of *Leymus chinensis* than burning in autumn.

The yields of *Allium* spp. plants before and after burning were almost the same, or slightly increased before burning. *Allium* spp. plants are geophytes and burning does not cause any damage to their generating sprouts. These plants are usually associated with *Leymus chinensis*, *Stipa grandis* and other dominant plants, and *Allium* spp. are less important as competitors for moisture and nutrients. Fire does not cause significant effects on the yield of *Allium* spp. plants.

Fire does have an obvious effect on the growth of species of the Compositeae family by decreasing yield. In the typical communities of *Leymus chinensis* steppe, Compositeae species include *Serratula centauroides*, *Artemisia pubescens*, *Artemisia frigida* and other chamaephyta. Fire damages the generating sprouts of these plants. On the unburned steppe, the yield from Compositeae species was 10–15 g·m^{-2} and on the autumn burning steppe, the yield is also 10–15 g·m^{-2}. Fire can restrict the growth of *Artemisia* spp. and promote the growth of *Leymus chinensis* thus enabling an increase in steppe productivity.

Caragana microphylla is a bush on the *Leymus chinensis* steppe. Fire, especially in autumn, restricts the growth of this bush. On the unburned steppe, the yield of *Caragana microphylla* was 20–50 g/m^{-2} compared 5–20 g/m^{-2} on the burnt site. If the flames are higher than the bush height of *Caragana microphylla*, the fire will cause direct leaf scorch and kill the generating sprouts so that the yield in the following year is reduced. Although *Caragana microphylla* can control wind erosion of the soil and maintain snow on the steppe during winter and spring seasons, its presence affects forage production. Thus, burning is used to control the density of *Caragana* spp. and improve the utilization efficiency of the forage harvest.

The sharp thorns of *Stipa grandis* can penetrate the skin of livestock and damaging the leather industry. Burning can also reduce the cover of *Stipa grandis* and reduce damage from the thorny plant, helping the leather making industry by reducing the amount of scaring on animal hides.

The study of the effects of fire on steppe improvement contains two aspects, namely, the biological features of the various plants and the effects of burning on soil condition. Experiences from China and abroad show that the difference in location of the generating sprouts of the various plants affects their reaction to fire. Therefore, burning the steppe will promote the growth of some species and cause decline in others and altering the succession and community composition. Steppe fires can also change the soil structure and nutrient regime. First, the steppe fire clears plant litter above ground and alters the moisture regime, especially snow accumulation. It affects the light and temperature regimes of the land surface. Steppe fires can also accelerate the decomposition of soil organic matter on the steppe, and promote the vigorous growth of *Leymus chinensis* during the mid to late growing season leading to higher yield of improved quality forage. Fire has potential as a tool to speed up the restoration process of degraded steppe if appropriately used in a planned and controlled way consistent with local conditions and management aims (Bao et al., 2001).

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8 Biological and Technical Approaches to Control Windy Desertification

Longjun Ci and Yuhua Liu

Utilization of biotechnology is the most fundamental measure to control wind erosion and desertification. The use of vegetation (including trees, shrubs and herbs) can increase the land surface cover, improve soil physical and chemical properties are important. These measures would effectively reduce wind and water erosion by controlling or slowing down the direct disturbance of strong wind and rain on bare soil ground.

8.1 Classification of site conditions in drylands

The "site condition" refers to the environmental conditions in which a plant grows and develops, and is also called the "habitat" in ecology. The "type of site condition" of dryland vegetation is the overall environmental conditions where dryland vegetation grows as defined by physical space including geology, landform, climate, soil and biology. The classification of site conditions of dryland vegetation serves as the technical basis for ecological improvements and the design of sand-dust storm prevention measures in dryland areas. It also provides the basis on which adaptable species are selected for artificial planting areas to improve ecological efficiency and provide the socio-economic benefits of sand-dust storm control by virtue of dryland vegetation.

The success of sand-dust storm control through application of biological measures depends on the adaptability of selected species to the local environment. The primary environmental factors that determine the growth and distribution of vegetation are the solar radiation, light and water regimes in the region. To plan sand-dust storm control and prevention projects, top quality species are needed for planting, and an overall investigation and research on sand-dust storm control and prevention and the classification of site conditions must be implemented. This research should be aimed at surveying and studying the growing environment of dryland vegetation and the influence of environment upon dryland vegetation and its productivity.

8.1.1 Features of site conditions of drylands

Drylands, covering arid, semi-arid and dry sub-humid areas are extremely variable with respect to natural and geological conditions. The site condition refers to the growth conditions of a plant within natural and geographical zones under a specific climate. Due to the variability within the different climate zones, the type of site condition varies greatly. The key characteristics of drylands are as follows:

(i) The geographical locations include the vast area west of the Da Xing'anling Mountains and the northern part of the Qinghai-Tibetan Plateau, both of which are inland and distant from the ocean. Therefore, wet air currents do not enter the area where the desert and grassland vegetation prevails. This area also includes transitional desert steppe and semi-arid steppe;

(ii) Interspersed mountains and basins are characterized by the development of agriculture and animal husbandry in the oases and basins. This area includes the Altai, Tianshan, Kunlun and Qilian mountains, and other mountains interspersed with basins and watersheds, extending from east to west across vast desert and semi-desert areas generating different landscapes to the south and north. Snow melt water from the high mountains flows over the plains to form large-scale irrigated oases which are characterized by high productivity in the arid desert area and are also development zones for agriculture, forestry, animal husbandry and commerce. The foothills of the mountains are covered by desert and steppe vegetation;

(iii) The intermediate temperate and warm temperate zone areas have adequate heat, high levels of accumulated sunshine and large temperature variations which can boost the productivity; and

(iv) Drought is the most serious ecological problem in the area, seriously restricting the ability of vegetation to control the soil erosion. In the arid zone, the precipitation is much lower than total potential evaporation. Such an imbalance between temperature and water resources causes very high ground temperatures and aridization.

Basic characteristics of site conditions in drylands are described below.

8.1.1.1 Heat and water imbalance

The drylands are lacking in water, but have a lot of heat. Its aridity index and humidity index reveal that the available water is at least 3–4 times less than the required water. During the summer, due to the energy input from solar radiation, plants fail to utilize all the heat and the surplus heat warms up the surface of earth and radiates back. During the winter, due to the severe shortage of water, the thermal capacity is low and the heat cannot be retained resulting in cold weather.

The drylands of Northwest China are characterized by sufficient sunlight during the daytime and a high rate of sunshine. The total solar radiation energy is 540–725 $J \cdot cm^{-2} \cdot a^{-1}$, and the accumulated temperature $\geqslant$ 10 °C is typically above 2,500 °C. In the Tarim Basin the accumulated temperature $\geqslant$ 10 °C is over 4,000 °C, in the Turpan Basin it is up to 5,500 °C, the Junggar Basin and the Alxa Upland have an accumulated temperature $\geqslant$ 10 °C of 3,100–3,900 °C, and the Qaidam Basin has the lowest accumulated temperature at 1,500–2,000 °C.

The drylands are characterized by low precipitation, low relative humidity and high evaporation, and 80% of the drylands has an annual precipitation of less than 400 mm. The precipitation in and around the Tarim Basin is less than 25 mm and 50mm respectively. In Tuokexun County in Xinjiang, the annual precipitation is only 3.9 mm. The seasonal distribution of precipitation throughout the year is extremely uneven and over the whole year, the relative humidity is very low, less than 60% across 80% of the drylands. The desert and Gobi in the Tarim Basin, the Alxa Upland and the Qaidam Basin have a relative humidity of less than 40% while the evaporation rate is very high, up to 1,000–2,500 mm in almost areas.

8.1.1.2 Biology in drylands

In drylands, as an ecosystem where energy and matter interconvert, physical processes dominate to some extent while biological processes are extremely restricted. The productivity is very low because of insufficient water and harsh natural conditions in the area. The productivity of vegetation declines in parallel with the decrease in precipitation, and the density and coverage of vegetation decline as well. The distribution of vegetation in the drylands is extremely uneven, and changes with the variations in the landform and moisture regimes in different areas. The vegetation tends to grow in valleys and grooves where water accumulates. However, the land surface is typically bare and has no vegetation. Consequently, few animals and micro-organisms live on the plants. This lack of living organisms proves that the radiation cannot be converted into the normal energy of plants via photosynthesis and the converted energy is not sufficient to maintain and offset energy loss from physical processes. That means that the biological processes are weaker than the physical processes and as a result, a series of other reactions will occur.

8.1.1.3 Severe wind activity

The combined action of the west wind in the upper air, the East Asian monsoon and partial air circulation, excessive heat and air pressure differences are main reasons for high wind speeds and frequent sand-dust storms. Gale force winds occur 10–45 days a year, and sand-dust storms occur more than 30 days a year. These winds are extremely harmful.

Strong wind erosion and aeolian sands are frequent physical processes in arid and semi-arid zones. The imbalance between atmospheric circulation and heat causes frequent and severe wind movements, and the rare vegetation coverage on the plains cannot absorb this wind energy. Consequently, the wind accelerates the rate of wind erosion and the transfer of surface substances, generates a redistribution of earth surface material, and shapes the aeolian landform and desertified landform which features both wind erosion and aeolian accumulation as well as loess desert accumulation.

8.1.1.4 Coarse soil texture, low organic matter and weak microbial activity

Due to drought and scarce vegetation, the biological processes involved in forming soil are weak and the soil organic matter is rapidly mineralized. As a result, the organic matter content of the soil is typically less than 0.3–0.5% and not higher than 1%. The soil has a weathered crust and soil on the crust forms a very thin section which is usually 50–70 cm and can be less than 30 cm. The fine particles produced by the wasteland areas are mainly composed of coarse sands, fine particles and clay. The particles forming the pluvial/residual accumulation are mainly composed of gravel and scree. The subsurface stratum of soil shows obvious characteristics of iron transformation processes.

8.1.1.5 Water and salt imbalance

There are relatively high concentrations of soluble salts accumulated in the soil in this region. The salt accumulation occurs because the soil lacks in the washing action of rainwater and the evaporation caused by high temperatures is dominant and brings the salt from the lower soil levels up to the ground surface. The carbonate salts (mainly calcium carbonate) are accumulated on the soil surface, and the soluble salts are accumulated in the middle and lower parts of the soil profile.

8.1.2 Categories of main types of site conditions in drylands

Categories of site condition refer to areas with the same site condition features. These areas have the same natural factors (climate, soil, etc.) that affect the plant community and restrict the growth of plants. Wind erosion control by vegetation is designed based on categories of site conditions in drylands. Both the national plan and local plans to control sand movement or to stabilize sand dunes at the province and county levels are the essential to combat desertification. A group of scientists familiar with the site conditions should define a detailed general wind erosion control plan. The plan should calculate reasonable proportions of different land uses such as agriculture, forestry and animal husbandry. The conditions of water resources should also be classified according to the purpose and task of wind erosion control to specify the area of wind erosion control by reforestation and revegetation of grass scheme according to the intensity of sand-dust storms and the available ecological water supply. Construction of protection systems should be determined according to plan and appropriate tree varieties and seedlings should be selected.

A relief map at a minimum scale of 1:5,000 should be prepared for mature areas which details the plan of wind erosion control by vegetation. The wind erosion control by vegetation must be carried out in accordance with the detailed plan based on field surveys and be properly organized and managed. The required information for the classification of site conditions of drylands is as follows:

(i) Data on the natural conditions of the area for the past ten years should be collected and analyzed, including air temperature, soil temperature, wind direction, wind velocity, days of strong wind, precipitation, evaporation, relative humidity, soil type and basic soil properties;

(ii) The socio-economic conditions of the area should be analyzed, including population, annual income per capita, land use, agriculture policies in recent years, land deterioration processes, the development of animal husbandry, and reforestation. Satellite images, aerial photos and reports from different periods should also be collected;

(iii) The development plan should be well recognized and existing problems in the area should be fully understood;

(iv) The scale of work required to combat desertification and the quality of project implementation in recent years, including the establishment of a plant nursery and expertise and skills in management, should be assessed; and

(v) The allocation and management of central governmental investment and the use of local auxiliary capital and all funds should be understood.

8.1.2.1 Classification system for type of site conditions in drylands

The zoning and classification of site conditions with no forest can be undertaken according to two different methods: direct gradient analysis and indirect gradient analysis.

Using the direct gradient analysis method, sites are classified according to the environmental factors that influence the growth and distribution of forests and plants.

Using the indirect gradient analysis method, sites are classified with an advanced method for the analysis of vegetation biology that is objective and accurate and subject to sequencing and sorting based on the dominant environmental factors and the structure and quantity of plants (more than one factors). However, such analysis is only effective when the primitive and natural vegetation is well managed and has little interference, which is not applicable in cases where the vegetation is seriously damaged (Chang and Gauch, 1986).

In combination with the demands of the current wind erosion control project, specific principles for classification of site conditions of dryland vegetation are described below.

(i) Principle of integrated vegetation and environmental factors

In the dryland ecosystem, sand is the foundation, water is a lifeline and vegetation is the key factor. In the feedback process and relationship between soil, water and plants, the most important issue is how to balance the various requirements to achieve relative stability in the ecosystem and the sustainable development of production. Otherwise, the ecosystem will deteriorate, and the environment will be damaged, causing land desertification and the reduction in productivity and economic outputs.

(ii) Vegetation as an indicator of environmental factors and a regulating valve

From among the three factors of soil, water and plants, the latter is the one which humans can effectively control and regulate, and which is a key factor in maintaining balance in dryland ecosystems.

Humans can establish and maintain a suitable vegetation structure to control the wind erosion and create favorable moisture conditions through the correct selection and combination of plant varieties to maximize the potential productivity of drylands. However, inappropriate land use, damage to the land or unsuitable planting structures may cause an imbalance in the ecosystems, resulting in changes to the drylands and even deterioration of plants and environment. For example, the compaction and crusting of the ground surface may cause changes to the water permeability and air exchange capabilities of drylands.

The integrated relationship of vegetation and environmental factor are regulated by the principles of adjusting measures to local conditions to prevent damage and appropriate tree planting. The categorization of site conditions of vegetation should take into account the multiple aspects and factors influencing the growth of vegetation as well as the main factors restricting the distribution of vegetation and biomass.

(iii) Principle of multi-level classification

When the site conditions of drylands are classified, site conditions for reforestation should be zoned according to the macroclimate conditions and then classified based on the secondary environmental factors in various regions, including vegetation type, landform, land relief and soil characteristics. However, specific indicators used in the categorization of site conditions vary with the geographical regions and primary ecological factors that affect the growth plants.

The primary factors for categorizing the site condition of drylands vegetation include climate, landform and relief (parent rock, drylands category, and sand dune height), soil characteristics (texture of soils, thickness of the sand layer, depth to the groundwater table, and intensity of soil salinization) and vegetation coverage.

Drylands cover a wide range of biological climate zones and geographical areas and are located in areas with extremely complex natural conditions. To set up objective and scientific categories of sites, a multilevel classification is required: the first level is the biological climate type, (arid, semi-arid or dry sub-humid) based on zones consistent with the definitions of desertification by the UNCCD and China; the second level relates to geology and relief, where the classification is based on the geographical and relief types in the different bio-climate zones; the third level classifies the meso-relief or geographical unit of geology and relief based on the second level of classification; and the fourth level relates to the grades of soil fertility (nutrition and water availability) in the drylands. The fourth level is the element of the site condition most closely related to the reforestation and revegetation plans for degraded rangeland and steppe.

(iv) Combination of practicality and scientific basis

The site conditions for vegetation include various complicated and diverse categories which may have widely different natural and environmental conditions. However, extreme and complicated variations and planning cannot be easily incorporated in the construction of a project, as it will cause economy and technical difficulties, challenge people's understanding and be difficult to undertake. Therefore, both the practicality and scientific basis should be considered during project planning.

8.1.2.2 Classification of site condition of vegetation of sandland and indicators

(i) First level: bioclimatic type

The drylands are distributed in the arid, semi-arid and dry sub-humid zones. The bioclimatic types in the drylands of China are classified based on moisture index (the ratio of annual precipitation to potential evaporation). A ratio of 0.05–0.65 is used to classify areas as arid, semi-arid or dry sub-humid (Ci, 1994).

The arid zone of drylands in China covers the largest area, about 1,426, 700km^2 or 14.9% of the total area of China. The arid zone is located to the south of the Tianshan Mountains, east of the Pamirs Plateau, west of the Helan Mountains, and north of the Kunlun Mountains and the Qilian Mountains. It includes five provinces (regions) in the northwest of the Qinghai-Tibetan Plateau and 91 cities (banners). The extremely arid zone is mainly located in the middle of the Tarim Basin, the Alxa Upland, the Qaidam Basin and the Turpan Basin.

The semi-arid zone of drylands has a total area of 1,139,200 km^2, 11.9% of total land area in China, of which the eastern part comprises typical grassland and desert steppe. There are alpine areas and meadows on the Qinghai-Tibetan Plateau which consist of desert and semi-desert. The semi-arid zone is mainly located in seven provinces (regions), 141 counties (cities) and the administrative regions in Inner Mongolia, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang and other provinces (including provincial-level municipalities and autonomous regions).

The dry sub-humid zone of drylands covers a total area of 75,100 km^2, accounting for 7.8% of the total area of China, is mainly located in the Hulun Buir Upland to the west of the Da Xing'anling Mountains. The eastern border extends between a typical grassland and meadow through the north of the Loess Plateau, then moving towards the west of the Qinghai-Tibetan Plateau, around Qaidam Basin to the south, to the southwest part of the Qinghai-Tibetan Plateau. The area has an annual precipitation of 300–500mm. The administrative regions of dry sub-humid zone are located in 18 provinces (municipalities or autonomous regions) and 377 counties (cities and banners), in Xinjiang, Inner Mongolia, Gansu, Qinghai, Ningxia, Tibet, Shaanxi, Yunnan, Sichuan, Hainan, Henan, Shandong, Jilin, Liaoning, Shanxi, Hebei, Tianjin and Beijing.

(ii) Second level: classification by geological and relief conditions

There are diverse relief types and widespread mountains in China (Fig. 8.1). Some plateaus and uplands were uplifted by geological movement, and low-lying basins and plains are also present. The diversity of relief types greatly enriches the ecological categories of the desert, sandland and desertification-prone land. High mountains are interspersed with basins to create relief conditions for the formation of large deserts, there is a large area of desert steppe in the arid northwest, and the Loess Plateau and glaciers are found in the high mountains to the west, which nourish a large number of

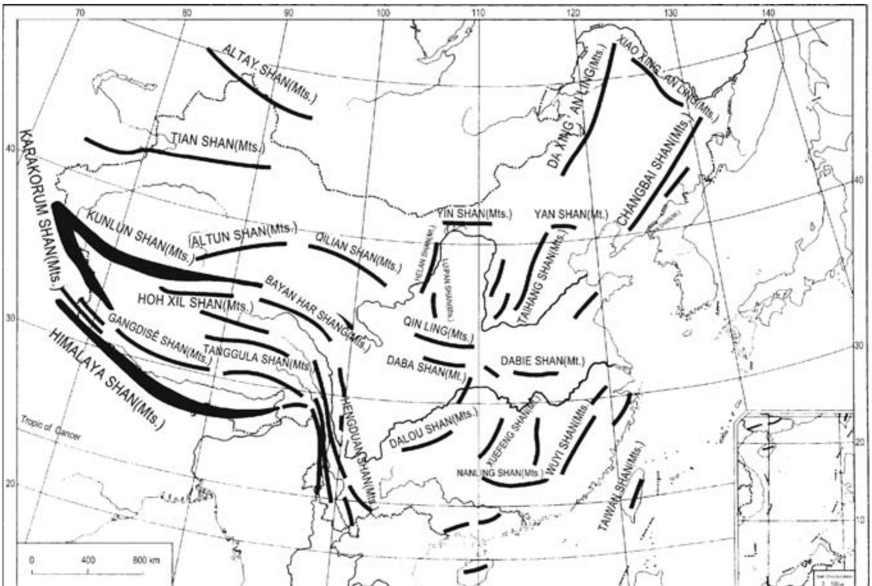

Fig. 8.1 Schematic diagram of main mountains in China (Zhang, 1997, with permission from Science Press)

oases.

(iii) Third level: meso-relief and geographical unit

Different site conditions are categorized according to meso-relief and geographical units, including:

- Surrounding areas of basins;
- Central areas of basins;
- Mountain-piedmont diluvial and alluvial fans;
- Mountain-piedmont diluvial and alluvial fan edge zones;
- Oases;
- River terraces;
- Flood plains;
- Wind-eroded relic hills;
- Lake edges;
- Dry river and lake beds;
- Loess Plateau desertified land;
- Deteriorated meadows;
- Sand-covered farmlands;
- Waste lands;
- Small towns in sand-dust storm-prone areas;
- Both sides of railway lines and highways in sandstorm-prone areas; and
- Large plains between sand dunes.

(iv) Fourth level: soil nutrients and moisture

The nutrient concentrations and moisture regimes of the soil are important in selection of appropriate measures and tree varieties for wind erosion control by vegetation. There are many factors that influence the fertility of soil, such as landform, sand dune height, the origin of sandy soil, underlying materials, level of groundwater and water-replenishing conditions.

The soil of the drylands mainly includes aeolian sandy soil, chestnut soil, meadow soil and alkaline saline soil, of which the aeolian sandy soil is most widely distributed. It is a wind-selected sediment with some thickness and has developed on the aeolian sandy parent material. It is different from the "desertified" soil that refers to a coarse soil layer, where fine particles (i.e., smaller than silty sand) from the soil layer have been blown away by wind, or a soil where the surface is covered by sand and has a higher degree of roughness (Chen et al., 1998).

The physical and chemical characteristics of soil greatly influence the fertility and water content of the soil. The particles of aeolian sandy soil are well sorted. In mobile aeolian sandy soil, medium sands (particle diameter 0.25–1 mm) and fine sands (particle diameter 0.05–0.25 mm) dominate in the whole soil profile, and clay particles (particle diameter $\leqslant$ 0.001 mm) comprise a slight proportion of the soil profile. In the semi-fixed aeolian sandy soil and the fixed aeolian sandy soil, coarse silty sands (particle diameter 0.01–0.05 mm) and clay particles comprise a higher proportion of the soil profile. The mineral content in aeolian sandy soil varies greatly due to the influence of parent source material and the degree of wind erosion (Chen et al., 1998), mainly comprises fine-particle minerals including 46–68% quartz, over 20% feldspar and a high percentage of silicon rock fragments. Due to the differences in aeolian sandy soil, its mineral contents will vary.

The water content of soil is vital for the control of wind erosion by vegetation. The mobile aeolian sandy soil has a dry sand layer which is loose and dry and has a water content of less than 0.5%. The thickness of the dry sand layer varies in different positions on the sand dunes, with a thin dry sand layer on the windward slope but a thick layer on the dune tops and leeward slopes. The status of the dry sand layer plays an important role in the wind erosion control using vegetation because the dry sand layer is a coating layer, and prevents the moisture in lower layers from evaporating, and also absorbs water vapor from the lower layers to moisten soil particles and generate hygroscopic water. The water content about 40 cm below the dry sand layer is stable at about 3–4%. The dry sand layer of semi-fixed and fixed sandland is thicker than on mobile sandland which affects the water content in lower soil layers. For example, in fixed sand areas, the soil around the root systems of *Hedysarum scoparium* and *Caragana intermedia* has a low water content while around *Artemisia ordosica* and yellow willow the water content is better.

In summary, the growing conditions for vegetation in drylands are subject, first of all, to the biological climate conditions in the region. Within in the same type of climate conditions, differences in geology and relief determine the local climate, micro-climate and different site conditions occurring in various locations. In different types of drylands, the site condition may vary significantly due to different soil textures, moisture conditions and salinization intensity even under the same climate conditions (Table 8.1).

The site condition of vegetation is closely related to sand dune height, sand movement, the nature of the parent material, the depth to groundwater and grass growth. The compilation of the categorization system of site conditions will attempt to simplify the categories for ease of use.

(i) Classification of soil characteristics

Primary factors are selected from factors (nutrient and moisture content) that influence the fertility of soil including: fine particle content in sandy soil, nature and thickness of the parent material, sandland mobility and groundwater status. Accordingly, soil can be divided into five levels as follows:

i) Level 0: coarse sand, no silty or fine sand interlayers, highly mobile, no vegetation, loose soil with no structure, deep groundwater or high salt content of the soil;

ii) Level 1: fine sand, mobile sandlands and sand dunes, loose soil with no structure, sparse vegetation;

iii) Level 2: mineralized groundwater or soil salinization occurs, fine sand or coarse silty sand, sandy soil as the substrate material, sandy soil interlayers, or low lands or bottomlands between dunes;

Table 8.1 Main relief types and geographical units of drylands in China

Site areas		Main indicators			Code
		D	AT	HI	
Heilongjiang-Songhuajiang-Nenjiang Rivers Plain		$\leqslant 105$	$\leqslant 1,700$	$\geqslant 0.65$	III
Songhuanjiang-Liaohe Rivers Plain	Songhuajiang-Nenjiang Sandland Horqin Sandland	106–180	2,600–3,300	0.65	III
Yellow River-Huaihe River-Haihe River Plain	Yellow River watershed Sandland Yellow River-Huaihe River Sandland	181–225	4,000–4,500	0.65	III
North China Plain		181–225	3,500–4,500	0.65	II
Loess Plateau		181–225	3,500–4,500	0.65	II
Fenhe River-Weihe River Watershed Valley		181–225	3,500–4,500	0.65	III
Yangtze River-Huaihe River Plain		226–240	4,500–5,300	0.65	III
Brahmaputra River-Lancang River-Watershed Valley		241–285	5,300–6,500	0.65	III
Yunnan-Guizhou Dry Valley					II
Guizhou-Guangxi Iimestone Hills		286–365	6,500–8,200		II
Hainan Island Coastal Sandland		365	8,000–8,200		III
South Valley of the Eastern Himalayas		365	8,200–8,700		I
Inner Mongolia Upland	Hulun Buir Sandland Wuzhumuqin Sandland Otindag Sandland	105–180	1,930–1,960	0.21–0.50	II
Ordos Plateau	Qubqi Sandy Desert Mu Us Sandland Ningxia Hedong Sandlands	105–180	2,000–3,190	0.21–0.50	II
Alxa Upland	Ulan Buh Desert Tengger Desert Badain Jaran Desert Yamaleike Desert	105–180	3,010–3,400	0.21–0.50	I
Junggar Basin	Gurban Tonggut Desert Wusu-Jinghe Desert Buerjin-Habahe-Jimunai Desert	162–180	2,490–3,530	0.21–0.50	I

Continued

Site areas		Main indicators			Code
		D	AT	HI	
Hetao Irrigation Area at Yellow River		105–180	1,700–3,500	0.21–0.50	I
North slope of the Tianshan Mountains		181–225	4,000–5,500	0.05–0.20	I
South slope of the Tianshan Mountains					I
Bositeng Lake Basin					I
Turpan Basin					I
Hami Basin					I
Tarim Basin	Taklimakan Desert Tuokelake-Buguli Desert Kuluke-Yaketuokelake Desert		4,000–5,000	0.05–0.20, (Taklimakan Desert: ⩽0.05)	I
Hexi Corridor of Gansu	Middle and lower reaches of Shiyang River valley sandlands Middle and downstream Heihe River sandlands Dunhuang Sandland		3,150–5,000	0.05–0.20	I
Alluvial/Diluvial Plains Piedmont Kunlun Mountains and the Qilian Moutains				0.05–0.20	I
Qinghai-Tibetan Plateau	Qaidam Basin Desert Gonghe Basin and Qinghai Lake sandland Shiquan River valley sandland Kumukuli Basin sandland Brahmaputra Valley sandland South Qinghai Shanyuan Sandland Qinghai-Tibetan Plateau freezing-melting zone Qinghai-Tibetan Plateau River headwaters	50–180 ⩾50	910–2,200	0.21–0.50, (Qaidam Basin desert: 0.05–0.20; Qinghai-Tibetan Plateau freezing-melting zone: 0.21–0.50)	I II I I II II II II

D:Days⩾10 ° C;AT:Accumulated temperature⩾10 ° C;HI:Humidity index.

iv) Level 3: fine sand or coarse silty sand in semi-fixed sandland, sandy soil as the substrate material, waste lands, bottomlands or river valley, or floodplains with good moisture conditions; and

v) Level 4: coarse silty sand or fine sand, fine clay soil interlayers at the root layer, some structure present, no or slight alkali or salt content, or sandlands on river banks with good moisture conditions.

(ii) Classification of site conditions for vegetation on drylands

The categories of site condition for vegetation on drylands are divided into four levels in sequence. Each level is designated with a code and four codes form a category of site condition. I, II and III are used for the first level for indicating arid, semi-arid and dry sub-humid zones, respectively. The second level is classified by the types of the geology and relief and is ordered from the Sanjiang Plain sandland to the Qinghai-Tibetan Plateau by number (1, 2, 3 and 4). The third level is classified by landform and geological type and is also ranked by number. The fourth level is classified by the fertility of soil (nutrients and moisture), and is the lowest level in the classification and also has the most specific categories. This level is divided into five types given a number from 0–4. Each level can create a separate category of site condition using these five types (Table 8.2).

The classification of site condition for vegetation on drylands is designed to meet the requirements of the project of wind erosion control by vegetation. Proper tree species, reforestation and revegetation of grass and other design elements are selected according to the different categories.

8.1.3 Selection of plant species for reforestation with different site conditions

The vegetation in the drylands is restricted by harsh climate conditions and soil factors. Only some species of arid plants can grow in the harsh climate and difficult soil conditions. Plants which grow in drylands are tolerant to drought and reduce the consumption of moisture to maintain the growth. They can also fix mobile sands and improve the environment. The adaptation characteristics mainly include:

(i) A developed root system: The roots of drought tolerant plants have a very strong ramification ability, and are horizontally distributed throughout the surface layer of the drylands and can reach up to 30 m in horizontal directions;

(ii) Degradation of leaves: Some leaves are replaced by assimilated column-type green branches. Some leaves or assimilated branches wither at high temperatures during the summer, or large leaves evolve into small ones to reduce the evaporative surface;

(iii) Change in organ and physiological functions: The mechanical processes in the plant have adapted so that epidermic cells have thick walls, a

Table 8.2 Examples of the main categories of site conditions of vegetation of sandland

Classification level					Classification system
1^{st} level	2^{nd} level	3^{rd} level	4^{th} level	Code	Notes (properties)
Arid zone	Tarim Basin	Basin edge	0	I-1-0	Tarim Basin edge, mobile sandland with no vegetation, alkaline saline soil
Arid zone	Tarim Basin	Basin edge	1	I-1-1	Tarim Basin edge, mobile sandland, sparse vegetation, fine sand
Arid zone	Tarim Basin	Basin edge	2	I-1-2	Tarim Basin edge, semi-fixed sandland, waste land, good moisture
Arid zone	Tarim Basin	Basin edge	3	I-1-3	Tarim Basin edge, semi-fixed sandland, good moisture
Arid zone	Tarim Basin	Basin edge	4	I-1-4	Tarim Basin edge, fixed sandland, good moisture, no alkali or saline soil
Arid zone	Tarim Basin	Basin center	0	I-2-0	Tarim Basin center, mobile sandland, deep groundwater
Semi-arid zone	Mu Us Sandland	Deteriorated rangeland/ grassland/steppe	3	II-13-3	Mu Us Sandland, deteriorated rangeland/grassland/steppe, semi-fixed sandland, medium moisture
Semi-arid zone	Ningxia Hedong Sandland	Waste land	4	II-14-4	Ningxia Hedong sandland, waste land, fixed sandland, good moisture
Semi-arid zone	Hetao irrigation area	Farmland	2	II-11-2	Irrigation area of the Yellow River bay, sand-covered farmland, with sandy soil as substrate material
Semi-arid zone	Hetao irrigation area	Farmland	3	II-11-3	Irrigation area of the Yellow River bay, sand-covered farmland, good moisture, fine clay soil interlayer
Dry sub-humid zone	Horqin Sandland	Sandland	2	III-12-3	Horqin sandland, sandy soil as substrate material, medium moisture
Dry sub-humid zone	Songnen Sandland	Sandland	3	III-18-4	Songhuajinag-Nenjiang rivers sandland, plain between hills, soil with fine clay soil interlayer, good moisture

lardaceous layer or a furry surface, and stomata of leaf tissues lapse or are partially closed, and have many veins. Some plants remain in thanatosis during the hot summer months;

(iv) Variations in tissue structure, and adaptability to sand burial: Desert plants can survive even if it is buried in the sand layers and

(v) Highly tolerant to salt: The plants on salinized land are tolerant to salt and contain many water soluble salts (sodium chloride and sodium sulfate) in their own tissues, which can reach 35% of the dry weight of the plant.

Xerophytes evolve into different types during their long term adaptation to different moisture, temperature, salinization and mobile sand regimes. Common xerophytic types include shrubs; semi-shrubs; perennial herbs with a long growing period; perennial herbs with a short growing period; and plants with short growing periods.

The knowledge of these characteristics can help in selecting appropriate species for wind erosion control.

8.1.3.1 Relationship between species selection and site condition category on drylands

In the reforestation (including afforestation) and revegetation plans for controlling wind erosion, the differences in the site conditions on drylands should be fully considered when selecting plant species (including trees, bushes, shrubs, etc.), and in general, attention should be given to the following:

(i) The plant species used for revegetation in drylands areas should first guarantee that the species (tree, shrub, grass) can cope with the harsh environments of drought, sand-dust storms and alkali and saline soil, and grow and improve in the unfavorable conditions.

(ii) The principle of selecting appropriate tree species for different sites should prevail, and appropriate tree species should be selected according to the category of site condition. For example, a large area of Poplar-Willow plantation should be prohibited in drylands with no irrigation; otherwise, the completion of the sand control reforestation project may leave a large scale dwarf forest which has no sand control effect or economic benefit. The *Populus* spp., a high quality fast growing tree species in North China, have many varieties. Only high quality species should be selected in consideration of the purpose of reforestation and favorable moisture conditions to achieve the maximum output. However, in drylands, the output of Poplar species is directly related to the adequate water and fertilization.

(iii) The mode of a characteristic combined tree, shrub and grass area that integrates belts, zones and grids. The tree species and integrated configurations of trees, shrubs and grass should be scientifically selected according to the category of site condition. A comprehensive management mode including agriculture, forestry and animal husbandry should be used in drylands to maximize their overall effectiveness. A grass and shrub belt should be set up at the edge of farmlands facing the common wind direction to reduce the wind speed on the ground and reduce the damage of farmland by wind and blown-sand. Various shelterbelts networks should be planted within the farmland area, including long lived and fast growing tree species. Within the shelterbelt networks, tree species of different heights should be selected to shape a multi-level tree canopy and produce "narrow windbreaks and small forest networks" to effectively control and prevent wind and blown-sand.

(iv) Local tree species and shrubs with good adaptations should be selected. In drylands, there are many shrubs with high biomass productivities, high adaptability and high economic value which can be used as main or auxiliary revegetation species. In drylands, herb plants, trees and shrubs can be selected for planting together to improve the effectiveness of wind erosion control measures. Inappropriate introduction of shrubs should be avoided.

(v) Actively and prudently introduce tree species into drylands. Popularizing cash crops and trees, and developing local production suitable to drylands can play an important role in improving the living conditions of the people in drylands. However, in consideration of the harsh water and soil conditions in drylands and the unstable climate conditions, tree species should be prudently introduced.

Research is required before introducing high quality tree species for special purposes suitable for local climate conditions. In some cases, the successful pilot planting of some tree species in an area will not guarantee success in planting across the entirety of North China. Any arbitrary imitation may cause failure. Moreover, some people are concerned with the invasion of harmful species and thus the introduction of new species is limited in an arbitrary way while hindering the normal and active introduction of species.

8.1.3.2 Example of selection of the main species for different categories of site conditions

As shown in Table 8.2, vegetation is a comprehensive indicator of all site environments. Before the classification of site conditions, a survey of vegetation is required. When the survey is completed, the variety, distribution and growth of tree, shrub and grass species should be determined and the relevant data should be inserted into a database. A list of the main species of trees and shrubs suitable for different categories of site conditions in drylands should be compiled. This can provide examples of tree species suitable for different categories of site conditions, and provide a reference for reforestation design and seedling cultivation (Table 8.3).

Table 8.3 Example of selection of plant species suitable for different site conditions of vegetation

1st level	2nd level	3rd level	4th level	Code	Plant species
Arid zone	Tarim Basin	Basin edge	0	I-1-0	Herb plants, *Nitraria tangutorum*, *Calligonum mongolicum* and *Tamarix chinensis*.
Arid zone	Tarim Basin	Basin edge	1	I-1-1	Herb plants, *Nitraria tangutorum*, *Haloxylon ammodendron*, *Tamarix chinensis* and other shrubs and semi-shrubs.
Arid zone	Tarim Basin	Basin edge	2	I-1-2	*Tamarix chinensis*, *Calligonum mongolicum*, *Elaeagnus angustfolia*, *Nitraria tangutorum* and other shrubs and semi-shrubs.
Arid zone	Tarim Basin	Basin edge	3	I-1-3	*Elaeagnus angustfolia*, *Tamarix chinensis*, *Ulmus* spp., *Prunus armeniaca*, *Molus alba* and other shrubs and semi-shrubs.
Arid zone	Tarim Basin	Basin edge	4	I-1-4	*Fraxinus chinensis*, *Molus alba*, *Elaeagnus angustfolia*, *Tamarix chinensis*, *Ulmus* spp., *Prunus armeniaca*, *Populus* spp. and other shrubs.
Arid zone	Tarim Basin	Basin center	0	I-2-0	*Agriophyllum squarrosum* and *Phyllostachys propinqua* and other annual herb plants on the interdunes, and *Calligonum mongolicum* and *Tamarix chinensis* on the suitable land.
Semi-arid zone	Mu Us Sandland	deteriorated rangeland/ grassland/steppe	3	II-13-3	Various fodder plants, *Caragana korshinsk*, *Astragalus adsurgens*, *Artemisia sphaerocephala*, *Hedysarum scoparium*, *Salix psammophila*, *Hedysarum laeve*, *Glycyrriza uralensis* and *Ammopiptanthus mongolicus*, etc.
Semi-arid zone	Ningxia Hedong Sandlands	waste land	4	II-14-4	*Fraxinus chinensis*, *Populus* spp., *Ulmus* spp., *Lycium Barbarum*, *Ailanthus altissima*, *Caragana korshinsk*, *Salix psammophila*, *Tamarix chinensis* and *Gleditsia simensis* etc.
Semi-arid zone	Hetao irrigation area in the Yellow River	farmland	2	II-11-2	*Populus* spp. (variety carefully selected), *Fraxinus chinensis*, *Ulmus* spp., *Lycium Barbarum* , *Ailanthus altissima*, *Caragana korshinsk* *Salix psammophila*, *Tamarix chinensis* and, *Gleditsia simensis*, etc.
			3	II-11-3	*Populus* spp., *Ulmus* spp., *Lycium Barbarum*, *Ailanthus altissima* , *Caragana korshinsk*, *Salix psammophila*, *Tamarix chinensis*, *Gleditsia simensis*, *Amorpha fruticosa*, and *Hippophae rhamnoides*, etc.
Dry sub-humid zone	Horqin Sandland	sandland	2	III-12-3	*Pinus sylvesthis* var. *mongolica*, *Populus* spp., *Ulmus macrocarpa*, *Salix psammophila*, *Lespedeza bicolor*, *Armeniaca sibirica*, *Medicago sativa*, *Sanguisorba officinalis*, and *Astragalus adsurgens*.
Dry sub-humid zone	Songhuajiang-Nenjiang Sandland	sandland	3	III-18-4	*Populus* spp. (variety carefully selected), *Ulmus macrocarpa*, *Quercus mongolica*, *Lespedeza bicolor*, *Pinus sylvestris* var. *mongolica* ,*Caragana korshinsk*, *Armeniaca sibirica* , *Medicago sativa*, *Astragalus adsurgens*, *Sanguisorba officinalis*, etc.

8.2 Development of vegetation protection techniques

Planning of vegetation protection is a basic task in vegetation protection, where the main purpose is to determine the background state of the prevention and control targets, including natural conditions, land resources and socio-economic conditions in the ecological improvement area. Based on the classification of types of site conditions, an analysis and appraisal of wind erosion, water erosion, and secondary soil salinization should be carried out to determine measures suitable to local conditions and disaster-oriented protection. A scientific and operational prevention and control plan should be compiled, for which up-to-date and applicable prevention and control techniques are required during the design process. At present, modern technology makes large scale satellite images available which, along with field surveys, allow detailed land use maps and planning details of the project area to be determined. These data can also be used to produce the prevention and control network for the whole project area.

8.2.1 Vegetation protection planning

8.2.1.1 Planning preparations

(i) Define the purpose and task of vegetation protection in the project area. The purpose of wind erosion by vegetation is to prevent the drylands from expanding, weaken the drought winds through various reforestation and revegetation measures, prevent the mobile sands from burying irrigated farmland, railways, highways, oil fields and mines, provide fuelwood for local residents and establish forage-fodder farms and nurseries and forest plantations. wind erosion control mainly includes two aspects: preventive measures to stabilize mobile sand area and stop them enlarging; and measures for reusing deteriorated land and improving its productivity;

(ii) Carefully and accurately calculate the requirements for wind erosion control, and specify the engineering requirements of various wind erosion controls by vegetation and the irrigation water source;

(iii) Compile a list of the categories of site conditions for local vegetation. Work out a list of the categories of site conditions for the local area according to the classification of site condition of vegetation to guide the reforestation and revegetation grass and tree species selection;

(iv) Organize the implementation of the project as scheduled.

8.2.1.2 Operational procedures for vegetation protection planning

The planning and design are the preparatory tasks for the prevention project and also key links for determining the scale, investment and completion time of a project. The operational procedures include the preparation, field survey, data collection and preparation for a project proposal.

8.2.2 Construction project of dryland revegetation

Drylands have formidable natural conditions and fragile ecosystems. The protected areas lack the capability for self-adjustment. As a result, the protection systems are an integration of various interactive protective measures with a rigid structure. The construction of dryland revegetation systems includes many components, such as shelterbelt network systems, compound agriculture and forestry systems, farmland systems, rural irrigation systems, animal husbandry systems for the plains and greening systems for residential areas. In drylands, the construction of shelterbelt networks includes the following processes.

8.2.2.1 Three North Shelterbelt Network Project

The Three North Regions shelterbelt network project started in 1978 and will be completed in 2050, covering a period of 73 years and including three stages and eight phases of projects. To date, the project has achieved the goal of increasing the vegetation coverage by up to 14.95%.

The Three North Regions Shelterbelt Network Project was approved and endorsed by the State Council in 1978. The coverage area starts from Binxian County, Heilongjiang Province in the east, and extends to Wuzibieli Pass in Xinjiang in the west and the Chinese border in the north and extends from Tianjin, the Fenhe River and Weihe River, downstream of the Taohe River and Buerhanda Mountains to the Kalakunlun Mountains. The project area is 4,480km long from east to west and 561–1,460 km wide from south to north.

In the Three Northern Regions (Northeast China, Northwest China and North China), the grassland and steppe account for 43.5% of the total land area, of which 22.3% is desert steppe. sand-dust storm, soil erosion and soil salinization are very severe in the area. Due to natural disasters and human interference, the lands in the area have extremely low productivity resulting in harsh living conditions for local residents. To improve the harsh natural conditions causing low outputs as well as the environment, the task of controlling soil erosion with vegetation is very difficult. The Three North Regions Shelterbelt Network Project is being carried out in three stages, which are mainly specified according to the administrative divisions in combination with natural climate zones and socio-economic conditions.

The first stage took a total of 23 years, included three phases and completed 62.1% of the total engineering work. This stage of the project was mainly located in 12 provinces (autonomous regions, municipalities) including Heilongjiang, Jilin and Liaoning in Northeast China, Inner Mongolia, Hebei, Beijing and Shanxi in North China, and Shaanxi, Ningxia, Gansu, Qinghai and Xinjiang in Northwest China and has constructed a series of regional shelterbelt networks, with key works as follows:

(i) Plains, irrigation oases and farmland shelterbelt networks;

(ii) Stabilizing mobile sands with woodland in the Mu Us Sandland;

(iii) Controlling mobile sands in the Horqin Sandland;

(iv) Tree belts on both sides of the Beijing-Baotou and Baotou-Lanzhou railway;

(v) Tree plantations around Beijing and Tianjin;

(vi) Protective forests on both sides of the main course of the Yellow River;

(vii) Soil and water conservation forests on the Loess Plateau from the north of the Weihe River to the southern end of the Luliang Mountains.

The second phase will be completed over a period of two decades in two stages. When the second phase of the project is complete, the protective system of Three North Regions Shelterbelt Networks Project will have been formed. In total, 87 counties of Heilongjiang, Jilin, Liaoning, Beijing, Hebei, Tianjin, Shanxi and Gansu are involved in the second phase of the program and the following five key sub-projects have been prioritized:

(i) Soil and water conservation forests and agricultural protection forest on the Loess Plateau in the eastern part of Gansu Province;

(ii) *Populus diversifolia* reforestation along the banks of the Hetian River in Xinjiang Uygur Autonomous Region and farmland shelterbelt networks;

(iii) Shelterbelts networks along the Hexi Corridor of Gansu Province;

(iv) Rangeland shelterbelt networks in the southeast of the Xilinguole Upland; and

(v) Soil and water conservation forests along the Shanxi-Shaanxi river gorge and boundary areas.

The third phase of the project is aimed to improve and perfect the shelterbelt network system. The projects of the Three North Regions Shelterbelt Networks Project described above have been underway for more than 30 years and have had a far reaching influence on the ecology, environment, climate, society and culture. The coverage of reforestation and revegetation of grass proves the long term significance of the project (Li, 2007; Cai, 2009).

8.2.2.2 Sand control project

According to the characteristics of the bioclimatic zone and the natural and geological belt, the sand control project has different tasks in the drylands. The overall structure of the project involves focusing on the protection and enlargement of forest and grass vegetation and desert plants in northwest and north China and the western part of Northeast China to establishing a project which integrates prevention, control and utilization. In the “Tenth Five-Year Plan” for national economic construction, the central task of the sand control project changed because the 2008 Olympics were to be hosted in Beijing and thus the protection of Beijing against sand-dust storms became a political task, and one which has continued even after the closing of the Olympics. Consequently, the sand control project specified in the “Tenth Five-Year Plan” involves controlling the source of sand in Beijing and Tianjin, including the mobile sand control tasks in 78 counties around Beijing and Tianjin (Li and Shi, 2007; Gao, 2008).

The desertification monitoring network is related to the sand control projects. China's National Desertification Monitoring Center under the leadership of the State Forestry Administration, is authorized to focus on the dynamic monitoring of land desertification nationwide and guides the implementation of the sand control project over time.

8.2.2.3 Construction of shelterbelt networks in sandlands or deserts

The shelterbelt networks in sandlands or deserts are mainly comprised of large grass planting belts or artificial shrub and grass belts. They can also comprise sandbreaks with internal "narrow shelterbelts and small tree networks" around the protected area. These networks operate as a system that is integrated with the belt, zone and network involving different sub-systems. These networks serve to maintain the eco-balance in sandlands or deserts, thus facilitating the energy conversion of living organisms and allowing the circulation of various materials. In other words, shelterbelt networks are an important component of the dryland ecosystem and have a far-reaching influence upon a series of ecological factors (Fig. 8.2).

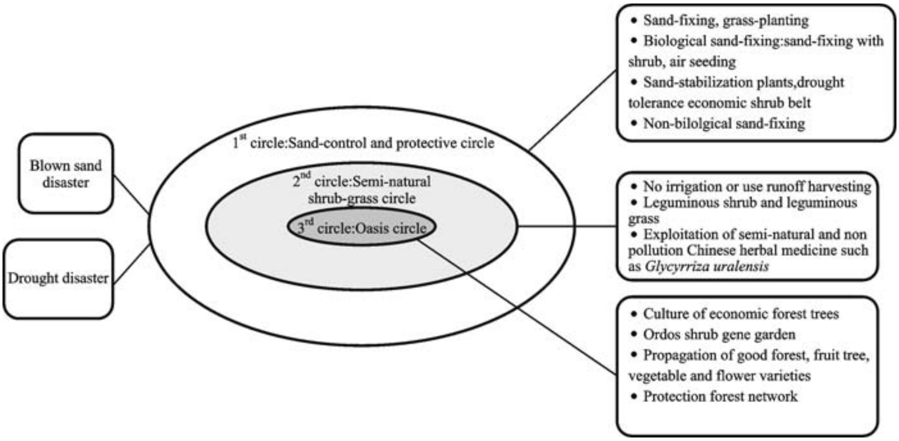

Fig. 8.2 Sketch map of dryland shelter system

(i) Establishment of shelterbelt networks in drylands

Since 1949 the government of China has attached great importance to wind erosion control and led the people living in drylands in making a huge effort towards reforestation and wind erosion control. There are many such examples of these efforts in Xinjiang, Inner Mongolia, Gansu, Ningxia, Qinghai and Shaanxi. In Chifeng (Inner Mongolia), Yulin (Shaanxi) and Hetian (Xinjiang), demonstration sites have been set up based on different bio-climatic zones, natural conditions and geographic locations.

At the very start of the construction of shelterbelt networks in drylands, the cultivation of waste lands, and the development of shelterbelt networks or renovation of small areas of farmland are carried out at the same time, with reforestation occurring alongside planning. The plan for the reforestation is integrated with the basic layout of the farmland and uses a combination of forests, farmland, trenches and roads to develop a farmland protection network featuring narrow shelterbelt and small tree networks. The protective effects of shelterbelt networks and effective reforestation are maximized with minimal land occupation, low water consumption and low levels of investment.

The scientific results from using combined forest and grass to control sand-dust storms won the 1st National Science Conference Award and these results came from many years of consecutive testing and observation in Turpan and Maigaiti counties in xinjiang. In these counties, the annual precipitation is only 36.8–61.3 mm, aridity is 14.6–26.1, there are 21 days of strong wind per year, 10 to 21 days of sand-dust storms per year, and over 50 dry wind events occur mainly in May and June.

During the construction of shelterbelt networks in this area, a network of farmland shelterbelts, narrow shelterbelts and small tree networks were built along the trenches, roads and farmland at various levels inside the farmland. The mobile sand controlling forest zones, comprising multi-level narrow shelterbelts, were established on the edge of the sandy desert, while flood control and windbreaks mainly comprising trees and shrubs were set up on both sides of the flood-prone land. Artificial plantations of trees for "blocking sands in windward slopes and pulling sands on the leeward slopes" were set up to stabilize mobile sands and fix mobile dunes in oases so as to improve the shelterbelt networks.

(ii) Construction of shelterbelt networks in drylands

i) Establishing sand-fixing and erosion-resistant shrub belts at the edge of the sandlands or deserts

Sand dunes or wind erosion prone areas around sandlands or deserts are enclosed with shrub-belts to protect natural vegetation. Flooding of the sandlands or deserts in summer and the remaining irrigation water in winter is used to irrigate the shrub-belts, and desert plants are sowed to improve the coverage of vegetation and generate 200–500 m wide shrub-belts. Local plant species such as *Artemisia sphaerocephala*, *Artemisia ordosica*, *Alhagi pseudalhagi*, *Hedysarum scoparium*, *Tamarix* spp., *Salix* spp.,*Calligonum mongolicum* and other shrubs and semi-shrubs are selected according to local conditions. When the vegetation coverage reaches 60% or more, the roughness of the shrub-belt surface can be increased by 30–40 times so that air currents on the ground surface produce a turbulent flow both inside and outside the vegetation belt to reduce the kinetic energy of blown-sand winds, which protects the ground surface against wind erosion and reduces the wind speed entering the farmland area. When wide shrub and grass-belts have become stable and improved the habitat, they can be used for animal husbandry or medical herb planting and harvesting.

ii) Construction of sand-breaks at the edge of the sandlands or deserts

The sand-breaks on the edge of the sandlands or deserts, located in a "transitional belt" between the protected farmland and the shrub and grass-belts, comprise tall tree species and auxiliary tree species. These sand-breaks form sparsely structured sand-breaks with even transmittance throughout the shelterbelt. In the sand source and sandstorm-prone areas, multi-strip sand-breaks featuring combined tree, shrub and grass plants and consisting of 5–6 rows of trees with a strip distance of 20–30 m can be constructed. Perennial rangeland, grassland and steppe plants or sand-tolerant plants can be planted between the forest strips. The following tree species can be selected for reforestation: *Elaeagnus angustifolia*, *Ulmus pumila*, *Fraxinus americana*, *Tamarix* spp., *Populus euphratica*, clones of *Populus nigra*, *Caragana intermedia*, *Hedysarum scoparium* and *Nitraria* spp. Flexible planting is required according to the specific landforms within the sand-breaks to ensure the survival of the newly planted trees.

iii) Construction of farmland shelterbelt networks within the protection area

This is a core part of the shelterbelt network for ensuring that the protected farmland, rangeland, grassland, steppe and industry can achieve rapid and profitable economic growth. The protected traffic network can alleviate or eliminate damage to the road and rail systems. The networks can also protect residential areas within the zone, allowing them to become greener and more attractive places to live. The various aspects of the protection system can be organically integrated to form an overall network.

Four to six rows of trees and shrubs are arranged along the direction of the main wind direction and generate sparsely structured sand-breaks. The main sand-breaks have an interval of 250–300 m, which can be shortened to about 150–200 m in areas where sand-dust storms are very severe. The auxiliary sand-breaks usually consist of four rows of trees forming a low-density ventilated structure with an interval of about 500m. The interval of auxiliary sand-breaks can be specified according to the requirements of the agricultural machinery.

The selection of tree species is very important. Within the protection area, where there are good moisture conditions and a highly protected environment, numerous varieties of trees, shrubs and grasses can be selected to combine rapid growth with longevity, ecological and economic effects, trees and shrubs with grass, and protection with beautification. Tree species should be selected according to local conditions. Some drought-resistant *Populus* spp. can be planted on river banks and around both sides of dry trenches. Additionally, *Ulmus pumila*, *Fraxinus americana*, *Morus alba*, *Ulmus densa*, *Elaeagnus angustifolia*, *Pinus sylvestris* var. *mongolica*, *Platycladus orientalis*, *Robinia pseudoacacia* and *Populus euphratica* are some of the key tree species for farmland shelterbelts. The construction of the farmland shelterbelt network should be configured so that it considers the irrigation system and roading system as well as the location of cultivated land, so that it fully utilizes the irrigation water ensuring sound growth of the forest.

8.2.3 Function of the vegetation protection project

The vegetation protection project (construction of shelterbelt networks in drylands) has functions of sand-dust storms prevention and improvement of the micro-climate. The function is determined by the structure.

The shrub and grass belts and shelterbelts at the front of the protection area influence the redistribution of wind deposited substances. Sand-dust storms transport sand close to the ground, with approximately 80% (depending upon the composition of sand in the local area) traveling at a height of 0–20 cm, particularly in air currents 10 cm above ground. Therefore, changes to the wind speed at the ground surface affect sand accumulation and the wind erosion intensity of wind deposited material.

In areas affected by severe sand-dust storms, a 200–500 m wide shrub and grass belt is established along the edge of the sandlands or deserts surrounding the protection area to increase the roughness of the ground surface, reduce the kinetic energy of the sandstorm flow, and settle the sands in the air currents so as to control sand-dust storms. Our measurements from shelterbelts with a width of 55–200 m reveal that a grass-belt with plant coverage of 40–60% increases the surface roughness to 9.28 cm when the wind velocity in the field is $10\text{m} \cdot \text{s}^{-1}$. The resistance of grass-belts to air currents is 17–27 times higher than that of other plant belts without grass coverage. The density and height of grass-belts is in direct proportion to the surface roughness and air current resistance.

After being weakened by the grass-belts, the sand-dust storm flow enters the sand-breaks, whose shelter effect depends on their vertical biological composition. The sand-breaks with a ventilated structure have ventilation in their lower parts, resulting in air currents accumulating in the air gap between the trunks of the sand-breaks. This causes an increase in wind speed between the trunks, and usually causes wind erosion on the surface of the sand-breaks generating sand accumulation at a distance of 50–80 m behind the sand-breaks. Many aeolian sands accumulate in front of and inside sand-breaks with a compact structure, causing large sand mounds to form inside the sand-breaks, sometimes burying the sand-breaks completely. Inside sand-breaks with four to six rows in an open structure comprising different heights of tree canopies, only a small amount of sand accumulation occurred within the sand-breaks or accumulated at a distance of 30–40 m behind the sand-breaks.

A suitable structure for shelter systems enables the sand carried by air currents to pass through the intercepting broad grass-belts, but the air currents are weakened. This results in less sand-dust storm flow being able to pass the sand-breaks, reducing sand accumulation. The forest can be stabilized and improve its overall protection function.

The structure of the sand-breaks determines their protection function. Depending on the ventilation coefficient, sand-break structures are usually divided into three categories: a ventilated structure, an open structure and a closed structure. The air currents generate different aerodynamic effects when they pass through sand-breaks with different structures. The sand-break structure should be selected according to the protection requirements. Usually, a closed or open structure is selected. For farmland shelterbelt networks, narrow sand-breaks and a small network of trees is used for sparse-ventilation structures. A ventilated structure is typically used for roadside tree planting networks. After the forest network and biological system are developed, the structural effects of sand-breaks are less rigid than single-strip sand-breaks.

8.3 Principles and techniques for enclosing degraded lands

In arid and semi-arid area, degraded vegetation and habitat should be protected and improved with effectively artificial measures, in the following section, enclosure, one of often-used measures, is introduced from principles to techniques.

8.3.1 Vegetation reservation measures and their significance for combating desertification

The enclosure, protection and regeneration of degraded vegetation (i.e., a vegetation reservation) is intended to improve the degraded vegetation, protect its habitat and prevent the fragile rangelands, grasslands and steppe from further reclamation, undue collection of plants for fuelwoods and overgrazing. Various measures, including vegetation cultivation measures, prevention against natural disaster and prevention against damage from biological invasions will be adopted to promote the revegetation of degraded vegetation and restoration of the deteriorated habitat soil. The aim is to provide a rehabilitation opportunity for vegetation and soil so that enough nutrient material can be accumulated to gradually resume or increase the biomass productivity of vegetation and soil. The protection measures are also intended to provide adequate time for seedling or biomass reproduction to promote the natural revegetation of degraded plant communities.

In drylands, the reservation and cultivation of natural vegetation play an active role in protecting the land from desertification and degradation because enclosure measures greatly promote the growth of plants. When deteriorated rangeland (caused by excessive utilization including overgrazing, undue collection of fuelwoods and herb medicinal plants and illegal felling), is enclosed, the root systems of plants can begin to absorb adequate moisture and mineral nutrition from soil, while the leaves of the plant accumulate energy and organic substance through photosynthesis. This leads to normal growth and reproduction of the plants, improving the productivity and vegetation coverage, increasing the windbreak and sand stabilization capacity of the vegetation and retarding sand movement and the reactivation of fixed sand dunes. On the other hand, enclosure measures change environmental condition of vegetation. Following enclosure of deteriorated land, the plants begin to bloom, and the ground coverage increases while the area of bare soil decreases. Higher plant coverage and a higher organic matter content in the soil can reduce the evaporation of soil moisture, reduce wind speeds, increase the water holding capability of soil, and protect the soil against wind and water erosion, thus effectively maintaining soil moisture and reducing soil erosion.

The measures used for the enclosure are extremely important in the control and prevention of land degradation. First, the input into enclosure measures is low. Second, the enclosure measures can have a rapid effectiveness. Third, the gains from enclosure are huge. Most enclosure and cultivation areas have multiple layers of trees, shrubs and grasses, and can produce numerous forestry and animal husbandry products, improving the productivity level of forestry and animal husbandry and creating socio-economic benefits.

8.3.2 Methods and techniques of enclosure

8.3.2.1 Types of enclosure

The types of enclosure include complete enclosure, partial enclosure and rotational enclosure. The appropriate enclosure type will be applied depending on the variety of vegetation, vegetation degradation intensity, and habitat condition of the enclosed land as well as the potential use of the vegetation.

Complete enclosure, also called absolute enclosure, refers to all-round enclosure and protection of the degraded land. This method is generally used on exposed ground and steep slopes where the vegetation is severely degraded and the habitat of rare species is deteriorated. This type of enclosure prohibits all human activities unfavorable for the growth and reproduction of plants, such as burning, reclamation, grazing, felling and grass harvesting. In general, the enclosure period of grassland is 3–5 years while that of forestland is over 8–10 years.

Partial enclosure, also called flexible enclosure, includes two methods: seasonal enclosure and enclosure by species. The seasonal enclosure means that the enclosed is open during some seasons for grazing, grass harvesting and felling during the enclosure period provided that there is no impact on the rehabilitation of the vegetation. Seasonal grazing on the grassland is the main form of seasonal enclosure. The enclosure by species refers to the enclosure and protection of plant species that may develop for the future. “Felling (or shrub cutting and grass harvesting) while trees left” is the main method of enclosure by species.

Rotational enclosure involves the whole enclosure zone being divided into different sections for rotating enclosure. Provided that there is no unfavorable impact on vegetation reproduction and the conservation soil and water, some areas are retained for the collection of plants, grazing or grass harvesting while the remainder is enclosed. The interval of rotational enclosure varies according to the category and use of the vegetation. Rangeland rotation (by season or year) is main method of rotational enclosure on grassland. Rotational enclosure allows the vegetation of the whole enclosure zone to recuperate.

Usually, the three enclosure methods described above are combined and used in different areas, locations and periods of enclosure. For example, once the vegetation has regenerated to some degree, partial or rotational enclosure measures can be used for cultivation. With rotational enclosure, the vegetation may be opened by season or species and this becomes a partial enclosure for cultivation; while if excessive use of vegetation occurs with partial or rotational enclosures, complete enclosure and cultivation measures are used for rehabilitation (Wang, 2003).

8.3.2.2 Enclosure methods

Enclosure methods vary with the different categories of vegetation. Enclosure methods for forestland are simple, while, comparatively speaking, enclosure methods for grassland are very complicated. In case of large areas of grassland, some of the following enclosure methods can be used (Wang, 2003).

(i) Barbed wire enclosure

This enclosure method is strong and durable, requires less effort to install, does not occupy the grassland, and has no influence upon livestock grazing. However, there are significant inputs required.

(ii) Grid enclosure

This method requires less manpower for installation, and less steel in the enclosure but construction of the enclosure is difficult in areas with undulating landforms.

(iii) Biological enclosure

This method involves planting small thorny trees or shrubs suitable for local conditions in a dense green barrier to stop the access of live stock into the enclosure of the degraded grassland.

The main purpose of grassland enclosure is to prevent livestock foraging and trampling the vegetation and having other unfavorable influences on the vegetation. In addition, the excessive reclamation, excavation, collection of fuelwood, bushfires and other destructive behaviors of humans should be controlled and prevented through application of integrated measures and monitoring of grazing intensity.

8.3.2.3 Cultivation techniques

Irrespective of the type of plants, proper cultivation measures can speed up the rehabilitation of vegetation in enclosed areas. The cultivation techniques for enclosed vegetation include the approaches described below.

(i) Replanting and re-seeding

In the enclosure zone, the original and newly planted vegetation is not evenly distributed and it is difficult to form an even coverage in a short time period. Therefore, appropriate tree or grass species should be selected for replanting or re-seeding to improve the vegetation coverage and to reduce the exposed surface area.

(ii) Natural regeneration of artificial plantings

Depending on plant reproduction modes, measures such as ploughing of soil, leveling fields, excavating trenches and pruning roots can promote the reproduction of vegetation and increase the quantity of natural vegetative coverage.

(iii) Cultivation of vegetation with mixed tree, shrub and grass species

In general, plantations of single species are not particularly stable and are vulnerable to insects and diseases. To avoid these risks and improve the economic value of the vegetation in the enclosure, a mixed tree, shrub and grass multi-layer vegetation community can be developed at an early stage during the enclosure, considering the successional patterns of vegetation and the natural conditions of the enclosed land to increase biodiversity and maintain the ecosystem. In particular, special attention should be given to the role of the perennial semi-shrub community, which comprises many long-lasting species of desert plants which have a significant role in combating desertification.

(iv) Cultivation and intermediate cutting

Cultivation measures, such as increasing soil moisture, irrigation, loosening of soil and land flattening, weed control, fertilization, seedling thinning, leaf removal, trunk fixing and stubble cutting can create a favorable growth environment for natural vegetation and improve plant growth. At the same time, understory trees are felled according to the natural density of the forest. The rangeland, grassland and steppe areas that have flourished can be harvested to accelerate vegetation growth, aimed at achieving quick growth of vegetation and improving the coverage of ground surface. In arid and semi-arid areas, the precipitation is low and variable, and plants lack water in some years. Water storage, irrigation and other water replenishment methods can effectively promote the growth and reproduction of plants.

8.3.3 Appropriate use of vegetation reservation measures

The outcomes of enclosure are directly related to the appropriateness of the enclosure measures. The selection of appropriate enclosure measures should be undertaken following the principles below.

(i) Enclosure and cultivation are closely related

Enclosure is a tool while cultivation is the expected output. Without enclosure, cultivation is not possible; and without cultivation, enclosure will not achieve the desired outcomes. The measures should be adjusted to local conditions.

(ii) Adopt flexible enclosure methods

When the type of enclosure, method of enclosure and cultivation measures are selected, environmental and socio-economic factors should be considered together. The coordination and balance between the type and method of enclosure and cultivation measures should be taken into account.

(iii) Proper opening the enclosed area and reasonable use

The vegetation within enclosure needs many years to achieve the desired results. Therefore, the planning and implementation of enclosure measures should consider the interests of local people and manage the issues of firewood collection, animal husbandry and forest by-products properly.

(iv) Strengthen management to protect the enclosure

The establishment and fine tuning of the management system is a key factor in achieving the targets of the vegetation reservation. Regulatory management of the enclosure under legal statutes is a key link for perfecting the management system. Effective management should be consistent with the forest law, grassland law, environmental protection law and local statutes to exercise legal restraint for illegal behavior. Further, the management division between different administrative departments should be specified, and a responsible system of management targets should be implemented, using reward, punishment, supervision, demotion and promotion tools to motivate all management departments. Only regulating the behavior of people can effectively protect the vegetation reservation.

8.3.4 Case studies of vegetation reservation measures in China and internationally

The use of vegetation reservations in China and internationally have proved that these measures have positive influences on the types of vegetation, plant growth, quantity and nature of plant communities and living and environmental conditions of vegetation. However, the degree of influence is subject to the types of vegetation, habitat condition, types of enclosure, reservation methods, cultivation techniques and years of enclosure.

The research of Cheng et al. (2001b) on deteriorated grassland and vegetation reservations (by enclosure with barbed wire fences) in Guyuan, Ningxia on the semi-arid Loess Plateau (Table 8.4) show that:

After 18 years of enclosure, the *Stipa bungeana* steppe community distributed on the semi-shaded slopes and partially sunny slopes of the typical steppe zone have changed a lot. In particular, the succession of the community follows a natural progress, and the establishment of communities and the distribution of companion species are increasingly obvious. The number of species on semi-shaded slope increased by 52%, the height of the grass layer increased by 81.1%, vegetation coverage increased by 60.3% and the biomass of fresh grass increased by 6.2 times. In comparison, on the partially-sunny slopes, the number of species increased by 48.1%, the height of grass layer increased by 84.3%, vegetation coverage increased by 60% and the biomass of fresh grass increased by 7.5 times. The differences in the profiles of the two areas within the enclosure are significant and the two types of communities are stable. In comparison, two types of communities are not significantly different in unenclosed areas, and their community structure is simple and unstable.

Table 8.4 Changes of different plant communities in enclosure of typical grassland belt (Cheng et al., 2001b)

Community types		①				②				③	
Slope direction		NE		SE		N		S			
Years of growth		1982	1999	1982	1999	1982	1999	1982	1999	1982	1999
Enclosure	SQ	6	15	5	13	5	19	3	9	8	18
	C	25	95	20	80	20	65	20	35	20	55
	GLH	10	54	5	55	8	52	5	18	3	9
	GO	750	6,050	500	4,500	550	4,200	550	1,550	750	2,255
Unenclosed area	SQ	5	6	5	6	5	7	3	5	8	9
	C	25	30	20	30	20	30	20	20	20	25
	GLH	9	7	5	6	7	7	5	5	3	9
	GO	700	450	450	430	490	460	500	510	550	420

①: *Stipa bungeana* community; ②: *Stipa grandis* community; ③: *Thymus mongolicus* community; SQ: Species quantity (species·m^{-2}); C: Coverage (%); GLH: Grass layer height (cm); GO: Grass output (kg·ha^{-1}).

The Thymus vulgaris community, which formed after severe deterioration of *Stipa bungeana* steppe community on the typical grassland belt, reveals that with a longer enclosure period, plant growth changes continuously. An enclosure period of 3–5 years in good heat and water conditions is comparable with an enclosure period of 6–8 in poor heat and water conditions. The quantity of species, the height of grass layer, coverage and biomass yield of fresh grass on shaded slopes were increased by 63.1%, 60%, 55% and 5.1 times, respectively, and during the whole procreation period, prominent plants dominate and shape an obvious layer.

Obviously, appropriate enclosure measures are favorable for the rehabilitation and succession of degraded vegetation. Enclosure can optimize the varieties and structure of the plant community, improve the function of the plant community, increase the diversity and stability of the plant community, promote the growth of individual plants, populations and communities and increase the biomass of plants and vegetation coverage on the ground surface.

Enclosure measures can also reduce soil erosion and improve the fertility of soil. The case study conducted by the Binxian County Soil and Water Conservation Testing Station in Ganxian and Yongshou counties of Shaanxi Province shows that sloping farmland can have a runoff coefficient of 71.1% and soil erosion of up to 80.58 $t \cdot ha^{-1}$ while the same slope after enclosure and grassing has a runoff coefficient of 3.6% and soil erosion of only 0.25 $t \cdot ha^{-1}$. That equates to decreases of 94.9% and 97.7% respectively.

Yu et al. (1999) concluded that after two years of manual protection methods used for the enclosure of sandland vegetation from the southeast edge of the Horqin Sandland to Zhangwu County, Liaoning, the organic matters in lowland soils between dunes in the sandland, on dune slope and on dune top were increased by 296.03%, 220.38% and 78.92%, respectively, compared with an unenclosed site. Higher soil fertility accelerates the positive succession of the vegetation, leading to a higher coverage of vegetation in the enclosure zone, more plant species and an increased biomass yield of dry grass by 228.17% comparison with the unenclosed site.

The case studies described above are successful examples of enclosure measures in China for combating desertification and controlling land degradation. International case studies also prove that enclosure measures used for reducing grassland deterioration played active roles in combating desertification and controlling land degradation.

In summary, the specific practices of enclosure and vegetation reservation measures show that these practices provide an important channel for combating desertification and controlling land degradation in arid and semi-arid zones. The principles, techniques and methods used for vegetation reservations play a significant role in improving the eco-environment and biodiversity protection in arid and semi-arid zones.

8.3.5 Limitations of enclosure and vegetation reservation measures and future trends

Enclosure and vegetation reservation measures play an important role in combating desertification and controlling land degradation in arid and semi-arid zones. Despite the effectiveness of these measures there are some limitations in the operability of enclosure measures, mainly associated with weak integration of the eco-environment and the productivity of the vegetation. Enclosure measures should be designed alongside some auxiliary methods, such as economic compensation, ecological migration, changes in production mode and reorientation of the industrial structure. These measures will allow for accelerated improvement of the ecological environment by leveraging economic growth and increasing awareness of the importance of enclosure measures at local levels in the affected forest and rangeland areas.

8.4 Large scale transformation and rejuvenation of natural desert vegetation

Natural desert forests are typical desert vegetation after a long-term history of natural selection since the Quaternary period, these forests, in spite of small area in desert habitats, play an important role in ecological conservation and combating desertification.

8.4.1 Natural desert or sandland vegetation in China

In general, the natural desert or sandland vegetation in China is characterized by a decrease in area, sparseness of vegetation cover, simple structures and vegetation degradation.

8.4.1.1 Small trees

Small desert trees are represented by *Haloxylon ammodendron* and *Haloxylon persicum*, which are super-xerophytic leafless small trees with heights of 2–4 m or more, and undertake photosynthesis through small green branches. The area of the small desert tree is about 12,000,000 ha, of which 68.1% is located in Xinjiang, covering 9% of the total desert area of China.

The *Haloxylon ammodendron* is mainly located in the Junggar Basin, the eastern part of the Tarim Basin, the Hashun Gobi, the Nuomin Gobi, the Alxa Upland, the Qaidam Basin and the western part of Inner Mongolia. The distribution zone of *Halloxylon persicum* is relatively limited, and it is mainly found in the Gurban Tonggut Desert in the Junggar Basin, in the desert area to the east of Aibi Lake, and some other sandy areas alongside riverbanks in Xinjiang (Table 8.5).

The hard trunk of *Haloxylon ammodendron* makes excellent firewood, and the fresh branches are good fodder. The desert *Cistanche* parasitizes the roots of *Haloxylon ammodendron* in desert, and is rare medicinal herb. In recent years, because of activities such as the undue collection of fuelwood, overgrazing and medicinal herb collection, *Haloxylon ammodendron* has become severely degraded. It is reported that *Haloxylon ammodendron* covers only 32% of its original coverage areas of the Junggar Basin, based on the results of an aerial survey.

It has also been noted that while a research report from the Institute of Desert Research, Chinese Academy of Sciences shows that the spacing between *Haloxylon ammodendron* plants in Ejina Banner was 2–3 m, the current spacing has actually widened to more than 10 m. In addition to the increasing plant spacing, the plant area has typically been reduced and the natural regeneration of young plants is getting worse (Huang, 2000).

Table 8.5 Distribution of the desert small trees and shrubs in western provinces of China

Type of the desert small trees and shrubs		Inner Mongolia	Xinjiang	Qinghai	Gansu	Ningxia	Shaanxi	Tibet
Small trees	*Haloxylon ammodendron*	*	*	*				
	Haloxylon persicum		*					
Shrubs	*Ephedra przewalskii*	*	*	*	*			
	Zygophyllum xanthoxylon	*	*	*	*			
	Nitraria sphaerocarpa	*	*		*			
	Nitraria tangutorum	*						
	Nitraria roborowskii	*	*	*	*			
	Gymnocarpos przewalskii	*	*					
	Calligonum roborowskii		*					
	Ammopiptanthus mongolicus	*			*	*		
	Potaninia mongolica	*				*		
	Tetraena mongolica	*				*		
	Helianthemum songaricum	*	*					
	Caragana korshinskii	*						
	Caragana tibetica	*						
	Calligonum mongolicum	*	*	*				
	Calligonum leucocladum		*					
	Calligonum rubicundum		*					
	Calligonum alaschanicum	*						
	Ammodendron bifolium		*					

* distribution area

8.4.1.2 Shrubs

Desert shrubs are the typical zonal vegetation in arid areas of China, especially in the desert sub-regions in Central Asia. Chinese desert shrubs have rich varieties of plants with complex structures. These community structures can be classified into 19 groups according to the dominant shrub species in the plant community (Table 8.5). In recent years, due to the effects of excessive cutting and overgrazing, degradation has occurred to varying degrees on the desert shrubs.

Ephedra przewalskii is mainly found in the Alxa Upland, the Hexi Corridor in Gansu Province, the Qaidam Basin, the Hashun Gobi, and the Gobi on the edge of the Tarim Basin as well as in the Junggar Basin.

Zygophyllum xanthoxylon is mainly found in the Alxa Upland, the Hexi Corridor in Gansu Province, the Nuomin Gobi, the northeastern part of the Qaidam Basin and over the stony low-relief terrain in the eastern part of the southern slopes of the Tianshan Mountains. *Zygophyllum xanthoxylon* is also found in the Erlian Gobi in Central Inner Mongolia Plateau, and on the Ordos Plateau.

Nitraria sphaerocarpa is widely found in the Alxa Upland, the Hexi Corridor in Gansu Province, the Hashun Gobi in Hami and the Tarim Basin.

The bushlands of *Nitraria tangutorum* are widely distributed in the southeastern areas of the desert region, concentrated mainly in the central and western parts of Ulan Buh Desert, in the eastern area of the Alxa Upland, and extending westward into the valley terraces in the desert areas of northern slopes of the Kunlun Mountains.

Ammopiptanthus mongolicus is mainly found on the gravelly piedmont alluvial fans and the low rocky mountain and hilly regions from the eastern Alxa Upland to the western Ordos Plateau.

Potaninia mongolica is mainly found on the gravelly piedmont alluvial fans and the low rocky mountain and hilly regions from the eastern Alxa Upland to the western Ordos Plateau.

Hedysarum laeve is mainly found on the gravelly piedmont alluvial fans and the low rocky mountain and hilly regions from the eastern Alxa Upland to western part of the Zhuozi Mountains.

Helianthemum songaricum is mainly found on the gravelly piedmont alluvial fans and the low rocky mountain and hilly regions from the eastern Alxa Upland to the western Ordos Plateau.

Caragana tibetica is mainly found on the northeast Alxa Upland, the eastern area of the Tengger Desert and the eastern slope of the Zhuozi Mountains to the west of the Ordos Plateau.

Caragana microphylla is mainly found in the eastern Alxa Upland and the western area of the Ordos Plateau.

Calligonum spp. are widely found from the Tengger Desert and the Badain Jilin Desert to the east, westward via the Hexi Corridor in Gansu Province, the west Gobi and the Hashun Gobi to the northeastern area of the Tarim

Basin and the Qaidam Basin.

Other varieties of *Calligonum* spp. are mainly found on fixed and semi-fixed dunes in the desert areas of Inner Mongolia, Xinjiang and Qinghai.

8.4.1.3 Semi-shrubs and small semi-shrubs

The semi-shrubs and small semi-shrub are the most widely distributed vegetation type in temperate zones, and are usually associated with the distribution of small trees and shrubs, and are found on gravel Gobi, denuded tablelands, loamy plains, deserts, and stony and loess hills. The semi-shrubs and small semi-shrubs can be further divided into halophytic semi-shrubs and small semi-shrub, succulent halophytic semi-shrubs and small semi-shrub, and semi-shrubs and small semi-shrubs, comprised of *Artemisia* spp., depending on the species composition. Although these semi-shrubs and small semi-shrubs have simple species compositions, they have obvious dominant species, forming different plant community types (Table 8.6). In recent years, due to human activities, such as over-collection of fuelwood and overgrazing, the desert semi-shrubs and semi-shrubs have been degraded and are disappearing in some areas.

(i) The halophytic semi-shrub and small semi-shrub

Reaumuria soongarica is one of the most widely distributed zonal vegetation types in the desert areas of China. It is distributed in the east, from the west of the Ordos Plateau, via the Alxa Upland, the Hexi Corridor in Gansu Province, the Qaidam Basin, and the Hashun Gobi, to the Junggar Basin and the Tarim Basin. This area includes the major habitats of mountains, hills, denuded monadnocks, piedmont diluvial plains and piedmont gravelly alluvial fans. This species is also found sometimes on severely saline areas.

Ceratoidess latens is widely found across the Junggar Basin, the southern slopes of the Tianshan Mountains, the northern slopes of the Kunlun Mountains, the western mountainous areas of Ali in Tibet, the western area of the Qaidam Basin, the Helan Mountains in the east of the Alxa Upland, the piedmont plains of the Langshan Mountains, and the gravel Gobi in central Alxa.

Sympegma regelii is widely found on the southern slopes of the Tianshan Mountains, the northern slopes of the Kunlun Mountains, the Hashun Gobi and the Tengger Desert on a common habitat of stony hillsides and denuded monadnocks.

Salsola collina has a small distribution area, while *Salsola passerina* and *Salsola abrotanoides* are comparatively widely distributed.

Anabasis brevifolia is mainly found in Xinjiang, while *Anabasis salsa* is one of the common zonal desert plants in Xinjiang.

(ii) The succulent halophytic semi-shrub and small semi-shrubs

These plants are mainly located on highly salinized soil in lacustrine plains, river banks, alluvial fan edges and some lowlands. *Halocnemum strobilaceum* is widely distributed over the piedmont plains at the south foot of the Tian-

Table 8.6 Distribution of semi-shrubs and small semi-shrub and matrix-shaped shrubs in the western provinces of China

Types of natural semi-shrubs and small semi-shrub and matrix-shaped shrubs			Inner Mongolia	Xinjiang	Qinghai	Gansu	Ningxia	Shaanxi	Tibet
Semi-shrubs and small semi-shrubs	Halophytic semi-shrub and small semi-shrubs	*Reaumuria soongarica*	*	*	*	*	*	*	
		Ceratoides latens	*	*	*	*	*		*
		Salsola passerina	*			*	*		
		Salsola laricifolia	*						
		Salsola abrotanoides	*	*	*	*			
		Salsola arbuscula			*		*		
		Sympegma regelii	*	*	*	*	*		
		Iljinia regelii		*					
		Nanophyton erinaceum		*					
		Anabasis aphylla		*					
		Anabasis salsa		*					
		Anabasis brevifolia	*	*					
	Succulent halophytic semi-shrub and small semi-shrubs	*Halostachys caspica*		*					
		Halocnemum strobilaceum		*					
		Atriplex cana		*					
		Suaeda microphylla, *Suaeda physophora*		*					
		Kalidium schrenkianum		*					
		Kalidium cuspidatum							
Artemisia spp. semi-shrubs		*Artemisia sphaerocephala*	*				*		*
		Psammochloa mongolica							
		Artemisia desertorum	*	*	*				
		Artemisia santolina		*					
		Artemisia terrae-albae		*					
		Artemisia boratalensis		*					
		Artemisia kaschgarica		*					
		Artemisia nanschanica		*					
		Brachathemum gobicum	*						
		Asterothamnus centrali-asiaticus	*	*					
		Ajania fruticulosa							*
		Ajania pallasiana fruticulosa (Ledeb.)	*					*	
Matrix- shaped small semi-shrubs		*Ceratoides compacta*		*	*	*			
		Ajania tibetica		*					
		Artemisia rhodantha		*					

*distribution area

shan Mountain, the Lop Nur Lake basin, the Arjin Mountains piedmont plain, marginal regions of the Turpan Basin and the Manasi lacustrine plains in northern Xinjiang. *Kalidium culpidatum* is a special plant in Inner Mongolia, Xinjiang, Shaanxi and Gansu, and is widely distributed on the salinized lands of low lakesides in desert areas.

(iii) The *Artemisia* spp. semi-shrubs

Artemisia sphaerocephala and *Psammochloa villosa* are the most widely distributed varieties on the mobile sand dunes of the Alxa Upland from the middle of the Badain Jilin Desert in the west to the Ulan Buh Desert in the east. There are also fragmented areas in Shaanxi, Ningxia and Tibet.

Artemisia nanschanica is a specific variety found in the Kunlun Mountains.

Artemisia kaschgarica is mainly found in the Yili Valley, the Tacheng Basin in Xinjiang and over the southern and northern slopes of the Tianshan Mountains.

Artemisia boratalensis is mainly found on the foothills of the northern slope of the Tianshan Mountains and low mountains ranges.

Artemisia intramongolica is mainly found on the desert areas in Xinjiang with a fragmentary distribution in Inner Mongolia and Qinghai.

Artemisia santolina is mainly found in the desert areas in Xinjiang.

Artemisia terrae-albae is mainly found in the desert areas in Xinjiang

Ajania pallasiana is mainly found in the Langshan Mountains in the eastern part of the Alxa Upland and in the gravel Gobi region and fixed dune areas at the foothills of the Helan Mountains.

Ajania fruticulosa is mainly found in the Langshan Mountains in the eastern part of the Alxa Upland and in the gravel Gobi region and fixed dune areas at the foothill of the Helan Mountains.

8.4.1.4 Matrix-shaped small semi-shrubs

It is a typical vegetation type with tolerance to extremely cold and arid conditions mainly located in the continental plateau climate zone, concentrated in the inland mountainous areas of the Kunlun Mountains, the northwest of the Qinghai-Tibetan Plateau and Pamirs Plateau with three major varieties (Table 8.6). This type of shrubs has also been affected by human activities, such as overgrazing and medicinal herb collection and the matrix-shaped small semi-shrub bushlands have deteriorated to a severe degree.

Matrix-shaped *Ceratoidess latens* is mainly found in the lacustrine basin, sloping terraces and the stony slopes on the lower hillsides between the Kunlun Mountains and the Karakoram Mountains. This species is also found around the lake basin areas to the north of the Qiangtang Plateau, over the alpine belt of the Aljin Mountains and in the western areas of the Qilian Mountains.

Ajania tibetica is mainly found in the inland mountainous areas of the Kunlun Mountains in Xinjiang, on the mountainous uplands between the Karakoram Mountains and the Kunlun Mountains and over the alpine belt of

Pamirs Plateau, cutting across plantings of matrix-shaped *Ceratoidess escens* but with a narrower distribution.

Artemisia rhodantha is only distributed in the mountainous regions of the Pamirs Plateau, where the altitude ranges from 3,900–4,200 m.

8.4.1.5 Natural forests on sandlands

These natural forests are coniferous forests and broadleaf tree forests formed with medium to large phanerophytes as the dominant species on the sandlands in grassland and rangeland regions. The typical natural forests in sandlands are the forests of *Pinus sylvestris* var. *mongolica* in the Hulun Buir Sandland, and the forests of *Pinus tabulaeformis*, *Picea mongolica*, *Ulmus pumila*, *Betula platyphylla* and *Populus davidiana* in the Horqin Sandland and the Otindag Sandland.

The forests of *Pinus sylvestris* var. *mongolica* in sandlands are mainly found in the eastern part of the Hulun Buir Sandland, the middle reaches of the Hailaer River (from Wangong to Heerhongde), over the fixed dunes along the branch of the Yimin River (Honghuaerji), in the Huihe River valley, upstream of the Halaha River in a sand-break 13–14 km long and 2 km wide and along the river banks between Cuogang and Wangong. Several thousand individual *Pinus sylvestris* var. *mongolica* trees (4,632 in total) grow in the Hailaer National Park, and a sand-break 150 km long and 10–20 km wide was established on Honghuaerji sandland. *Pinus sylvestris* var. *mongolica* typically grows 7–16 m high with a trunk diameter of 20–22 cm and a canopy density of 0.4–0.6. At present, other than in the Hailaer National Park, the forests of *Pinus sylvestris* var.*mongolica* have been degraded forming sparse forest stand with patches of jungles, where single plants or several plants grow sparsely and some areas are covered by mobile dunes mainly due to the influence of livestock and human activities. When damaged by human activities or bushfire, the forests of *Pinus sylvestris* var. *mongolica* in sandland areas will degenerate into meadow, grassland or bushland of *Betula platyphylla* and bushland of *Populus davidiana*. The recovery of the natural community requires a long period of time often measured in centuries.

Picea mongolica forests are mainly distributed in the sandland of the Baiyinaobao Natural Reserve in the Keshiketeng Banner at the eastern margin of the Otindag Sandland. This forest covers an area of 6,700 ha, which is the largest, most concentrated and most representative area of *Picea mongolica* in China. In addition, a small area of forest is located in the Wulasutai Ranch in the upstream reaches of the Xilin River in a simple community of 2 ha, where the *Picea mongolica* is the dominant plant. *Picea mongolica* has a typical height of 15–17 m, a trunk diameter of 20–40 cm and a canopy density of 0.2–0.7. At present, due to the influence of livestock and human activities, the forests of *Picea mongolica*, and on shady slopes are in danger of being gradually replaced by forests of *Populus davidiana* and *Betula platyphylla* and shrubs and will be turned into steppe desert. The forests of *Picea mongolica* on sunny slopes are gradually being replaced by grassland and covered with mobile dunes. The recovery of degraded forests requires centuries.

Pinus tabulaeformis forests in sandlands are mainly distributed over the fixed dunes at the edge of the eastern part of the Otindag Sandland in Xilinguole League, Inner Mongolia, and the sandland areas of Chifeng City, Songshu Mountains, Huanggang Mountains and Dajuzi District. The *Pinus tabulaeformis* forests in the Songshu Mountains, in Wengniute Banner, cover the largest area about 200 ha. In addition, in Shunjinzi and Baiyingkulun, Bahanaer Banner, Xilinguole League, there are two stands of *Pinus tabulaeformis* forests with about 80 plant varieties. The structure of the plant community is simpler and the typical height is 5–13.5 m with a trunk diameter of 17–80 cm. When *Pinus tabulaeformis* forest is destroyed, the vegetation on the sunny slopes will be degraded forming *Quercus mongolica* and *Pinus koraiensis* forest which, after further degradation, will be covered by *Quercus mongolica* forest and *Armeniaca sibirica* shrub. The forests on the shady slopes are degraded, forming *Populus davidiana* (*Betula platyphylla*) forests or *Ostryopsis davidiana* bushland.

8.4.2 Role of natural desert or sandland vegetation

The natural desert or sandland vegetation are the representative plant communities in different habitats in arid and semi-arid zones and they are the result of natural succession processes during the geological history of the area and also the result of plant adaptation to arid habitats since the Quaternary period. Under the lasting threats of the extreme habitats, nature desert or sandland forest have formed various biocoenosis skeletons in the desert or sandland ecosystem through its unique adaptive form and special survival mechanisms. These have laid the material and environmental foundations for the biodiversity of the desert or sandland ecosystem which allows for the sustainability of the desert or sandland ecosystem.

During the long process of combating desertification, natural desert or sandland vegetation has occupied a leading position and have played a very important role. First, although the natural desert or sandland forests have a narrower variety of plant species, this community as adapted to the extremely harsh environment and has played an important role in combating natural hazards such as blown sand and stabilizing the habitats in arid and semi-arid areas. Second, the low vegetation coverage of the natural desert or sandland vegetation from low prostrate thickets growing over the surface is advantageous for changing the physical conditions of the surface layer, and plays an important role in maintaining the stability of the desert ecosystem. The natural desert or sandland forests provide habitat and fodder supplies for animals and animalcules in the desert or sandland areas and form natural windbreaks for under-story grass communities which preserve and enrich the biodiversity in desert or sandland areas. In addition, the survival of natural desert or sandland vegetation relies on natural water resources rather than artificial irrigation.

Sand stabilization is an important function of the natural desert or sandland forests in combating desertification. For example, the branches of *Tamarix* spp. may block the blown sand so that sand accumulation phenomenon occurs around the plant community. In the areas with rich sand sources, sand mounds can grow gradually along with the growth of the plant community. The plants can grow widely along with the accumulation of sand mounds when there is an increase in the moisture of the sand soils. Sometimes, the accumulated sand mounds around *Tamarix* spp. can be as high as 30 m. These *Tamarix* spp. sand mounds can effectively block shifting sands and fix mobile dunes (Huang, 2002).

Reduction of wind velocity is another significant function of the natural desert or sandland forests in combating desertification. It was reported by Wang (1985) that, due to friction, when trees, shrubs and grasses covering the sand surfaces form dense and green woods, they can reduce wind velocity, and even stop the prevailing wind. The intensity of the reduction in wind force is directly proportional to the intensity of wind speed — when the wind speed is higher, the reduction in intensity is also higher. The *Pinus sylvestris* var.*mongolica* plantations in sandland can reduce wind speeds by 39.2–61.1% at a distance of 50 m from the edge of the plantations, and by 78.4–81.2% at a distance of 80 m away from the edge of the plantations.

Improvement in the physical and chemical properties of sandy soils is the major indirect function of natural desert or sandland forests. This occurs because when shifting sands are fixed by plants, the proportion of the coarse sand will be reduced and the proportion of dust sand and clay will be increased. The permeability and the water-holding capacity will be changed so that the rainfall will not be infiltrated as rapidly as occurs in the shifting sands areas. Instead, the precipitation is retained in the soil for some time at a certain depth, which allows the plants to make full use of the limited moisture. In addition, when the shifting sands have been fixed by plants, the pH value of the sandy soil will increase, and the nitrogen and potassium concentrations in the soil will also increase slightly due to the accumulation of salinity (Table 8.7).

Table 8.7 pH value, humus content, total nitrogen and total potassium of five plants in fixed-sand areas at 0–40 cm soil layer

Site	Latin name	pH	Humus (%)	Total Nitrogen (%)	Total Potassium (%)
Sand-fixed areas	*Salix gordejevii*	6.8	0.359	0.0657	4.913
	Artemisia spp.	6.8	0.281	0.0540	4.076
	Lespedeza bicolor	6.9	0.370	0.0546	3.741
	Caragana microphylla	6.8	0.345	0.0530	3.534
	Hedysarum laeve	6.8	0.486	0.0546	3.742
Shifting sands area		6.6	0.269	0.0434	2.860

Improvements to habitat conditions (moisture and soil quality) are beneficial for the growth and regeneration of desert or sandland vegetation, thus improving the ability of vegetation to reduce wind speed and control sand movement.

8.4.3 Technology for the rejuvenation of natural desert or sandland forests

The rejuvenation of natural desert forests aims to improve the growth conditions of the desert or sandland vegetation by artificial cultivation and maintenance measures to increase the canopy density and the productivity of the vegetation, thus enhancing the ecological services and economic benefits of natural desert or sandland forests. The maintenance and cultivation measures mainly include closed tending, reseeding, irrigation, fertilization, eliminating tillage, thinning, field planting, stumping and pruning.

8.4.3.1 Solutions and technology for restoring natural desert forests

The restoration of natural sandy desert forests involves adjusting the tree species composition of some forest stands with low-effectiveness in the forest structure, to increase forest density and therefore improve the capacity for windbreaks, sand-breaks and water/soil conservation. This, in turn, will increase the productivity, quality and economic value of the forest stand. Artificial methods such as tending and thinning can promote the rejuvenation of the natural desert forests.

The objectives for the restoration of natural sandy desert forest are focused on the following forest and bushland types: low-value brushwood with lower ecosystem services and less cultivation value for the future; open woodlands with low canopy density and low water conservation capacity; bushland with low natural productivity and less cultivation value; dilapidated and ruined forests with unhealthy natural rejuvenation; and multi-generation coppiced forests with a decline in growth, lower ecosystem services and less cultivation value.

Generally, the approaches and methods for improving forest stands are aimed to promote artificial desert forests and allow them to develop following the natural succession rules for the natural desert forest, and to heighten their productivity. Depending on the objectives of the rehabilitation, rehabilitation types can be divided as follows.

8.4.3.2 Restoration of sparse forests

In sparse forests with low canopy densities (generally lower than 0.3) and low growth, shade-tolerance tree species shall be selected to be planted under the canopies, so that the newly planted tree species can grow under the protection of the canopy. As the young plants achieve stable growth, the taller trees can be gradually cut based on the sunlight requirement of the young plants. It is also possible to select cutting methods along the horizontal belt of the mountainous to contour and plant the forests with sound tree species. The width of the horizontal mountain belt depends on the site conditions and the biological characteristics of the tree species — the mountain belt will be wider for light-loving tree species or bushland with good site conditions, but narrower for steep forest areas. Generally, the width of the preserved belt should be equal to the height of the forest stands and the selected cutting belt shall be 1–1.5 times the preserved belt, which allows for the maintenance of the forest environment to promote the growth of the young trees.

8.4.3.3 Restoration of residual forests

The restoration of residual forests mainly involves cutting off old and rotten wood, wind-broken trees and poorly formed trees, while preserving the large shelter trees, young trees and shrubs with small to medium diameters and good cultivation value. This process also involves reseeding and transplanting in the sparse areas and the forest gaps to transform the residual forests into mixed forests.

8.4.3.4 Cultivation of mixed forests

Generally, the stability of mixed forests is stronger than that of mono-culture forests. Therefore, when improving the eco-efficiency of natural forests, the restoration of forest stands should adopt a multilayer stereoscopic planting model combining trees, shrubs and grass to fully exploit the economic benefits of natural forests (Zhang and Runge, 2006).

8.4.4 Integrated application of preventive measures and techniques for revegetation

To combat desertification, proper measures for the prevention of vegetation degradation and control of vegetation must be adopted in accordance with the local conditions. The selection of appropriate measures such as enclosure, vegetation cultivation, artificial reforestation, grass plantation and regeneration and rejuvenation of natural desert or sandland forests, should be made on the basis of forest conditions, vegetation varieties, type of vegetation utilization and actual vegetation use. The principle of appropriate trees or grass for suitable land, should be used to when enclosing those areas that are suitable for planting. Vegetation prevention and control techniques should be adopted when possible in areas with favorable conditions. Under suitable conditions, different techniques and measures should be applied to implement multiple effects such as combining trees, shrubs and grasses, allowing balanced developments of agriculture, forestry and animal husbandry and providing equal attention to ecological servicing and economic benefits.

8.5 Principles and technology for establishing oasis shelterbelts

The vast areas in the northern part of the Qinghai-Tibetan Plateau and the southern part of the Helan Mountains are part of the temperate desert zone, where the plains and basins have an arid desert climate with large scale and expanding sandy deserts, Gobi and gravel deserts. Due to the inclement habitat in the deserts, animals and plants are sparsely distributed and rare with a low bio-productivity. The oases are scattered around the edge of the deserts and Gobi and in the low swamp flatlands among them, and these provide the base for agricultural production and most of the positive biological activities in the desert. The oases also form the land with the highest productivity in the deserts, and support the complex areas of desert forests, farmland and steppe which centered around water and maintain the livelihood of people living in the deserts.

Oases are widely found in deserts and Gobi all over the world. The oases in the deserts are unique natural and geographical landscapes in the arid zones. They are often threatened by wind and sands, drought and salinization. Consequently, it is essential to establish, strengthen and enlarge the oases with stable, high levels of production, to reasonably protect and increase the productivity of the deserts, as this is a key for combating desertification and developing agricultural production in desert areas. The research and experiments of recent years have proved that establishing a complete protective system is the most effective means for maintaining the eco-system of new and old oases and controlling blown sand disasters. Water can also be used appropriately for the development of agricultural production in arid areas.

8.5.1 Necessity of establishing oasis shelterbelts

Oases are the base for human activities in arid areas. As well as existing oases formed in ancient times, many new oases have been established, which provides an important base for the development of production in arid areas. With increasing socio-economic development and population growth since 1949, China places great importance on the development and management of natural resources in arid areas, including exploiting the new oases to enlarge production and improve the economy. The State Production and Reconstruction Farms have made great contributions to improving production and economic growth.

Generally, new oases are located at the end of irrigation water systems in the desert, where soil is infertile and the ecosystem is fragile. Natural disasters, such as blown sand disasters, drought and salinization are the most severe threats to the oases. After fifty years of development, the establishment of all types of oases have become the important bases for the development of industry, agriculture, commerce, and culture, but also helped develop gardens where people can live, work and grow in peace and contentment with a reliable water source and complete protective system. The necessities in the establishment of oases are as follows.

8.5.1.1 Oasis eco-systems are the base for maintaining growth in deserts

Oases are widely distributed in deserts and Gobi all over the world, including the Sahara Desert in Africa, and deserts in Australia, South America, and Central Asia. The tropical, subtropical and temperate oases are found at different geographical locations in the northern and southern hemispheres. Oases are the land resource in desert areas with the highest value uses and the productive bases in arid areas. Oases are important for maintaining lifes in drylands and are called the “shining pearls in the deserts”.

Oases are defined differently in different areas, but are all related to drought, desert and water, that is, they are fertile lands in arid and desert regions with stable irrigation conditions which can support life and sustainable development. According to “Oases in China” by Shen et al. (2001), the oases are the “green islands” or “wetlands” in the vast deserts in Northwest China. Though the areas of the oases account for only 4% of the drylands in Northwest China, they are occupied by more than 90% of the population living in arid zone and more than 98% of the cities and towns in arid zone are located at the oases. The oases in Northwest China formed the brilliance of the ancient Silk Road, and also become the basis of the modern Euro-Asia Continental Bridge, form the frontline of the development of Northwest China and support the sustainable development in dryland areas. The oasis ecosystem relates to the complex system formed by society, economy and natural systems based on the constant cycling of material and conversion of energy between biology and the environment in the oasis.

The basic components of the natural system in the oasis are water, climate, soil, biology, mineral resources and the influence of humans on the environment. Humans are responsible for the oasis economic system, including various sectors, such as agriculture, forestry, animal husbandry, fisheries, commerce and industry, and social systems, as well as the complex interactions between oasis inhabitants, culture, education and public health, socio-economic status, environment and welfare. These factors are limited by material flow, energy flow, information flow but work together to eventually achieve about eco-efficiency, economic benefits and social effects.

In the vast arid desert areas, oases occupy only a small proportion of the area. For example, the oasis areas in Xinjiang only cover 5% of the total area in Xinjiang, but the oasis ecosystem connects with rivers, lakes, swamps and groundwater, and productive activities are mainly based on irrigation (including underground canal system), so that without irrigation, the oases would not exist.

For thousands of years, the oasis ecosystems have been responsible for the economic development and social progress in arid and desert areas. For example, the groups of oases in south Xinjiang, including Kashgar (named Shule in ancient times), Hetian (Khotan in ancient times), Shache and Kuche (Quici in ancient times) and Aksu (Gumuo in ancient times), form the political, economic and cultural centers in Xinjiang. Irrigation channels spread in all directions from these centers, the soil is rich and fertile, there is abundant heat and plentiful snowmelt water resources, and advanced agricultural techniques allow two harvests per year. These old oases are either the key stations and passes on the ancient Silk Road, or important modern bases for agriculture, forestry, and animal husbandry in Xinjiang, where the yield and quality of the cotton is superior and wheat, rice, sericulture and variety of melons and fruits are special agricultural products from this area.

The ancient oases have experienced thousands of years of climate change and human activity, and have influenced a gradually increasing area with flourishing development. In recent decades, large areas of new oases have been established in the Gobi deserts, which have the potential to create wealth reconstruction in the remote countryside, and provide material for the development of industry. This is especially important for the development of oil and natural gas industries after the reconstruction of new and old oases, while the development of industry can promote urbanization and improve the development of the local economy. Historical experience shows that the development of oases benefit from protective systems to resist attacks from all kinds of natural disasters.

The fragility and stability of the oasis ecosystem interact with each other, and are the most important properties in the development and degeneration of the oases. The oasis ecosystem has evolved from the desert, meadow and swamp systems, due to the water-rich habitat. Disturbed by a variety of natural and human factors, the oases are in a changeable and unstable state, especially, the oases that exist in particularly dry environments, surrounded by arid deserts and Gobi. In these dryland areas, the harsh natural conditions such as blown sand, drought and salinization cause land desertification, aridity and long-term degradation of vegetation resulting in the fragility of the oasis ecosystem. Furthermore, the oasis depends on the supply of the water resource.

Water is the first condition that determines the existence of oases, and any changes to the surface runoff regime, rivers, or the exhaustion of water resources caused by both human and natural factors will destroy oases. For example, the ancient city of Loulan in Xinjiang was an important center in the ancient western states some 2000 years ago. It was ruined by wars, a shortage of water resources, natural disasters and human interference, eventually becoming a ruin in the desert and lost forever. In Shajingzi District in Minqin County of Gansu Province, and in Shouchang County, relic sites from the Tang Dynasty near South Lake in Dunhuang County of Gansu Province were once oases with graceful aquatic biology but have now been swallowed by shifting sands.

Oases are the main source of human livelihood and production in arid regions. They are also the system with the most complex structures and the most important services in the desert ecosystem. With sufficient irrigation water, sunlight, temperature differences and favorable soil structure, oases can produce superior quality crops varieties with high productivity. Oases are the important bases for the agricultural production and most of the positive biological activity in the deserts. Therefore, the establishment, stability and improvement of productive oases are keys for developing agriculture and livestock production in the desert areas, and to protect and improve the productivity of deserts and combat desertification.

History experience shows that the oasis ecosystem is fragile and this can be seen in the following aspects.

(i) Unstable water sources

The existence and development of oases are limited by water resources, their quality and distribution, and these factors are key to the size and carrying capacity of the oasis. Research and experiments show that 1 km^2 of oasis will use 5,420,000 m^3 water (Han, 1995). In inland desert regions of Northwest China, oases are mainly located in the areas of piedmont diluvial-alluvial fans, fluvial plains, river deltas, and inland river bank terraces. The water resources of oases are mainly sourced from perennial rivers, rainwater in the high mountains, melt water from glaciers and snow, surface runoff and groundwater. The inland rivers with abundant water volumes can supply sufficient water resources to meet the needs of the oases. However, water supplies downstream of the oasis may be cut off if the river course is changed. The mean annual precipitation in the three northern regions of China (i.e., Northeast China, North China and Northwest China) is 274 mm and the total annual precipitation is 1,070 billion m^3, of which 311.764 billion m^3 forms runoff, river flows and groundwater, accounting for 11% of the total water resources in China.

In the arid desert regions, particularly in the Tengger Desert, the Baidan Jilin Desert, southern Xinjiang, and the Qaidam Basin, annual precipitation varies from several tens of millimeters to 100 mm. Because of this low precipitation, these regions are unsuitable for humans to live in. According to the UN the minimum water resource per person is 1,000 $m^3 \cdot a^{-1}$ which provides the necessities for human existence. The average water resource per capita in Tianjin (153 m^3) and Ningxia (186 m^3) are much lower than the resources of some arid countries, such as Israel (275 m^3) and Saudi Arabia (268 m^3) (Yuan and Zhang, 2001).

With the effects of global warming, the climate of Northwest China is changing from dry and warm during the 19th century (1860s to 1880s) to drier and warmer by the later 1980s (about 1987). The temperature is rising, precipitation is declining, river flows are decreasing, lakes are shrinking and the eco-environment has been deteriorating over the past ten decades (Shi et al., 2002). Over quite a long period, the global climate has been getting drier and warmer, and this is particularly seen in the obvious reduction in precipitation and river flows, which has resulted in a lack of flow in some rivers and the drying up of some lakes. At present, there are more than 60 rivers which have dried up in Inner Mongolia and Western Gansu, and around the desert area of Xinjiang, more than 100 rivers have disappeared. When the Kongque River stopped flowing, 20,000 km^2 of Lop Nor Lake dried up.

Located in the south of Xinjiang, the Tarim River is the largest inland river in China and is linked with all the main water courses around the Tarim Basin and Taklimakan Desert. With a length of 2,137 km^2 and an irrigation area of 1.16 million ha, it cultivates and nourishes all of the medium and large oases along the inland river. In recent decades, with intensive development along inland rivers and the gradual northwards movement of the source rivers of the Tarim River, many of the large or medium water courses that flow into the Tarim River have stopped flowing, and consequently, the eco-environment in the middle and lower reaches of the Tarim River has been degraded. This includes vegetation degradation, land degradation and severe water and soil loss. Meanwhile, upstream areas are overflowing and waterlogging is also causing serious damage and loss of production. In the downstream areas, one third of the rivers have stopped flowing and only one tenth of water volume recorded during the 1930s remains. The water quality is also worse.

Large areas of Poplar forests have been degraded due to water conflicts. The green corridor is under pressure from degradation risks and even disappear due to the low self-generation capacity of Poplars. Forests are severely limited by restrictions in water flow from rivers. Several main oases in downstream areas have shrunk and farmlands are degraded and deteriorated resulting in large numbers of farmers moving and re-settling as migrants in other villages or towns.

From the middle and later period of 1980s, the temperature has been rising continuously. Air temperature in Northwest China during 1987–2000 has increased by 0.7 °C compared with 1961–1986. The 1990s was the warmest decade in the past one hundred year. Comparing the 1960s, 1970s and 1980s, the air temperature has increased from one decade to the next by 0.8 °C, 0.7 °C and 0.5 °C, respectively. Along with the increasing air temperature, the precipitation has also been increasing. The average annual precipitation rate during 1987–2000 increased by 22% in northern Xinjiang, 33% in southern Xinjiang, 12% in the Tianshan Mountains, and 10–20% in some areas of the Qilian Mountains, the central-west Hexi Corridor and the Qinghai-Tibet Plateau when compared with precipitation in 1961–1986. The eastern part of

Northwest China is still influenced by a warm and dry climate, with precipitation rates declining by 5–15%, and thus droughts occurred frequently (Shi et al., 2002).

In areas where the rainfall increased, the hydrological and ecological systems changed accordingly. With an increase in rainfall of over 5% (between 1987–2000 and 1956 –1986), the flows of rivers in Xining, the Hexi Corridor in Gansu, central and western areas of the Qilian Mountains, and southeastern areas of the Qaidam Basin in Qinghai Province began to increase in 1987 with increases typically 20–40%. The increase in precipitation also had a significant influence on inland lakes, such as Bositeng Lake, Aibi Lake and Aiding Lake where the water level has risen continuously since 1987. The area of Aibi Lake has increased from 499 km^2 in 1987 to 1,064 km^2 in 2002, recovering to size measured in 1957. Due to the increase in moisture levels, the vegetation has also increased significantly and the amount of sand-dust storms weather events has decreased. This illustrates the interdependence between the stability of water resources and the functions of oases.

(ii) Harsh natural conditions

Drought, blown sand disasters and salinized-alkalized soils are the three common natural disasters in arid desert areas. Areas around oases are often dry and rainless with high rates of evaporation, and these can lead to frequent blown sand weather events such as sand-dust storms which cause significant damage. Severe sand-dust storms are the main weather disasters in semi-arid regions. These can occur suddenly and affect a large area, causing serious losses to the national and local economies and living environments. For example, Ejina Oasis, a key desert steppe and protective barrier for the Alxa Plateau, is located on the downstream reaches of the Heihe River. During the 1970s, the water consumption upstream of the oasis increased sharply reducing the water flowed into the oasis. By the early 1990s, there was almost no flow of river water into the oasis, and a large area of Poplar, *Haloxylon* spp., Tamarisk and other plants withered and died. The ecological environment declined dramatically, and desertification and sand-dust storms occurred frequently, threatening the livelihoods of local residents, and resulting in abandonment of the desert steppes, and emigration by local herdsmen. Overall, the damage was disastrous to the local people and adjacent communities.

In arid desert areas in Northwest China, there is a large area of salinized land, which was mainly caused by mismanagement of water resources, inappropriate irrigation and evaporation of soil moisture. In the oasis areas, the drainage is poor, the groundwater level is relatively high, and evaporation rates are also high, thus the soil can be easily salinized. Areas downstream of oases, such as lake margins and watershed areas along rivers in arid desert areas are also easily salinized, such as occurred in the large area of secondarily salinized soil in Jiashi (Xinjiang) and the Weiganhe Delta. In areas with serious salinization, no grass or other vegetation will grow and land degradation expands rapidly.

(iii) Damage caused by human activities

The damage caused by human activities is largely related to the following issues.

i) The imbalance between population growth and the supporting capacity of the oasis

As mentioned above, the oasis has the highest productivity in the arid desert areas, but its size is limited by the available water resources. However, the population of oasis continuously increases, eventually exceeding the supporting capacity of the oasis. Consequently, the relationship between oasis, water and population is unbalanced and the system is disordered.

ii) The contradiction between protection and development

The protection and development of oasis should be undertaken on the basis of the sustainability of the environment, supported by scientific knowledge. Protective measures for the oasis should be undertaken with positive targets (rather than negative targets), and the protective measures should be directed toward systematic and scientific initiatives. For example, in areas affected by serious blown sand events, protective measures should include techniques for stabilizing dunes and fixing shifting sands, and for establishing shelterbelt networks with sound planning and best management practices. Any development should be well planned and carried out in a sustainable way.

The Regional Agricultural Planning Office of China conducted a large scale survey in 53 counties of Heilongjiang, Inner Mongolia, Gansu and Xinjiang using satellite images and remote sensing techniques from 1986 –1996. The results showed that grasslands, steppes and desert steppes have been destroyed and degraded in these provinces and autonomous regions in Northern China. One percent of the cultivated lands have been abandoned as wastelands. In total, 1.74 million ha of croplands have been reclaimed for development during the past 10 years, yet the total remaining arable land is approximately 884,000 ha, or 50.4% of the total newly reclaimed croplands. The typical process is that land is reclaimed from the grassland in the first year, some grain is harvested in the second year and then the land is abandoned as wastland after three to five years. When the newly reclaimed grasslands are abandoned, they become desertified lands, which form the sand source areas for sand-dust storms, causing further deterioration.

History experience shows that some large areas of desertification-prone lands and shifting sandlands are closely related to the large scale reclamation of grassland. Since 1949, three large scale projects reclaiming grassland were launched, resulting in large areas of natural vegetation being destroyed. This plunder-like destruction of the grassland vegetation has turned the fixed and semi-fixed sandlands into shifting sandlands or allowed them to be covered by mobile dunes.

Development should be aimed to increase biological production and create maximum property by fully using local natural resources under optimum protective systems. Furthermore, unwise collection of fuelwoods and inappropriate grazing are the main causes of destruction of the ecological balance in the oasis.

iii) Lack of scientific planning and mismanagement

The production structures and land uses on the oases are based on unsustainable planning. In previous decades, a policy of developing food production as an key development goal was practiced nationwide, ignoring the principles of appropriate land use depending on the natural conditions. This unsustainable strategy has created a single structure in oasis production which has caused an imbalance in the oasis ecosystem, sometimes even leading to complete destruction of the oasis ecosystem.

8.5.1.2 Particular characteristics of oasis ecosystems

Oases originated from the desert but are significantly different to the desert. Similarly, the oasis ecosystem and the desert ecosystem are also different. One of the most important differences is the high efficiency production and optimal compound capacity and coexistence of the natural systems in the oasis. For example, the oasis at the foothills of the northern part of the Tianshan Mountains illustrates the nature of the oasis ecosystem.

Oasis is a key component of regional agricultural production and economic development. The area of oasis at the foothills of the northern part of the Tianshan Mountains accounts for 4.5% of the total land area of this region, but holds 95% of the total population. When the external environment was degraded, oasis ecosystem was fragile and the economic system was vulnerable, the internal environment of oasis became salinized, alkalized and degraded due to the use of a single production structure, over-exploitation of groundwater, inappropriate irrigation, pollution of arable soils, deterioration of soil quality, sand movement, and dust and sand-dust storm disasters.

With abundant wildlife resources and valuable genetic resources, the Junggar Desert is unusual compared with most temperate deserts in the world. Due to excessive land reclamation, overgrazing, over-harvesting of fuelwood and medicinal plants, hunting and other human activities, the environment was severely degraded and many species that lived in the desert are under threat. The preservation of the oasis ecosystem, the development and protection of natural resources and the promotion of sustainable socio-economic and environmental development are important responsibilities and missions for mankind.

Characteristics of the oasis ecosystem are in the following aspects.

(i) High production efficiency. Because oases have favorable geographical locations in desert regions, they have better irrigation conditions, soil is relatively fertile and vegetation creates a good microclimate environment. Due to the advantages of water, soil, and other natural resources, oases are the most dynamic and productive systems and have potential for development of agriculture, forestry, animal husbandry, resources development and urban growth. However, this requires the integration of modern science and technology and social and economic resources, to maximize the productive potential.

(ii) Highly complex systems. The oasis ecosystem is a complex system, and through thousands of years of development and long term management, it has become a fertile land for modern people to live on and engage in social and economic activities in desert regions. The oasis ecosystem has formed a complex natural, social and economic system. Although the oasis ecosystem has a highly effective biological productivity, it is also the most vulnerable. The occurrence of desertification, however, is a chaotic process causing an increase in entropy which then feeds back into the desertification process until a relatively stable ecosystem condition is reached through the regulation of various factors in the oasis. There are many difficulties during the development of the oasis, such as land degradation caused by inappropriate land use or mismanagement, which may destroy the oasis. Therefore, these inappropriate activities should be controlled and mismanagement should be corrected through knowledge, best practice and monitoring tools.

(iii) Capacity for natural coexistence. All factors associated with the oasis ecosystem are externally and internally linked to each other, and they interact with each other to maintain the development of the oasis. After thousands of years of management, the factors associated with the ancient oases are closely interdependent because the closed economy in early times and remote locations is only weakly self-sufficient. These factors are limiting and as consequence, these oases have only been slowly developed. Along with the development of science and technology, people have enhanced their capacity to regulate the ecosystem and consequently, the self-development capacity of the oases has been improved, as have the transportation, communication and information links. This has lead to the oases becoming increasingly dependent on the outside world. This development process from a closed system to an open system has enhanced the productivity of the oasis, and enriched and promoted further development.

8.5.1.3 Necessity for establishing protective systems in oasis

In the relationship between humans, oases and the environment, humans play the principal role, the environment is an underlying condition and the oasis is the physical entity. The establishment of a protective system in the oasis is important to reduce outside effects on the ecosystem and enhance the positive feedback cycle.

Oasis protective systems are key components in the oasis ecosystem, and have a far-reaching effect on a series of ecological factors. The protective systems can be aimed at the hydro-thermal imbalance in the ecosystem of desertification-prone land. The processes of production of organic matter consumption of thermal energy can act to block the dynamic power of wind friction in sandy desert area when the hydro-thermal balance and radiation balance increase. The physical activity of the whole system balances the spontaneous increase in entropy and energy loss of materials, and puts the energy and material (including plants, animals and people) in an orderly state. It can also strengthen the order, balance and stability of oases in the desert to allow humans to create a solid energy storage and material foundation that can transform desert areas with low productivity into prosperous areas with a strong agriculture, forestry and animal husbandry production base.

8.5.2 Establishment of oasis protective systems

The establishment of oasis protective systems was initiated one hundred years ago. During the past ten decades, the damage of natural disasters and the difficulties inherent in maintaining a good living environment for people were initially recognized, and then scientific planning and ecological improvement projects were implemented. These projects have involved establishing shelterbelt networks inside oases and desert regions to prevent cities, villages, roads, farmlands and grasslands from damage.

The shelterbelt network system is aimed at preventing degradation and destruction of oases. It involves a complex network system of shelterbelts and tree networks composed of various species of trees, shrubs and grasses, characterized by a particular structure and ecological service. Shelterbelt protection system is an intrinsic integration of natural systems, such as mountains, water, farmlands, forest, rangeland, grassland and steppes, roads, drainage channels and infrastructure developed in accordance with the specific requirements of the local area. In combination with farmlands, cities, settlements and rivers, shelterbelt systems form a complicated and large scale system, which can promote energy and material exchanges, improve the environment, and establish and optimize the ecological model.

8.5.2.1 History of shelterbelt systems around oases

In China, the construction of shelterbelt systems around oases has a long history. It is well recognized that “dwarf grasses can reduce strong wind” and with this simple theory, and of the concept of a “wind barrier” people can create a small area habitat suitable for living. In Northeast China before 1949, and in Xinjiang during the early 1950s, the large scale establishment of shelterbelts and biological protective networks was initiated to prevent desertification.

Over more than 60 years of effort, particularly following the launch of national projects and action programs for establishing shelterbelts and protective forest networks and National Action Program to Combat Desertification (NAP) in China, approximately 24 million ha of artificial forests have been planted and about 933,000 ha of degraded grassland or steppe have been revegetated. About 2.47 million ha of degraded sandlands have been enclosed to allow for cultivating of grasses. The forest coverage in desertification-prone regions has been increased from 5% in the past to 9% currently. It is estimated that 21.33 million ha of farmland and 8.93 million ha of grazing lands have been protected with artificial vegetation. Around 10 million ha of areas affected by soil erosion have been controlled. According to the statistics of the China National Monitoring Centre, mobile sand dunes and shifting sand areas in China have been reduced by 3.22 million ha from 1994 to 1999. It is also estimated that the area of fixed and semi-fixed sandy areas has increased by 4.22 million ha. These efforts and initiatives for combating desertification have achieved great success during the past 60 years.

In China, along with implementation of national projects and the NAP to combat desertification, a nationwide awareness of ecology is well developed and a nationwide campaign to combat desertification and stabilize sand dunes or fixing shifting sands was launched in 1994. Ecological improvement and environmental protection are prioritized as core objective of the Western China Development Strategy and six national projects or national programs on ecological improvement have been formulated and launched. On June 25th, 2003, the State Council of China issued the Solution on Promotion of Forest Development, which has provided a new guideline for forest development and ecological improvement and set new milestones for the projects to combat desertification.

8.5.2.2 Establishment of oasis shelterbelt systems

Oases are the core region of farmland, forest, rangeland, grassland and steppe production in arid and semi-arid areas, and are the regions with high biology productivity. However, oases are surrounded by a harsh natural environment, and are often affected by severe winds, sand-dust storms, drought and salinization, which cause instability and imbalance in the oases. Consequently, oases need sound management for maintaining their existence and development. The protective systems for oases include biological measures (including protective forest networks, shelterbelt systems) and non-biological measures. This section focuses on the shelterbelt systems, in accordance with the research achievements of Ci Longjun and the Xinjiang Forest Research Institute, which were honored at the First National Conference on Science in 1978(Ci,1980).

Shelterbelt systems and protective forest networks around oases are complex systems composed of shrub and grass belts which form windbreaks and sand-breaks at the peripheries of oases, the sand-breaks beyond the outskirts of the oases and shelterbelts and tree networks around the farmlands, settlements and along roads and irrigation canals. Shelterbelt systems and protective forest networks are integrated and complex forms composed of various tree networks and farmland protective forest belts, which consist of various species of trees, shrubs and grasses. Usually, protective forest networks and shelterbelt system around oases comprise 3–4 components (Fig. 8.3).

The sandland and wasteland areas located on the windward side of the oases, are the sand sources and forward peripheral areas for sand invasion of

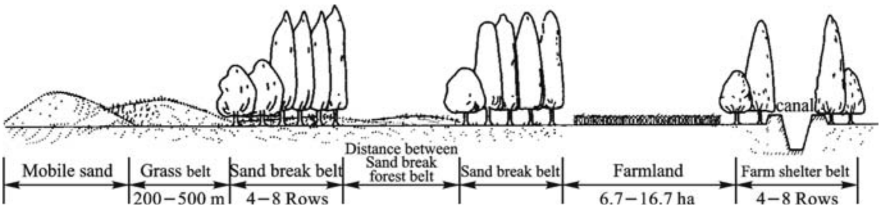

Fig. 8.3 Diagram of the composition of oases protective networks and shelterbelt system (Ci,1980, with permission from author)

the oases. These sandland and wasteland areas are neighbors to the deserts and Gobi with a harsh habitat. To control the locally sourced blown sand and block sand invasion from outside of oases, shrub and grass belts of a certain width should be planted in front of the protective forests networks to increase the coarseness of the land surface, to decrease wind speed at ground level, to control the dynamic spread of sand drifts, to prevent topsoil from eroding, to stabilize shifting sands and reduce denudation, and to stop sand movement.

8.5.3 Function of oasis protective windbreak systems

8.5.3.1 Farmland protective forest network

(i) Impacts of farmland protective forest network on local climate

The local climate is a sub-set of the macroclimate. In addition to being influenced by atmospheric circulation, the effects of geomorphology and geographic latitude, surface conditions and local topography changes are important factors in the formation of the local climate. Table 8.8 shows the impacts of farmland forest networks to local climate in Hetian County of Xinjiang.

Table 8.8 Local climate change in Hetian Oasis, Xinjiang

Years	AMT	MTJA	MTJU	HMT	LMT	FFP	AMRU	AP	AE	AMWV	YGW
1970–80	12.4	–5.4	25.6	39.1	–15.6	232.3	40.0	30.0	2,704.6	2.2	5.8
1988–92	12.4	–3.4	25.1	38.1	–13.6	232.6	44.8	46.2	2,662.9	1.3	2.2

AMT: Annual mean temperature (°C); MTJA: Mean temperature in January (°C); MTJU: Mean temperature in July (°C); HMT: Mean of highest recorded temperature (°C); LMT: Mean of lowest recorded temperature (°C); FFP: Frost-free period (days); AMRU: Annual mean relative humidity (%); AP: Annual precipitation (mm); AE: Annual evaporation (mm); AMWV: Annual mean wind velocity ($m \cdot s^{-1}$); YGW: yearly⩾8-grade wind (days).

It can be seen from Table 8.8 that, following the establishment of farmland protective forest networks evenly distributed across the whole oasis, the annual mean wind velocity decreased from $2.2\ m \cdot s^{-1}$ to $1.3\ m \cdot s^{-1}$, which equates to a 40% drop in wind velocity. Days with a wind force $\geqslant 8$ on the Beaufort scale decreased from 5.8 days to 2.2 days per year, representing a decrease of 62%.

The farmland protective forest networks and green vegetation coverage of the oasis have reduced the solar radiation reflectivity and increased the absorption rate of solar radiation. The decrease in wind velocity has weakened the dry and hot air current exchange between oases and deserts and reduced strong evapotranspiration rates of crops inside the oases. Additionally, the farmland forest networks are effective in retaining the water vapor in the oasis. All of these factors have changed elements of the local climate. The annual mean temperature and frost-free period are basically the same, but the monthly mean temperature in January increased by 2.0°C, the monthly mean temperature in July decreased by 0.5°C, and the annual temperature difference decreased by 2.5°C. The mean value of the highest recorded annual temperature decreased by 1.0°C, while the mean value of the lowest recorded annual temperature increased by 1.6°C. The annual precipitation increased by 16.2 mm, and the annual evaporation potential decreased by 41.7 mm. These data show that when the farmland protective forest networks were established, the local climate of Hetian Oasis was changed in a favorable environmental direction for farmland production and human livelihoods (Liu and Liu, 1998).

(ii) Effects of farmland protective forest networks on sandy desertification

Using remote sensing techniques, research and observations on land degradation and desertification processes have been conducted on an area of 2×10^4 ha inside and at the periphery areas of the Hetian Oasis. The results show that when the farmland protective forest networks were established and local climate improved, the number of plant species increased as did the quantity of the vegetation around the Hetian Oasis which had obvious effects on the prevention and control of desertification.

From 1974 to 1983, along with the establishment of farmland protective forest networks and the effective performance of these protective systems, the total area of land affected by desertification in the study area was reduced by 1,211.9 ha (or 20.3%), of which, the area of severely desertified land was reduced by 161.4 ha (76.06 ha inside the oasis and 85.34 ha at the periphery of desert), the area of moderately desertified land was increased by 47.47 ha (46.39 ha inside the oasis and 1.08 ha at the periphery of desert), and the area of slight desertified land was reduced by 1,197.94 ha (911.4 ha inside the oasis and 286.54 ha at the periphery of desert). Note that the increase in area of the moderately desertified land inside the oasis was mainly the result of the rehabilitation of the severely desertified land (Cui and Liu, 1990).

(iii) Improvement of eco-environment conditions of farmland

i) Effectiveness of farmland protective forest networks in controlling wind

Research data in China and internationally show that the effectiveness of a single protective forest network to control wind is related to the structure of the protective forest network. When the farmland protective forest networks are established, the inherent nature and structure of the protective forest network will remain. However, the effectiveness of the protective forest network to control wind is mainly determined by the spacing between the protective forest networks and sand-breaks (Table 8.9) (Ci, 1980).

Table 8.9 Effectiveness of the main protective forest networks with different spacings to control wind

Spacing between main protective forest networks (m/H*)	70/10	92/14.2	175/21.8	250/29.8	400/35
Reduction of mean wind velocity inside main protective forest networks (%)	52.8	50.2	38.4	29.8	25.0

*H means the average height of the forest networks in meters, used similarly in the remainder of the chapter.

With respect to the systematic weather processes, the kinetic energy from air flows consumed by the protective forest networks is insignificant. It is the obstruction of the protective forest network that causes the air flow to rise and changes the flow structure of the air current, consequently, reducing speed of the air currents within a certain height of the ground. It can be seen from Table 8.9 that the effectiveness of small networks size is more significant than that of large networks size. For instance, the ground wind speed inside the small networks size with a spacing of 70 m/10H can be reduced, on average, by 52.8%, while the ground wind speed inside the large networks size with a spacing of 400 m/35H is reduced, on average, by only 25%. The effectiveness of small networks size is more significant than large networks size, and this is closely related to short spacing between the main tree belt, as strong winds will be immediately blown into next tree belt before wind speed recovers in open fields. It can be concluded, therefore, that the spacing between the main tree belt is the key factor in the effectiveness of forest networks. Conversely, if the spacing between the main tree belt is too large, then the wind speed recovers across open fields, and is not reduced as much.

Although shorter spaces between main tree belt, provides for greater effectiveness, these networks will occupy more land area. Thus, a reasonable spacing between the main tree belt should be designed according to the intensity of the sand disasters and the height of tree species in different regions.

To understand the wind regimes in different parts of an oasis with protective forest networks, ground observations were conducted at observatory stations installed in different parts of the oasis with established protective forest networks during the spring season when the weather conditions are warming. It can be seen from the results that from the periphery to the center of the oasis, the wind speed decreased under the protection of multiple farmland protective forest networks, and that the reduction of wind speed close to the ground surface is larger than the reduction in wind speed above ground. It is observed that at a height of 4 m above the ground, the wind speed decreased by 26.8 –39.2%, at a height of 2 m above the ground, the wind speed decreased by 30–52.8%, and at a height of 0.5 m above the ground, the wind speed decreased by 33.8–69.7% (Table 8.10).

Table 8.10 Wind velocity in different parts within the oasis with established protective forest networks

Height above ground Location	4 m		2 m		0.5 m	
	WV	C	WV	C	WV	C
Area beyond oasis (reference for comparison)	5.9	100	5.7	100	4.7	100
Periphery of oasis	4.3	73.2	4.0	69.6	3.1	66.2
Center of oasis	3.6	60.8	2.7	47.2	1.4	30.3

WV: Wind velocity ($m \cdot s^{-1}$); C: Comparison (% of wind velocity beyond the oasis)

In areas where protective forests networks and sand-breaks have been established, each forest network grid can form an area of coarseness, so the combination of the forest networks or shelter belts can change the degree of roughness of the land surface under the shelterbelts or forest networks. Wind velocity varies with a logarithmic distribution at different distances from the ground, and so the degree of roughness can be obtained through calculation using the relevant formula and values of wind velocity at two unconditional heights or using the diagrammatic presentation of a logarithm table (Bagnold, 1941). At the outside of the oasis, on the periphery and in the center of the oasis, the roughness values are 1.4791 cm, 3.667 cm and 10.7252 cm respectively. These results confirm that sands from farmlands that have been controlled, caused by strong winds in the spring season, are primarily harmful to cotton crops at the center of oasis where the protective forest networks and sand-breaks have been planted.

ii) Impact on ground temperature

Fig 8.4 (a,b,c,d) show the changes in the soil temperature regime on uncovered land surfaces with a wide (60 cm) spacing of spring wheat (commonly 30 cm high), during the day and night times.

It can be seen that after the soil temperature rises to a stable level during the spring season, the temperature of the soil shows rapid diurnal variations. At increasing soil depths, the fluctuation of soil temperature decreases. In the farmland under the protection of forest networks and sand-breaks, the soil temperatures at the periphery and center of the oasis are 0.4–2.6 °C and 1.2–3.0 °C higher, respectively, than outside the oasis. At other times, the soil temperatures are lower than those outside the oasis. From the periphery to the center of the oasis, the daily mean soil temperature decreases by 1.1–5.7 °C (Table 8.11).

During the peak of summer (at the beginning of August), when the second seeded corn plants are 45–50 cm tall, the soil temperature is different from the spring in the following aspects: (i) At any time during the day or night, the soil temperature inside the oasis is lower at the periphery; and (ii) The differences in temperature between different soil layers are greater than in the spring. At the warmest time of day, from the edge to the center of the oasis, the soil temperature can decrease by 3.8–8.5 °C, while at the 20 cm depth,

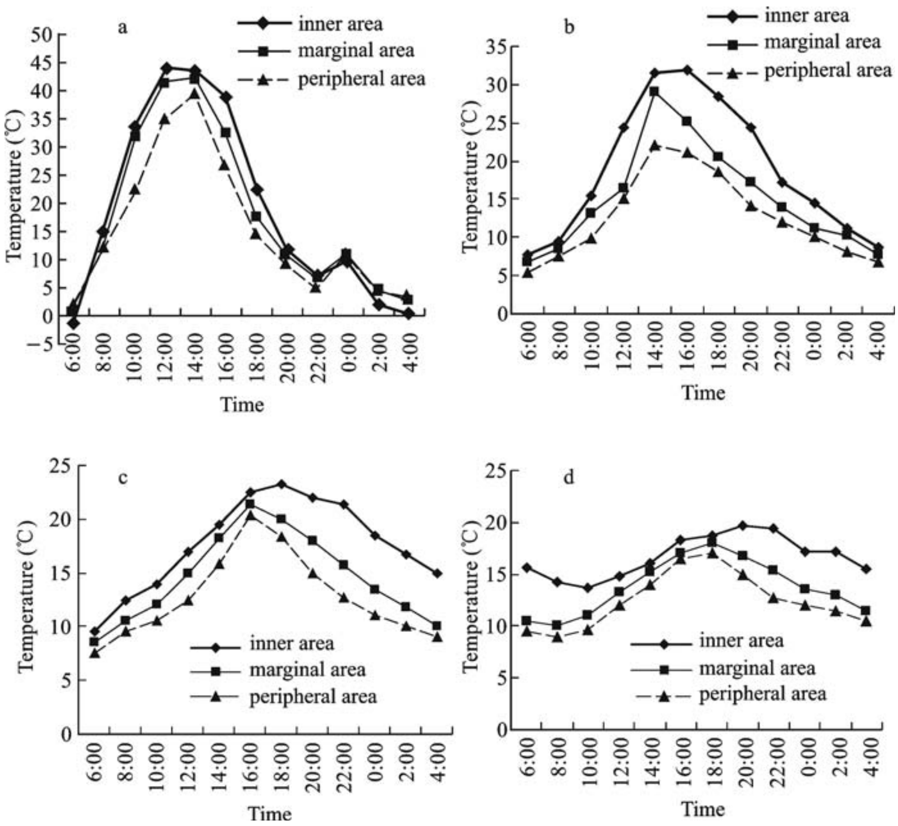

Fig. 8.4 The change of soil temperature regime during the day and night times

a, 0 cm; b, 5 cm, c, 10 cm d, 15 cm

the temperature can decrease 7.8–8.5 °C. During the coolest time of day, the differences in temperature decrease while the extent increases. The range of temperature decreases are 0.5–2.1 °C and 9.8–10.6 °C (Table 8.12).

Table 8.11 Daily mean soil temperature in spring inside the oasis

Site	Soil layer (cm)									
	0		5		10		15		20	
	ST	CCP	ST	CCP	ST	CCP	ST	CCP	ST	CCP
Outside the oasis	19.0		18.7		17.5		17.1		16.9	
Periphery of oasis	17.9	–1.1	15.1	–3.6	14.6	–2.9	14.1	–3.0	13.7	–3.2
Center of oasis	16.0	–3.0	13.0	–5.7	12.9	–4.6	12.7	–5.6	12.2	–4.7

ST: Soil temperature °C; CCP: Contrast to control point.

Table 8.12 Daily mean soil temperature in summer inside the oasis

Site	Soil layer (cm)									
	0		5		10		15		20	
	ST	CCP	ST	CCP	ST	CCP	ST	CCP	ST	CCP
Outside the oasis	35.5		33.7		32.9		32.3		32.2	
Periphery of oasis	26.1	–9.4	23.6	–10.1	23.7	–9.2	23.6	–8.7	23.4	–8.8
Center of oasis	25.5	–10.0	23.2	–10.5	22.6	–10.3	22.4	–9.9	22.2	–10.0

ST: Soil temperature °C; CCP: Contrast to control point.

The variations in soil temperature under the protection of farmland forest networks or sand-breaks described above are of great significance in southern Xinjiang where there is a rapid temperature increase in the spring, accompanied by drought threats and water shortages, and high temperatures and high rates of evaporation in the summer. The effect of farmland protective forest networks on climate conditions help improve seedling establishment and growth of wheat plants, reduce the over-consumption of soil moisture, preserve soil moisture, assist in drought control and reduce the salt accumulation process in the topsoil.

iii) Effect on air temperature

In late spring and midsummer when the temperature is stable, the air temperature in different locations within the oasis will be lower than that of the edge, or outside of the oasis. In the summer, the temperature decreases by 1.5–5.3°C between the outside and the center of the oasis, compared with decreases of 0.2–1.8°C in the later spring. In different seasons, the temperature in the center of the oasis is 0.8–5.3°C lower than outside the oasis, while the periphery is 0.2–4.1°C cooler than the outside of the oasis (Table 8.13).

Table 8.13 Daily mean air temperature in different seasons in oasis under the protection of forest networks or sand-breaks

Season	Site	Heigh (m)							
		4		2		1		0.5	
		T	CCP	T	CCP	T	CCP	T	CCP
Late spring	Outside the oasis	13.0		13.0		13.0		13.0	
	Periphery of oasis	12.6	–0.4	12.0	–1.0	12.6	–0.4	12.0	–1.0
	Center of oasis	12.2	–0.8	11.7	–1.3	12.2	–0.8	11.7	–1.3
Summer	Outside the oasis	25.9		25.4		25.9		25.4	
	Periphery of oasis	24.4	–1.5	23.2	–2.2	24.4	–1.5	23.2	–2.2
	Center of oasis	22.8	–3.1	22.1	–3.3	22.8	–3.1	22.1	–3.3

T: Temperature °C; CCP: Contrast to control point.

Under the effects of forest networks or sand breaks, the vertical distribution of the temperature varies at different locations. For example, during late spring, outside the oasis a super thermal-insulation stratification begins to form from 10:00 am, and the temperature gradient can reach 2.4°C (0.5–4 m). From midnight, a thermal inversion stratification begins to form at 2:00

am, and this lasts until 6:00 am with a temperature gradient of 1.7 °C. At the periphery and in the center of the oasis, the super thermal-insulation stratification begins to form at 12:00 pm and 2:00 pm, respectively, and the temperature gradients are minimal (1.6 °C and 0.6 °C, respectively). The thermal inversion stratification begins at 8:00 pm and lasts until 6:00 am in next morning at the periphery of the oasis or until 8:00 am at the center, and the maximum temperature gradient can reach 2.7 °C and 3.1 °C, respectively.

During the growth period of the crops, the temperature changes caused by the effects of the forest networks or sand-breaks reduce the field evaporation and the damage from drought and prevailing winds.

iv) Effect on relative humidity

Due to the reduction in wind speed and the improved temperature conditions from the effects of forest networks or sand-breaks, the relative humidity in the oasis area is increased by varying amounts. The trend is that the relative humidity is higher during summer (8.5–26.8%) than that in the spring (0.7–15.5%); it is higher in the center of oasis (10.5–26.8%) than that at the periphery of oasis (0.7–15.5%); and it is higher on ground surface (11.8–26.8%) than that in higher layer of air (0.7–10.5%). These trends are related to the moisture content in the air in different locations inside and outside oasis. (Table 8.14).

Table 8.14 Relative humidity in different seasons in oasis protected by forest networks or sand-breaks

Season	Site	Heigh (m)							
		4		2		1		0.5	
		T	CCP	T	CCP	T	CCP	T	CCP
Late spring	Outside the oasis	41.3		40.0		38.3		42.5	
	Periphery of oasis	42.0	+0.7	43.8	+3.8	46.0	+7.7	54.3	+11.8
	Center of oasis	42.4	+1.1	47.5	+7.5	52.3	+14.0	58.0	+15.5
Summer	Outside the oasis	32.8		35.0				36.0	
	Periphery of oasis	41.3	+0.5	44.8	+9.8			57.5	+11.5
	Center of oasis	43.3	+10.5	47.8	+12.8			62.8	+26.8

T: Temperature °C; CCP: Contrast to control point.

v) Impacts on evaporation potential

Evaporation of water from the ground surface is the result of a combination of meteorological factors including wind, air temperature and relative humidity. Though this is different from the total evaporation under natural conditions, it reflects the maximum evaporation potential in different habitat conditions. In oasis ecosystems protected by farmland forest networks, the evaporation potential is obviously weaker than in the desert ecosystem. The degree of intervention and impact from the desert ecosystem is lower inside the oasis than that at the periphery of oasis and is most apparent in the summer compared with the spring.

From the outside to the center of the oasis, the maximum evaporation potential in spring decreases by 38.5–48.0% and can be as high as 52.7–57.6% during the summer (Table 8.15). The reduction in evaporation potential under natural condition is beneficial to the improvement of effective utilization of water.

Table 8.15 Water evaporation at ground surface inside and outside the oasis

Site	Spring		Summer	
	$mm \cdot d^{-1}$	Comparison (%)	$mm \cdot d^{-1}$	Comparison (%)
Outside oasis	7.90	100	12.55	100
Periphery of oasis	4.86	61.5	5.93	47.3
Center of oasis	4.11	52.0	5.33	42.4

(iv) Benefits of increased production

With the establishment of farmland protective forest networks, favorable environment for the growth and development of high yield of crops was created because of the various favorable ecological benefits from the protective forest networks.

i) Increase in cereal production on farmland with protective forest networks

Research and experiments have been conducted related to the implementation of the "Five-Combination" policy in Hetian, Xinjiang (involving plant variety, cultivation methods, seed quantity, irrigation and farmland management) at the beginning of the 1990s. Sampling was conducted through a combination of sample surveys and random sample selection (five repetitions). The results for the wheat yield are shown in Table 8.16.

Table 8.16 Wheat sowing and yield in an oasis protected by forest networks

Site	Tassel length		Tassel diameter		Tassel grain number	
	cm	CCP	cm	CCP	Grain	CCP
Periphery of oasis	5.42		0.95		25.2	
Center of oasis	5.67	+4.6	1.02	+7.4	29.7	+17.9

Site	1000-grain weight		Plant numbers (per ha)		Yield (per ha)	
	g	CCP	Individual plants	CCP	kg	CCP
Periphery of oasis	32.0		5.4885×10^6		3,825	4.6
Center of oasis	34.4	+7.5	6.711×10^6	+22.3	4,626	+20.9

CCP: % contrast to control point.

It can be seen from Table 8.16 that under the protection of the forest networks, all elements of wheat growth and yield within the oasis were improved. Following the improvements to the ecosystem outside and inside the oasis, winter wheat can survive through the winter and turn green, and thus is also obviously improved. The number of the individual plants per hectare was increased by 22%, the tassel length was less significantly increased, (only 4.6%), and the overall yield per hectare was increased by 4.6% at the periphery of the oasis, and 20.9% in the center of the oasis.

To determine the cause of the different yields of wheat in the center and at the periphery of the oasis, a U proof-test was carried out, $U = 4.3448 > U_{0.01} = 2.5758$, which was highly significant. This shows that the difference in wheat yield at the center and periphery of the oasis is caused by the formation of two different ecosystems.

Table 8.17 shows the results for the yield of second seeded corn.

Table 8.17 Corn sowing and yield in oasis with protection of farmland forest networks

Site	Tassel number		1000-grain weight		Plant numbers (per ha)		Yield (per ha)	
	Grain	CCP	g	CCP	Grain	CCP	g	CCP
Periphery of oasis	340.9		183.2		340.9		183.2	
Center of oasis	379.0	+11.2	200.6	+9.2	379.0	+11.2	200.6	+9.2

CCP: % contrast to control point.

It can be seen from Table 8.17 that in the center of the oasis, all the elements related to the yield of the corn have improved. The quantity of tassel seeds increased by 11.2%, the kernel weight increased by 9.2%, and the yield per hectare increased by 18.0%. A T proof-test, $t = 22.2704 > t_{0.01} = 2.750$, shows that these results are highly significant.

In farmland areas protected by the farmland forest networks, the tree belts themselves also occupy some of the farmland. Therefore, when studying the benefits to increased production, the reduced available land area should also be included. In doing so, the actual production increase effect of the farmland forest networks can be obtained.

The increase in crop production and the ratio of increased production of the farmland under protection of farmland forest networks can be calculated according to the formula below:

$$q_1 = Q/(A_1 + A_2 + A_3) \tag{8.1}$$

Where, q_1 is the average yield (kg$\cdot$ ha^{-1}) from farmland under the protection of forest networks; Q is the total yield (kg) of farmland under protection of forest networks; A_1 is the area of the farmland within the shelterbelts (ha); A_2 is the area of a main tree belt (ha); and A_3 is the area of a supplementary tree belt (ha).

$$\Delta Q = q_1(A_1 + A_2 + A_3) - q_2(A_1 + A_2 + A_3) \tag{8.2}$$

Where, ΔQ is the increase in crop yield of the farmland (kg); and q_2 is the original crop yield (kg $\cdot$ ha^{-1}).

$$P = Q/q_2(A_1 + A_2 + A_3) \tag{8.3}$$

Where, P is the ratio of increase of the crops (%)

The specification for most farmland forest networks in Hetian, Xinjiang is an area 600 m×300 m =18 ha, so $A_1 + A_2$=1.8 ha. Calculating from the formula above, the yield increase ratio of wheat is 11.0% and the yield increase ratio of corn is 10.7%.

The research shows that in Hetian in Xinjiang, the grain yield per hectare increases in accordance with the total yield, which is continuously increasing each year, although the tree networks or shelterbelts have occupied some area of farmland when the large scale farmland protective shelterbelts were established in the region.

ii) Impacts of Poplar shelterbelts on grain production

It is well-known that shelterbelts on farmland can increase the yield over a large area but reduce the yield nearby the shelterbelts. The shading and root systems of the trees are two key factors that reduce the yield. Research on these factors is aimed to develop appropriate techniques to reduce the negative impacts of shelterbelts on grain production.

A Poplar shelterbelt was selected for observation and investigation, oriented in a south-north direction (20° west of north) with an average height of 19 m. The crowns of the trees have linked up and form a north-south oriented "tree wall", and its shadowed area and timing vary according to the angle of sun (Table 8.18).

It can be seen from Table 8.18 that in the early morning or evening when the angle of the sun is lower, shadow from the shelterbelt is larger but the shading time is shorter. With an increase or decrease in the angle of the sun, the shadow range becomes smaller but the shaded time lasts longer. Clear shadows are formed to the east and west sides of the shelterbelts in the morning and afternoon. As shelterbelt is oriented 20° west of north, the shaded area is larger on the east side than that on the west side. The maximum extent of the shadow on the west side is 29.0 m (1.53H), while on the east side it is 41.0 m (2.16H). However, the shaded time on the east is shorter, while to the west, with a reduced shadow range, the shaded time has increased. The longer a shadow lasts, the greater the impacts on crop photosynthesis will be.

Table 8.18 Daily change in shadow by a north-south oriented (20° west of north) shelterbelt

Time		8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Direction		W	W	W	W	W	E	E	E	E	E	E
Range	H	29.0	19.0	10.0	5.5	4.0	3.3	5.2	10.3	17.1	25.5	41.0
	m	1.53	1.00	0.53	0.29	0.21	0.17	0.27	0.54	0.9	1.34	2.16
Shadow time (Hour)		1	2	3	4	5	6	5	4	3	2	1

H = height of trees.

Poplar shelterbelts have powerful root systems, and the distribution of the horizontal root system can reach 9.3 m or approximately 50% of the shelterbelt height. The vertical distribution of the root systems can be as deep as one meter, but the roots are mainly distributed in the soil layer at 20–60 cm. The volume, length and surface area of roots at this depth account for 69.2%, 57.6% and 59.0% of the total volume, total length and the total surface area, respectively. These conditions will unavoidably reduce the water and nutrients available to the crops. Experiments indicate that when the roots are properly pruned, the available water and nutrients to the crop field are improved (Table 8.19, Table 8.20).

Tables 8.19 and 8.20 show that following roots pruning, the conditions of water and nutrients in nearby farmland improve by varying degrees. Three days after irrigation, the water content in the cultivated soil layer, where the roots of the trees were pruned, begins to improve. Fifteen days after root pruning, the soil moisture had increased by about 25% at a distance of 0.5H from the shelterbelt. Within the distance of 0.5–1H, the soil moisture increased by 18–19%. After the roots of the Poplar. were pruned, the soil fertility was enhanced in all but two experimental areas. Organic matter, ammonia nitrogen, phosphorus and potassium have been improved by 7.7–22.2% within a distance of 0.5H from the shelterbelt, and at a distance of 0.51–1H, improvements of 4.0% to 11.1% were noted. The improvements in soil water and nutrients are undoubtedly beneficial for increased growth and yield of the crops.

The testing result for cotton on the west side of the shelterbelt was measured in the same way (five repetitions) and results are shown in Table 8.20.

The reduction in cotton yield near the shelterbelts is related to the functions of shelterbelt shadows and root connections. At a distance of 0.25H from the shelterbelt, there was only a 1.6% difference in the cotton yield with or without root pruning, while at a distance of 0.5H, about 9.6% difference within distribution scope of root systems of Poplar can reach that far. Therefore, it could be considered that the root pruning treatment could increase the cotton yield by about 10%.

From Table 8.21, it can be seen that the shadow from the north-south oriented shelterbelt cover the area 1H from the shelterbelt for 1 hour. In the area 0.75H from the shelterbelt, the shade time was about 2.5 hours, and this causes an obvious reduction in yield (11.3–14.8 %). The most seriously affected area, 0.5H from the shelterbelt has a shade time of 3 hours (with a yield reduction of 30.8–51.3 %). Therefore, it can be concluded that if the shade time of the shelterbelt is 1 hour or more, this can affect the yield of the crops, and if the shade time is as much as 2.5 hours, this can have a significant impact on crop yield. If the shading caused by the shelterbelt lasts for more than 3 hours per day, the can seriously affect crop yield.

To determine which of the threats to production from the shelterbelt are dominant, analyses have been carried out into the relevant effects of shelterbelts with or without root pruning. The results are as follows: (i) within the root pruning zone, light intensity > soil moisture content > organic matter > rapidly available phosphorus > ammoniacal nitrogen > rapidly available

Table 8.19 Water holding capacity (%) in soil depth of 0–40 cm after irrigation

Test period	Test points (H)	3 days after watering			7 days after watering			11 days after watering			15 days after watering		
		RP	WRP	WRP/RP(%)	RP	WRP	WRP/RP(%)	RP	WRP	WRP/RP(%)	RP	WRP	WRP/RP(%)
Jun.20–July 12, 1994	0.25	16.8	16.3	97.0	16.7	15.8	94.6	13.1	12.5	95.1	11.8	9.0	76.3
	0.5	16.6	15.7	91.6	16.1	14.3	88.8	12.8	10.6	82.8	11.9	8.9	74.8
	0.75	15.9	15.3	96.2	14.8	14.0	94.6	11.3	10.5	92.9	9.8	8.1	82.7
	1.0	15.7	14.7	93.6	14.1	13.3	94.3	12.6	11.6	92.1	9.0	7.3	81.1

RP: Root pruning; WRP: Without root pruning.

Table 8.20 Soil fertility status during cotton picking days (1993.10.7)

Height away trees belt	Organic matter (%)			Ammoniacal Nitrogen ($mg\cdot kg^{-1}$)			Available Phosphorus ($mg\cdot kg^{-1}$)			Available Potassium ($mg\cdot kg^{-1}$)		
	RP	WRP	WRP/RP(%)	RP	WRP	WRP/RP(%)	RP	WRP	WRP/RP(%)	RP	WRP	WRP/RP(%)
0.25H	0.45	0.53	117.8	13.5	16.0	118.5	14.2	15.9	112.0	152.0	184.3	121.3
0.50H	0.52	0.56	107.7	13.5	16.5	122.2	15.2	18.2	119.7	166.5	161.3	97.0
0.75H	0.50	0.52	104.0	14.0	15.0	107.1	15.3	16.0	104.6	181.5	193.0	106.3
1.00H	0.54	0.57	105.6	14.5	14.0	96.6	16.7	17.3	103.6	171.0	190.0	111.1

H: Height of trees belt; RP: Root pruning; WRP: Without root pruning.

Table 8.21 Lint yields with and without root pruning

Height away trees belt	Plants/m^2		Cotton plants/m^2		Weight of each cotton puff		Cotton plants/ha		Lint yield /ha			
									RP		WRP	
	RP	WRP	RP	WRP	RP	WRP	RP	WRP	kg	CK (%)	kg	CK (%)
0.25H	13.6	12.5	3.2	3.1	1.27	1.31	28,664	25,997	36.6	42.7	34.2	44.3
0.50H	14.5	14.0	4.0	3.6	1.51	1.35	38,896	34,096	58.8	69.2	46.0	59.6
0.75H	13.0	15.0	5.2	4.2	1.68	1.56	44,895	42,329	75.5	88.7	65.8	85.2
1.00H	13.5	16.5	5.5	4.2	1.67	1.60	49,995	46,428	83.3	98.0	74.3	96.2
CK	14.0	15.5	5.4	4.2	1.68	1.75	50,561	44,229	85.0	100	77.2	100

H: Height of trees belt; RP: Root pruning; WRP: Without root pruning.

potassium; and (ii) in the non-root pruning zone, light intensity> rapidly available phosphorus > organic matter> soil moisture content > ammoniacal nitrogen > rapidly available potassium (Liu et al., 1996). Although the different factors have varying levels of effects between the root pruning zone and non-pruning zone, light intensity is the most significant effect with both growing types. Therefore, it can be concluded that in irrigated agricultural areas of the oasis, reduced solar radiation leads to reductions in crop yield in the shaded area. Although root pruning can reduce the impacts on crop yield, the large scale implementation of root pruning is impossible, so it is proposed to grow alfalfa, and other shade-tolerant grasses or crops within the area 0.5 H distant from the shelterbelt.

8.5.3.2 Complex ecosystem of agroforestry

(i) Layout of complex ecosystems of agroforestry

Farm ditches provide an example that explains the function of agroforestry. Fig. 8.5 shows the layout of mulberry trees planted inside the forest networks or shelterbelts.

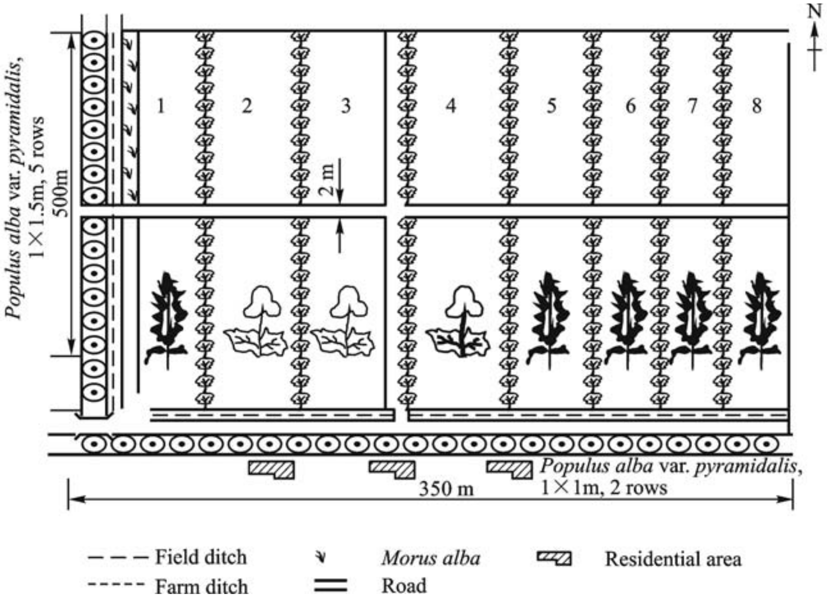

Fig. 8.5 Plane figure of experimental plot

The strip shaped field is 500 m in length, 350 m in width and covers an area of 17.5 ha, of which, shelterbelts or forest networks occupy 0.29 ha (or 1.6% of the area). Also within the field are a walking path covering about 0.27 ha (1.5%); farm ditches including mulberry trees covering 0.49 ha (2.8%); and farm land covering 16.45 ha (or 94% of the area). Within the farmlands, wheat is planted on 8.47 ha; cotton on 7.2 ha and alfalfa and clover grassland covers the remaining 0.55 ha. The main shelterbelts or tree and forest networks consisted of five rows of Poplar with a row spacing of 1 m and a distance between individual trees of 1.5 m. The average height (H) of the forest network is 31.15 m and the average trunk diameter is 18.9 cm. The total number of trees is 1,666. The sidelined tree belts consist of two rows of Poplar with a row spacing of 1 m and a distance between individual trees of 1 m. The height of tree belts is 20.5 m, the average trunk diameter is 12.4 cm, and the total number of trees is 700. The height of mulberry tree belts is 4 m, the trunk diameter is 9.8 cm and the total number of mulberry trees is 3,465. The mulberry trees are evenly divided between white mulberry and black mulberry species.

(ii) Ecological services

When shelterbelts or farmland protective forest networks were established, the complex operation of mulberry forestry was conducted on strip shaped fields inside the farmland protective forest networks. It can be concluded that the microclimate change inside the farmland is the result of the combined effects of the farmland protective forest networks and the mulberry belts planted along the farm ditches.

The wind prevention function is the most importance aspect of ecological service from the complex agroforestry ecosystem inside the oasis. The shelterbelts or protective forest networks can either prevent or control wind and sand disasters caused by local blown sands, and can weaken the air current exchange between desert and oasis ecosystems, thus improving the microclimate of the farmland. Table 8.22 shows the average values from 14 observations of wind speed at Experimental Strip Field No. 4 (with cotton seedlings 20–30 cm high) and a nearby strip field without mulberry belts and wasteland inside the oasis during April and May of 1993 and 1994.

Table 8.22 Wind velocity regime inside the fields of mulberry-crop complex ecosystem

Testing point	Comparison	Strip-shaped fields without mulberry belts	No. 4 Experimental strip field					
			E1	E3	CS	W3	W1	Average
Wind velocity ($m \cdot s^{-1}$)	4.5	1.7	0.6	1.0	1.4	1.1	1.0	1.0
Comparison (%)	100	37.8	13.3	22.2	31.1	24.4	22.2	22.2

E1: East side of mulberry belts at 1H distance; E3: East side of mulberry belts at 3H distance; CS: Center of the strip filed; W3: West side of mulberry belts at 3H distance; W1: West side of mulberry belts at 1H distance.

It can be seen from the results in Table 8.22 that wind speed at a height of one meter from the ground inside the farmland lined with forest networks was reduced by 62.6% compared with the open field outside the oasis. However, inside the Experimental Strip Field No. 4 the average reduction in wind speed at all testing points was 78.8% due to the double effects of farmland protective forest networks or shelterbelts and mulberry belts. Therefore, it is concluded that the mulberry trees reduced the wind speed by a further 16.6%.

During the day, the air temperature at 1 m above the ground at the No.4 Experimental Strip Field is 0.2–0.3 °C higher in the east than that in the west in the morning and 0.2–0.3 °C higher in the west during the afternoon due to the effects of direct sunlight, The temperature in the strip field lined with shelterbelts or protective forest networks was reduced by 0.5–1.1 °C compared with the strip field without mulberry belts and the comparison sites. On sunny days with a light breeze, the temperature reduction in the complex mulberry-crop fields is more significant. During the daytime, the temperature was reduced, on average, by 1.4 °C on the No. 4 Experimental Strip Field, suggesting that the effect of mulberries belts is to reduce the temperature a further 0.6 °C. Under the combined effects of the farmland protective forest networks and the mulberry belts, the relative humidity was increased by 6.6%, of which, the mulberry belts accounted for a 2.1% increase.

Therefore, the construction of a complex agroforestry ecosystem inside the farmland protective forest networks or shelterbelts can further optimize the eco-environment of the farmland.

(iii) Energy transformation

Green plants transfer solar energy into potential energy through photosynthesis, forming different materials that meet the production needs and livelihoods of humans. The complex agroforestry ecosystem can increase the leaf area per unit of land and thus can increase the utilization ratio of the light energy and the transformation ratio of the energy. This is an important reason why the complex agroforestry ecosystem is widely used.

The weight method is used to measure the leaf area index of crops and trees in the experiment strip field by determining the ratio between leaf area and weight, with results shown in Table 8.23.

It can be seen from Table 8.23 that leaf area index of the trees is much higher than that of the crops. For instance, if the minimum leaf area index of cotton is one (1), the leaf area index of a Poplar tree can be as high as 48.18, and the leaf area indices of white and black mulberry are as high as 3.45–4.88.

Table 8.23 Leaf area index of crops and trees in the experimental strip field

Crops	Cotton	Wheat	Corn	Alfalfa/ Clover	Poplar tree	White mulberry	Black mulberry
Leaf area index	2.10	2.57	4.97	2.61	101.17	10.24	7.25
Multiple of cotton	1.00	1.22	2.37	1.24	48.18	4.88	3.45

The light energy utilization ratio is the ratio between the energy contained in the harvested crops per unit area and solar radiation energy for a given period of time (Xu, 1989). It can be calculated as follows:

$$E = (1000HY/A\sum Q \times 666.7) \times 100\% \tag{8.4}$$

From equation (8.4), the utilization ratio for various plants in the strip-shaped fields can be calculated. For instance, the utilization ratio for alfalfa is highest, incorporating 2.40% of the solar radiation, the ratio for Poplar trees is 1.40% and the ratio for cotton is only 0.32% (Table 8.24).

Table 8.24 Light energy utilization ratio of crops and trees inside the strip-shaped fields

	Cotton	Wheat	Corn	Clover	*Populus bolleana*	Mulberry
Yield ($kg \cdot ha^{-1}$)	2,976	5,650.5	7,177.5	19,335	10,698	12,180
H ($MJ \cdot g^{-1}$)	0.01634*	0.01634*	0.01634*	0.01911	0.019648**	0.011931**
$\sum Q$ ($MJ \cdot m^{-1}$)	4,296	2,763	3,420	4,296	4,296	4,296
E (%)	0.32	0.95	0.97	2.40	1.40	0.97

* These data are cited from the Practical Manual for Agricultural Meteorology edited by Sub-Commission for Agricultural Meteorology, Shandong Meteorology Commission, published by China Meteorology Press, in 1992.

** These data were collected by the Quality Inspection Station of Coal Products, Xinjiang

The data in Table 8.24 indicate at, using a weighted average calculation on the basis of the growing area of crops, the light energy utilization ratio of crops alone is 0.73%, and the light energy utilization ratio of the complex agroforestry ecosystem is 0.82%. In other words, the agroforestry increased light energy utilization ratio by 0.09% compared with monocultivation.

The energy transformation ratio (C) is the ratio between the energy contained in the biomass above ground per unit area (P_{ci}) and the energy input during a specified period of time (T_{ci}).

It can be calculated using the following equation:

$$C = P_{ci}/T_{ci} \tag{8.5}$$

From equation (8.5), the inputs of various energies into the strip-shaped field can be calculated. For example, wheat requires the highest energy input at 76,810.5 MJ·ha, mulberry has lowest energy input at 4,156.5 MJ·ha and energy inputs for crops are 5.5–9.6 times higher than for trees (Table 8.25). In terms of energy outputs, Poplar trees have the highest outputs at about 225,085.5 $MJ \cdot ha^{-1}$, corn has the second highest energy output at about 217,933.5 $MJ \cdot ha^{-1}$, and the energy output from alfalfa is the lowest at about 62,109 $MJ \cdot ha^{-1}$ (Table 8.26).

In irrigated areas, the water required to produce one kilogram of grain is usually used to measure the production level, using:

$$P = B/W \tag{8.6}$$

Table 8.25 Annual energy input into the strip shaped field (T_{ci})

	Seeds		Organic manure				Fertilizers		Man power		Machine	Animal power	Water		Total
			N	P	K										
	kg·ha^{-1}	MJ·ha^{-1}	kg·ha^{-1}	kg·ha^{-1}	kg·ha^{-1}	MJ·ha^{-1}	kg·ha^{-1}	MJ·ha^{-1}	labor	MJ·ha^{-1}	MJ·ha^{-1}	MJ·ha^{-1}	m^3	MJ·ha^{-1}	MJ·ha^{-1}
Wheat	303	4,951.5	225	202.5	313.5	25,990.5	291	27,897	7.1	1,750.5	11,317.5	3,774	300	1,129.5	76,810.5
Corn	162	2,647.5	180	162	250.5	26,788.5	93	8,982	20	3,501	1,572	1,359	240	900	45,750
Cotton	102	1,543.5	270	243	376.5	31,191	210	19,948.5	28	5,442	9,657	3,730.5	300	1,125	72,637.5
Alfalfa	3	49.5	31.5	28.5	43.5	3,637.5			2	349.5	792			675	5,503.5
Poplar tree	625.5	12,291							3.9	681				900	13,860
Mulberry	166.5	3,054							6.3	1,102.5					4,156.5

Table 8.26 Annual energy output from strip shaped field (P_{ci})

	Crops						Trees						Total MJ·ha^{-1}
	Seeds			Stem and leaf			Branches			Bole			
	kg·ha^{-1}	MJ·kg^{-1}	MJ·ha^{-1}	kg·ha^{-1}	MJ·kg^{-1}	MJ·ha^{-1}	kg·ha^{-1}	MJ·kg^{-1}	MJ·ha^{-1}	kg·ha^{-1}	MJ·kg^{-1}	MJ·ha^{-1}	
Wheat	5,650.5	16.34	92,329.5	5,440.5	14.6	79,431							171,760.5
Corn	7,153.5	16.34	116,887.5	6,921	14.6	101,049							217,933.5
Cotton	2,976	16.34	48,628.5	2,989.5	14.6	43,647							92,275.5
Alfalfa				4,254	14.6	62,109							62,109
Poplar tree							4,141.5	15.78	65,353.5	8,559	18.66	1,597,161	225,064.5
Mulberry							682.5	11.08	7,560	3,486	19.42	67,705.5	75,267

Where: P is the water required to produce one kilogram of grain; B is average irrigation rate ($m^3 \cdot ha^{-1}$); and W is the yield per hectare ($kg \cdot ha^{-1}$).

The following two points should be noted: (i) the positive effect of farmland protective forest networks; and (ii) the positive effect of the complex agroforestry ecosystem. To calculate the positive effect of the complex agroforestry ecosystem and compare this with a typical cropping system, the financial gain (RMB) should be evaluated in terms of grain equivalent (kg) in accordance with the state procurement price.

The wheat yield per hectare in the experimental strip field was 5,650.5 $kg \cdot ha^{-1}$. If the positive effects of the agroforestry system are excluded then the yield should be reduced by 11%, or 621 kg so the net grain yield per hectare is 5,029.5 $kg \cdot ha^{-1}$. The total area of wheat which received the positive effects of the agroforestry ecosystem is 8.74 ha, so the annual positive effect of agroforestry management was 3,078.20 RMB (23.48 RMB per ha), which is equal to an increase in yield of 294 $kg \cdot ha^{-1}$ of wheat. From equation (8.6) the following can be calculated: P_1 is the water required to produce one kilogram of wheat by deducting the positive effects of ecological efficiency; P_2 is the water required to produce one kilogram of wheat including the positive effects of ecological efficiency; and P_3 is the water required to produce one kilogram of wheat with the positive effects of ecological efficiency it can be calculated separately:

$$P_1 = 300(\mathrm{m}^3 \cdot \mathrm{ha}^{-1})/5,029.5(\mathrm{kg} \cdot \mathrm{ha}^{-1}) = 0.89(\mathrm{m}^3 \cdot \mathrm{kg}^{-1})$$
$$P_2 = 300(\mathrm{m}^3 \cdot \mathrm{ha}^{-1})/5,650.5(\mathrm{kg} \cdot \mathrm{ha}^{-1}) = 0.80(\mathrm{m}^3 \cdot \mathrm{kg}^{-1})$$
$$P_3 = 300(\mathrm{m}^3 \cdot \mathrm{ha}^{-1})/5,323.5(\mathrm{kg} \cdot \mathrm{ha}^{-1}) = 0.85(\mathrm{m}^3 \cdot \mathrm{kg}^{-1})$$

These two aspects of ecological and agroforestry management can reduce the water requirements for the production of one kilogram of wheat by 0.14 m^3, resulting in an increase in the utilization ratio of water for farmland irrigation by 15.7%.

For corn the water required to produce one kilogram of grain under different management conditions is: $P_1 = 0.57, P_2 = 0.50$ and $P_3 = 0.51$. The two aspects of ecological and agroforestry management can reduce the water requirements for the production of one kilogram of corn by 0.13 m^3, so the utilization ratio of water for farmland irrigation is increased by 22.8%.

8.5.3.3 Combined pastoral-silviculture system

(i) Improvement of microclimate

A combined pastoral-silviculture system developed under the harsh conditions of saline and alkali wetlands, sandlands, aeolian sandy soil, etc., can improve the microclimate in the desert. During the growing season, if the trees of *Elaeagnus* spp. on the natural forage farm are 5 m high with a spacing of 4 m × 8 m and a canopy density 0.4 (Shule County, Xinjiang), the wind speed at a height of 1.5 m above ground in an open field can be reduced from

5.3 m·s^{-1}, to only 1.1m·s^{-1} which is a reduction in wind speed by 79%. When the wind speed is low and considered a breeze ($<$ 2 m·s^{-1}),the wind inside the shelterbelts or protective forest networks is still a breeze. Consequently, the land surface is effectively prevented from erosion by blown sands or sand movement.

During warm and hot summer months, the large tree canopies will consume heat through evaporation, and with the protection of shelterbelts and vegetation, the direct radiation from sun on the earth surface is decreased and the daily mean land surface temperature and the air temperature 1.5 m from ground level are significantly decreased. The surface temperature of open land varies significantly between day and night, with highs of up to 51.6 °C during the day and lows of down to 13.1 °C at night. However, inside the shelterbelts or protective forest networks, due to the shading from the tree canopies and the high heat capacity of soil, the maximum temperature ground temperature is 46.6 °C and minimum ground temperature is 16.7 °C. The daily mean soil temperature at a depth of 5–20 cm was reduced by 1.7–3.8 °C.

While the daily average temperature is reduced inside the protective forest networks or shelterbelts, the time of the highest temperature during the day is 2 hours later than in unprotected areas. The maximum daily temperature occurs at 16:00 in open fields and at 18:00 inside the protective forest networks or shelterbelts. The evaporation over 24 hours in an open field is 268.5 mm, but only 222.1 mm inside the protective forest networks or shelterbelts which equates to a reduction of 22.2% (Liu, 1987). The microclimate effects of a well managed pastoral-silvicultural system can create a favorable ecological environment for shaded shelter and fodder for domestic animals, such as cows and sheep, during the summer.

In winter, in an *Elaeagnus angustifolia* and natural forage farm (Hetian County, Xinjiang) with a tree height of 5.06 m, spacing of 2 m × 5 m and a canopy density of 0.6, the temperature in open fields or on bare sandland can be significantly increased or decreased. At 6:00 am, the minimum temperature can be as low as –17.5 °C, and the maximum temperature at 2:00 pm can be as high as 11 °C, which equates to a daily temperature variation of 28.5 °C. However, inside protective forest networks or shelterbelts, due to effects of both tree canopy and land surface, the daily change of land surface temperature is not as sharp, with a minimum temperature of –12.1 °C and a maximum temperature of 3.0 °C, giving a daily temperature variation of 15.1 °C. Because it is influenced by soil temperature, the temperature in open fields and bare sand land varies significantly. The temperature gradient at the time of the minimum temperature (6:00 am) can be as steep as –2.2 °C·m^{-1} while the temperature gradient at the time of maximum temperature (2:00 pm) is 0.4 °C·m^{-1}. However, inside the protective forest networks or shelterbelts, these minimum and maximum temperature gradients are 1.37 °C·m^{-1} and 0.30 °C·m^{-1}, respectively, and the daily temperature variation is 16.4 °C. The temperature characteristics inside the protective forest networks or shelterbelts and at ground level can reduce the energy consumption of the plants, which is favorable for their survival through the winter.

(ii) Improvement of soil

Trees have strong root systems which can access groundwater, effectively lowering the groundwater level. In Han'ai Lieke, Ying'a Wati and other townships of Hetian County, when *Elaeagnus angustifolia* (2 m×5 m) and natural forage farms, and *Hippophae rhamnoides* (2 m × 5 m) and natural grassland were maintained for 7–8 years (1985, 1986–1992), the groundwater level was reduced by 0.8–1.5 m in the saline and alkali wetlands, and was reduced by 3.5–4 m in sandland (Fig.8.6). Consequently, the rate of water evaporation from the soil surface and the speed of salinization processes in the topsoil were reduced. Inside the *Elaeagnus angustifolia* forest networks, there was no salt accumulation on the land surface, which natural grass-growing processes were occurring. Inside the protective forest networks, the total salt decreased by 2.6673% compared with wasteland areas, and the concentrations of Cl^- and SO_4^{2-}decreased by 12.5794 mg·(100g)$^{-1}$ and 6.6645 mg·(100g)$^{-1}$, respectively. The measurements from 10 year old *Hippophae rhamnoides* shelterbelt networks show similar results, with the total salt inside the Protective forest networks, decreasing by 2.3140% when compared with wasteland, and Cl^- and SO_4^{2-} concentrations decreasing by 24.9057 mg·(100g)$^{-1}$ and 13.3094 mg·(100g)$^{-1}$, respectively.

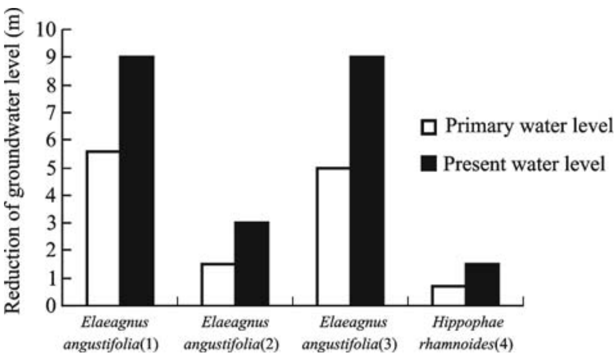

Fig. 8.6 Reduction of groundwater level under the effects of pastoral-forestry
(1) and (3): sand land; (2) and (4): low swamp land

Biology is the most important element of soil formation and material circulation processes. The dense root systems of *Elaeagnus angustifolia* and *Hippophae rhanmoides* have improved the physical structure of the soil, which has resulted in improved permeability and water-holding capacity. The fallen leaves and herb grass inside the protective forest networks are consumed by domestic animals and poultry, and their waste is returned to the soil as manure. The root systems of both *Elaeagnus angustifolia* and *Hippophae rhamnoides* are rich in nodule bacteria, which can stabilize free nitrogen from the air. As shown from testing inside a 13 year old *Elaeagnus angustifolia* shelterbelt network, there are an average of 67.4 root nodules per square meter and the average dry weight of the roots is 49.3 g·m^{-2}. The maximum rate of root nodules per square meter was 117.2, of which, 96.3% were distributed at a soil depth of 8–20 cm with a distance of 2 m from the *Elaeagnus angustifolia*. The root nodule contains 1.4% nitrogen, 0.12% phosphorus and 4.86% of potassium and the combined mass of these three nutrients is 6.38% of the root nodule, which leads to enhanced soil fertility (Table 8.27).

Table 8.27 Improvements in the physical and chemical properties of soil in combined pastoral-silvicultural systems with *Hippophae rhamnoides*

	OM	TN	AHP	I	IP	UW
Secondary salinized soil	0.9909	0.049	20	4	250	1.16
Soil around *Hippophae rhamnoides*	1.7094	0.081	18	11	1,150	0.99
Salinized meadow soil	0.5313	0.0515	10	1	1,246	

OM: Organic matter (%); TN: Total nitrogen (%); AHP: Alkaline hydrolytic phosphorus (mg·kg^{-1}); I: Instant phosphorus (mg·kg^{-1}); IP: Instant Potassium (mg·kg^{-1}); UW: Unit weight (g·m^{-3}).

(iii) Increased vegetation coverage

There are two types of artificial alfalfa plantations and natural vegetation within the combined pastoral-silvicultural system. With respect to the natural vegetation, prior to the artificial planting, they mainly comprise bare salinized and alkalized land or the land with sparse *Phragmites communis* and *Alhagi pseudalhagi* and other halophytes and xerophytes. Following the artificial planting due to implementation of irrigation and ecological and environmental improvements inside the protective forest networks, favorable conditions are created for the propagation of herbal plants and the revegetation process begins. Some new species, such as *Poa annua*, *Agropyron cristatum*, *Taraxacnm officinale* and *Diramthus chinensis* enter into the protective forest networks changing the botanical community structure and variety. The vegetation quantity increased by 355 plants·m^{-2}, the vegetative coverage increased by 25–30%, and the height of the grass increased by 40 cm (Shule County, Xinjiang) (Table 8.28).

Table 8.28 Plant diversity in combined pastoral-silvicultural systems

	Diversity (plants·m^{-2})	Coverage (%)	Height (cm)	Remarks
Combined pastoral-silvicultural system	520	39–40	5–40	*Elaeagnus angustifolia*, 1995 plants·ha^{-1}
Salinized meadow	185	0–10	5–10	

The vegetation quantity and growth pattern in complex pastoral-silvicultural systems is closely related to reforestation in terms of density, the percentage of reforestation cover and the utilization intensity. In addition to the increase of reforestation density and the percentage of reforestation cover, the vegetation quantity is reduced and growth is weaker. If the reforestation cover reaches 90%, the vegetation height may be only 10–15 cm, but if, in a woodland, the reforestation cover is 40–60%, rotational grazing is reasonable and vegetation can grow as high as 80–100 cm. Therefore, in areas where fodder is limited but there is a surplus of fuelwood, the reforestation structure should be designed so that the trees are further apart and strip planting should be undertaken. The space between the strip plantations should be used for growing artificially planted alfalfa and other natural herbs and grasses.

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9 Engineering and Technological Measures for Combating Desertification

Zhihai Gao, Chaosheng Li, Xiaohui Yang and Longjun Ci

China has accumulated rich experiences in combating desertification based on work in a number of regions and provinces. Various control measures have gradually been innovated and developed in recent decades. In addition to biological measures taken to combat desertification, mechanical approaches have been developed to stabilize shifting sands. Methods include technologies that release sand-accumulation, construction of sand barriers, chemical mulching and hydrologic solutions. Throughout China, various preventive measures have been adopted, practiced, integrated, and adapted to local conditions and suited to combat specific forms of desertification.

9.1 Mechanical stabilization and releasing accumulated sand

Initially, most efforts had been directed at blocking aeolian sand and fixing shifting sands. More recently, in addition to the long-term practice of sand dune stabilization, it was discovered that mechanical methods could artificially interrupt and control the processes of sand denudation, accumulation and movement. Release of accumulated sand is one of the mechanical measures used to control hazards caused by dune movement and sand transport. Mechanical stabilization and releasing accumulated sand are effective methods for mitigating and preventing hazards associated with sand movement.

9.1.1 Mechanical sand blocking techniques

9.1.1.1 Artificial walls (banks) to block shifting sands

Constructing sand-blocking walls (banks) is one of the simplest and oldest methods of controlling shifting sands. Walls or banks are installed downwind of mobile sand dunes and shifting sands or around settlements, mineral sites or oil fields, and along communication or transport facilities. The earliest sand-blocking walls or banks, dating back to historical times, were made of dried bricks or clay and were normally 100 cm high and 35–50 cm thick. Residual sand-blocking walls and banks can only be seen in areas with severe erosion, at the periphery of oases and in the Gobi region of northern China.

In recent decades, following long-term experiments and evaluation, methods to construct sand-blocking walls have been improved. Currently, it is more common to see sandbags used to make sand walls or banks to stop sand movements. These sandbags are made of materials durable under harsh conditions, such as hard paper covered with plastic films. This method not only reduces the high cost of material transport but is easier to install, provides quick and effective sand-blocking capabilities and is suitable for use in extremely arid areas including the Gobi desert region where materials are scarce. Sand-blocking walls or banks can be easily repaired and raised when the walls and banks are buried by shifting sands. Buried sandbags can also be reused to reconstruct new sand-blocking walls or banks after being flattened by drifting sands.

9.1.1.2 Sand sedimentation ditches

Sand sedimentation ditches are also one of the oldest methods used to block and settle shifting sand. Ditches slow wind speed and accumulate overloaded drifting sand. Based on the underlying coarse particles or adhering stratum, sand sedimentation ditches should be dug upwind of the protected target area, and the excavated soil should be used to build dykes on the outside of the sand sedimentation ditch. When the sand sedimentation ditch and dyke are overtopped by accumulated sand and are no longer effective, a new sand ditch with a dyke can be built outside of the old ditch. Alternatively, a concave profile (blow out) can be formed between the buried ditch (dyke) and the new ditch (dyke), thus extending the lifetime of the ditch.

Sand sedimentation ditches are normally used at the periphery of sandy deserts and Gobi. In these areas, there is typically a low amount of sand suspended in the air. This method is less effective in areas with a high amount of shifting sands because ditches are soon filled and quickly lose their function. The nature of the underlying soil layers should be considered while digging and constructing sand sedimentation ditches. Stones, gravel or straw should be utilized to protect dykes from wind erosion when the underlying layer is sandy. This method was used on a large-scale along the Lanzhou-Xinjiang Railway Line in the Yumen District of Gansu Province and along the Baotou-Lanzhou Railway Line in the Bohaiwan District of Inner Mongolia. Because the underlying layer is rocky and gravelly, the dykes did not need protection. In addition, the excavated rocks and gravel were used to cover nearby mobile dunes or stabilize shifting sands close to the sand sedimentation ditches.

9.1.1.3 Sand-blocking barriers

A sand-blocking barrier is also called a vertical sand barrier. The barrier changes the wind flow during turbulence and reduces wind speed upwind of the barrier. The sand-blocking barrier is made of *Phragmites australis*, *Achnatherum splendens* and *Salix sinopurpurea* or other crop residues. The upright barrier is about 1.3–1.7 m high, and its base is buried 20 cm into the ground. The base of the barrier is covered with wheat straw and stamped with sand to a height of 10 cm above the sand surface. Wooden posts or cement pillars about 1.5–1.7 m high are used as fixing posts. Depending on the strength of the materials, the pillars are installed every 2–8 m and buried to depth of 40 cm. All barriers are tightened between pillars and then attached to the pillars to ensure the stability of the barriers. The barriers are normally installed in late autumn to early winter, as the sand layer contains high moisture and it is easier to dig ditches at this time. Installation is, therefore, more cost-effective and reliable. This sand-blocking barrier is effective at stopping and accumulating shifting sands; however, this method requires a large supply of straw or other materials, which increases the cost.

Based on research and observation, the ability and effect of sand-blocking barriers to stop sand movement are significant. Barriers should be installed more than 200 m upwind and 100 m downwind of communication or transport lines, particularly in drifting sand areas of the Gobi and in flat sandland.

If the distance between the barriers is too wide, the barriers will easily erode or be destroyed, but if the distance between the barriers is too narrow, costs are too high. Therefore, a reasonable distance between barriers should be carefully calculated along with the costs of materials and manpower to ensure a cost-effective installation.

The distances between barriers erected at right angles to the main wind direction can be determined by reference to the topography and slope of the land and the proposed height of the barrier. The frequency, velocity and duration of the wind must also be considered when designing and installing the barriers. The distance between tall barriers should be wider than that of short barriers, and the distance between barriers on gentle slopes should be longer than that on steep slopes. Where wind is weak, the distance between barriers should be longer than where wind is stronger. On flat sand surfaces with less than 4° slope, the distance between barriers should average 15–20 times the height of the barrier. On windward slopes, the top of the second barrier should be parallel to the base of the first barrier.

9.1.1.4 Sand blocking networks

The theory behind sand blocking networks is similar to the sand-blocking barrier. It has been developed based on experience with sand-blocking barriers over the last 20 years. Networks are composed of interlinked polyamide and polypropylene fibers. They are also referred to as nylon network barriers.

They are characterized by their light weight, ease of transport and convenient operation. The mesh size (number of holes per unit area) and the diameter of nylon fiber threads used to create the network should be determined by characteristics of the blown sand in the area. The diameter of the nylon fiber should be bigger in areas with coarser sand particles in wind-blown sand.

9.1.2 Mechanical sand releasing and transporting techniques

9.1.2.1 Sand releasing and transporting by shallow troughs

When constructing highway or railway roadbeds in sandy deserts, shallow, crescent-shaped troughs are made on both sides of the roadbed. These can be paved with gravel or stone to prevent erosion. To transport shifting sands, sand dykes or blocking sand dykes should be created in front of shallow troughs 30–40 cm higher than the nearby mobile dunes. When mobile dunes move closer to the front slope of the dykes, updrafts to dyke tops are formed between sand dunes and dykes. Suspended sand particles that are moved to the top of sand dune ridges are blown by this updraft directly to the top of the dyke. Wind-blown sand flows form on leeward slopes of the dykes and are lifted up over the shallow troughs between the dykes and roadbeds. This updraft blows sand particles over roads without any accumulation. To stabilize dyke surfaces, a 2 cm thick gravel or stone layer can be spread and then covered with asphalt (see below) to protect the dykes. The asphalt is normally 1–1.5 cm thick. Stone sheets can also be used to protect the dyke slope.

Ground observation shows that when the ratio of the arc length (l) and the maximum depth (h) (l/h) of the shallow trough is around 10–20, airflows create enough updraft to prevent sand accumulation on that portion of the roadbed.

9.1.2.2 Transporting sand with wind baffle boards

Use of wind baffle boards is a technique used to blow away accumulated sand and clean up the effects of drifting sand in a protected area by increasing the wind intensity behind the board. The wind baffle board is composed of studs, crossbars and grids (Fig. 9.1). The grid is normally made of timber, steel or other materials and helps to funnel wind. The board used to funnel wind should be installed on the upwind edge to blow away sand accumulated on the road. The effect of the wind baffle board is optimal when the road runs 45–90° to the main wind direction.

The height of the wind baffle board is directly proportional to the width of the protected section; the taller the board is, the larger the protected width will be. However, taller boards are more costly and inconvenient to construct. In addition, more sand will accumulate in front of the board. If the board is too low (less than 1 m), the ability to funnel wind is reduced, and the effective

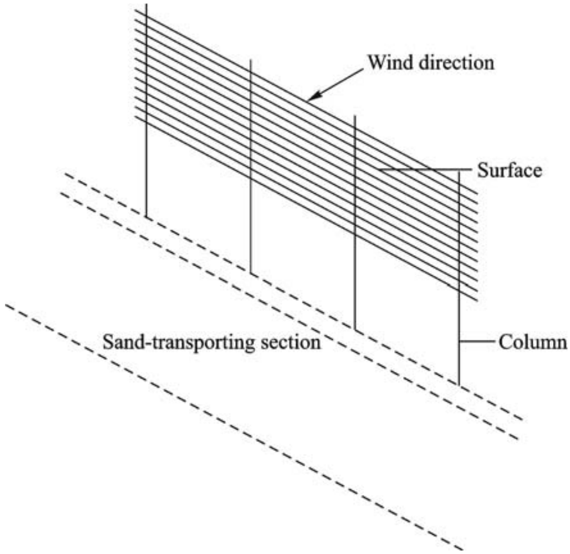

Fig. 9.1 Down baffling wind engineering to transport sands (Ci, 2002, with permission from author)

width for sand transport decreases. Studies indicate that the best height for the board is about 1.5–2.0 m. The height of the open space under the board is normally 1.2–1.5 m.

If the open space under the board is too small, the area of weak wind increases in front of the board, which results in sand accumulation. If the space is too big, the ability to funnel wind and release sand is weakened. The board used to release sand on the road is made of timber plates that measure 1.5 m high and 2 m wide. One hundred meters of board (about 50 plates) consumes 1.5 m^3 of timber. Boards should be connected to posts with a diameter of at least 10 cm. A 7 m length of wire can be used to tighten boards to the posts. One hundred meters of boards requires 3–4 m^3 of timber posts. If boards are made of metal plates, holes must be drilled in the metal plates to fix the boards to the network-shaped frame made of angle iron or flat iron. Metal posts should be buried, and then the metal plates should be screwed onto the metal posts. Metal boards are durable and effective but very costly.

Boards should be erected at an angle of $\sim$70°–80° to the main direction of the wind. The metal posts are buried 1.5–2.0 m deep and extend 4.5–5.0 m above ground. The width of the metal board should be longer than the portion of sand accumulation on the road. Otherwise, some sand accumulation will occur along the two sides of the boards.

In addition to wind baffle boards, horizontal and vertical boards have proven useful (Fig. 9.2 and 9.3). The only difference between the designs of the two boards is their installation.

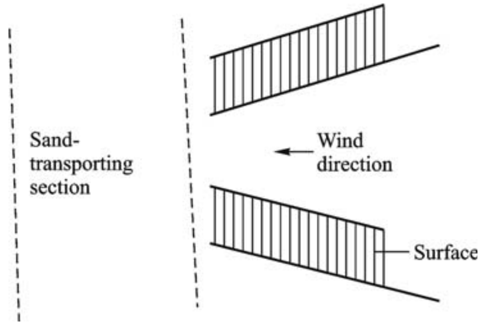

Fig. 9.2 Horizontal sand barriers (Ci, 2002, with permission from author)

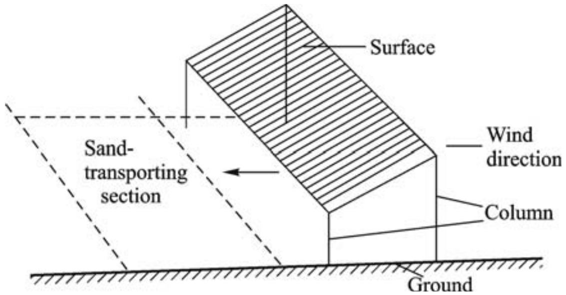

Fig. 9.3 Vertical sand barriers (Ci, 2002, with permission from author)

9.2 Mechanical sand barriers to control shifting sands

Mechanical barriers used to control shifting sands refer to measures to place various obstacles, made of wheat straw, hay, tree branches, clay, gravel, stone materials and sandbags, on moving sand surfaces. This technique is designed to change wind direction and velocity and to limit denudation and erosion. The nature of this technique is similar to the mechanical sand-blocking and sand transporting/sand-releasing techniques. Mechanical sand barriers have played a central role in controlling sand movement and dune stabilization in the sandy deserts of China. In regions with harsh environmental conditions, the mechanical sand barrier is the leading measure taken to control sand movement and stabilize dunes. In areas where conditions are less-harsh, the mechanical sand barrier is a necessary approach and ensures the success of biological approaches. During the past decades, practices for controlling sand movement and sand dune stabilization in China have shown that the mechanical sand barrier and biological approach are alternative solutions for fixing mobile dunes and stabilizing sand movement. Given the function of the mechanical sand barrier and its significant effects in sand stabilization and dune fixation, biological approaches will not replace mechanical barriers.

9.2.1 Types and principles of mechanical sand barriers

9.2.1.1 Types of mechanical sand barriers

Mechanical sand barriers can be classified into horizontal and vertical sand barriers according to sand control principles and different installation methods. Horizontal barriers can be classified into strip-installed and full-installed barriers. Vertical barriers can be classified into taller sand barriers (50–100 cm high over the sand surface), shorter sand barriers (semi-hidden sand barriers, 20–50 cm high over the sand surface) and hidden sand barriers (fully buried in the sand or only a small portion exposed on the sand surface). Vertical barriers can also be classified as ventilated, closed and unventilated types based on differences in their ventilation.

9.2.1.2 Principles of mechanical sand barriers for sand control

(i) Horizontal sand barriers: This type of barrier is designed to protect shifting surface sand from wind erosion. Mulch materials include straw, hay or grasses, stones and clays, emulsion asphalt and polyamide polypropylene fibers, and other chemical materials. These will prevent wind erosion from loose sand surfaces, which will not add more sand particles into the wind flows. However, this method is not very effective at catching sand particles in wind flows.

(ii) Vertical sand barriers: This type of barrier is mostly designed to accumulate drifting sand. Wind flow is disrupted by obstacles, and velocity is reduced. As a result, some sand particles or even sand drifts will be stopped, precipitate and accumulate around the obstacles. Vertical sand barriers are used along roads, communication lines and traffic facilities where shifting sand or sand drifts pass through.

(iii) Ventilated sand barriers: Scattered turbulence flows form as blown sand flows pass across the interspaces of this type of sand barrier. Friction increases, and kinetic energy is reduced as sand grains collide. The sand carrying capacity of the wind decreases as wind speed is reduced. Sand then accumulates both in front of and behind the sand barriers. Small amounts of sand accumulate in front of the sand barrier reducing the likelihood that the sand barrier will be buried. Large amounts of sand will be deposited behind the barrier which will stretch longitudinally and may extend for a long distance.

(iv) Unventilated or closed sand barriers: When blown sand flows pass through a sand barrier, they rise in front of the sand barrier and then immediately fall after passing through this type of barrier. Strong eddies will occur in front of and behind the sand barrier. The effects of eddies and sand particles colliding will cause wind velocity to decrease and the sand carrying capacity of the air current to weaken. Consequently, sand particles accumulate in front of and behind the sand barrier.

(v) Hidden sand barriers: A hidden barrier is a vertical sand barrier buried in the sand. The top of the barrier should be level with the sand surface or extend only slightly above the sand surface. This type of barrier does not affect blown sand flows above ground but stops the movement of sand across the ground surface. Hidden sand barriers control the base level of erosion. Although wind erosion will occur following installation of the hidden sand barrier, erosion process will not expand downward (Ding, 2007).

9.2.2 Technical criteria for designing sand barriers

9.2.2.1 Porosity of sand barriers

Usually, the ratio of the area of the open pores (or gaps) and the total area of the sand barrier is referred to as the porosity and is used as an indicator to measure ventilation performance. When the porosity is approximately 25%, sand accumulation in front of the sand barrier is two times the height of the barrier, and sand accumulation behind the sand barrier is 7–8 times the height of the barrier. When the porosity is 50%, almost no sand accumulates in front of the barrier, and sand accumulation behind the barrier is 12–13 times the height of the sand barrier. The smaller the porosity is the less sand accumulates behind the barrier. As a result, the sand barrier is quickly buried windward and its function to stabilize shifting sands is lost. On the contrary, as porosity increases, more sand is accumulated over a larger scale and the effective life for stabilizing shifting sands is longer. To achieve more effective sand control under local conditions, the size of the porosity should be determined based on wind speed and sand source. Usually, the ventilation performance with 25–50% porosity is reasonable. In regions with strong wind and less sand, the porosity should be smaller, but with more sand, the porosity should be larger.

9.2.2.2 Height of sand barriers

Under the same sandland conditions and sand barrier porosity, the amount of sand accumulation is directly proportional to the square of the height of the sand barrier. The height of a sand barrier is normally about 30–40 cm, and the maximum height is 100 cm.

9.2.2.3 Direction of sand barriers

Sand barriers should be installed at a right angle to the prevailing wind and normally erected on the windward slope of a sand dune. Before installing the barriers, a line should be drawn as a reference in the middle of the sand dune in the same direction as the prevailing wind. This is because the wind in the middle of the sand dune is stronger than at the two sides of the dune. Thus, the angle between the sand barrier and reference line should exceed 90°, but it should not exceed 100°. By doing so, the wind at the middle of the sand dune could shift to the two sides of dune. If the angle between the sand barrier and reference line is less than 90°, the air current is concentrated at the middle of the dune. Consequently, the sand under the barrier will be easily denuded or the barrier buried by shifting sands (Fig. 9.4).

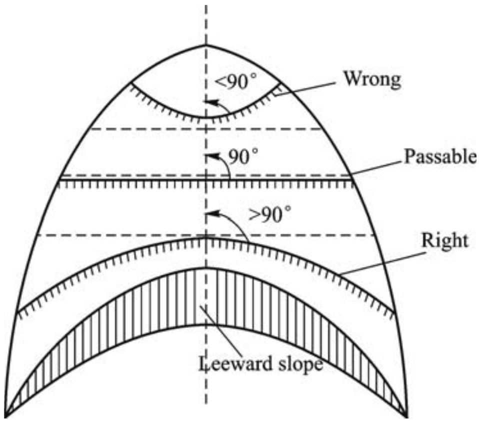

Fig. 9.4 Schematic diagram showing installation direction of sand barriers on windward slope (Ci, 2002, with permission from author)

9.2.2.4 Types and forms of sand barriers

Sand barriers are generally installed in row, network, herringbone, swallow wing and fish-bone shaped patterns. This section mainly describes rows and networks.

(i) Row-shaped installation: This kind of sand barrier is normally installed in the area where the prevailing wind is unidirectional. When the barrier is installed on the windward slope of a barchan dune, the top part of the dune should remain free of any barrier. The barrier should be erected along a barchan-shaped line. The barrier on barchan dune chains should be installed in arc shapes according to the shape of the barchan dune. Where two barchan dunes meet, wind funnels form resulting in severe denudation and frequent sand transport. Therefore, the distance between barriers should be small in these areas.

(ii) Network-shaped installation: This sand barrier is mainly used in sand areas with changing prevailing wind directions and strong side winds. Square network-shaped and rectangle network-shaped barriers should be selected based on wind direction.

9.2.2.5 Interspace between sand barriers

The interspace between barriers refers to the distance between two nearby barriers. When the distance between barriers is too large, the sand barrier is easily eroded and destroyed. If the interspace is too small, construction of the barrier will be too costly in terms of materials and manpower. Thus, the proper interspace between sand barriers should be reasonably determined before installation.

The interspace between barriers is related to the height of the sand barrier and the angle of the dune slope. Wind force should also be considered. High sand barriers should have large interspaces, and lower sand barriers should have small interspaces. The interspace should be small on dunes with steep slopes and large on dunes with gentle slopes. The interspace between sand barriers should be wide where wind is weak and narrow where wind is strong. On average, on a gentle dune with less than 4° slope, the interspace should be 15–20 times the height of the sand barrier. On undulating dune surfaces, the interspace should be calculated according to the height of the sand barrier and angle of the slope. The equation is:

$$D = H \text{ ctg } a \tag{9.1}$$

Where D is the interspace between sand barriers; H is the height of the barrier; and a is the angle of the dune slope.

The interspace of the clay sand barrier is 2–4 m, and the height of the barrier is 15–20 cm. Experiments show that the best design for a clay sand barrier in severely blown sand affected areas is a 1 m × 1 m or 1 m × 2 m square-shaped clay checkerboard. The amount of clay used for constructing a clay sand barrier should be determined by the barrier interspace and the size of clay bank. The equation is:

$$Q = 1/2 \; ahs \cdot (1/c_1 + 1/c_2) \tag{9.2}$$

Where Q is the required amount of clay for constructing the clay sand barrier; a is the bottom width of the clay sand barrier; h is the height of the barrier; c_1 is the interspace between the clay banks vertical to the prevailing wind; c_2 is the interspace between the clay banks parallel to the prevailing wind; and s is the total area of the installed barriers.

9.2.2.6 Selection of materials for sand barriers

When selecting materials for constructing sand barriers, durable local materials that have lower costs and no negative effects should be considered. Normally, wheat straw, stones or gravel, tree branches and clay or hard soils from local sources are good options for barrier installation materials (Ding, 2007).

9.2.3 Methods for installing sand barriers

9.2.3.1 High vertical sand barriers

Materials: Tall grasses, reeds, tree branches and tall crop residues (such as corn stalks).

Installation methods: Bundle the sand barrier materials having a height of 70–130 cm, and then bury them along the designated lines and shapes on the dunes or sandland to a depth of 20–30 cm. The base of the barrier must be packed tightly, and a small, 10 cm sand ridge should be made at the base. Installation should be done following rainfall, as wet sandy soil is easier to compact.

9.2.3.2 Movable high vertical barriers

Materials: Timber plate and nails.

Installation methods: A closed vertical barrier is made of timber plates and installed in rows. The height is similar to the height of the high vertical sand barrier (70–130 cm). This barrier is movable and can be re-installed or moved at any time in response to a change in wind direction.

9.2.3.3 Semi-shallow straw barrier

Materials: Straw and other soft weedy materials.

Installation methods: Draw guidelines with lime, and then spread the materials (straw or weeds) evenly on the sand surface along the lines. Use a spade and hoe to press the straw 10–15 cm into the sand, and then compact both sides at the base.

9.2.3.4 Low clay sand barriers

Materials: Clay.

Installation methods: Installation guidelines should be marked on the surface before beginning. Clay should be placed along the lines. Make a small, triangle-shaped, 15–20 cm high clay bank. Be aware that any breach of these clay banks will cause denudation in strong winds.

9.2.3.5 Mulching sand barriers

Materials: Adhesive or hard-textured materials such as clay, gravel, brick, debris, colloid material and crude oil.

Installation methods: Spread mulching materials evenly on the sand surface with a thickness of 5–10 cm. Gravel should be spread evenly without open holes to protect the mulched surface from denudation.

9.2.3.6 Sandbag barriers

Materials: Nylon or fabric sandbags.

Installation methods: These sandbags must be made of durable materials treated with antioxidants and filled with sands so that each sandbag is about 10 cm thick. They are then installed on dunes to control sand movement and denudation. Bags are easy to stack, transport and install and can be reused many times. This technique has recently become popular and is often used with new materials.

9.2.3.7 Scattered mulching sand barriers

Materials: Tree branches, crop residuals and other plant materials.

Installation methods: These materials should be cut to the proper length and spread evenly on the shifting sand surface. This method is normally used in sand areas with low wind velocity and weak denudation or erosion potential.

9.2.4 Effectiveness of sand barriers

Vertical sand barriers play an important and effective role in stabilizing shifting sands. They are suitable for dune fixation in undulating sand areas with trich sand sources for from the protected areas. The disadvantage of this sand barrier is that it can cause sand accumulation around itself. Therefore, this vertical sand barrier should not be used to stabilize shifting sands nearby the protected areas. Moreover, this type of sand barrier needs a lot of manpower and materials and requires frequent maintenance after installation.

Clay sand barriers are low-cost with local materials and require little transport and manpower. This type of sand barrier has high water-holding capacity, which is helpful to plant growth, but is limited to regions where clay is available. Network straw checkerboards, wheat straw networks, sandbags and other sand barriers need sufficient local materials but are easier to use, are inexpensive and can cause a remarkable increase in surface roughness, a sharp reduction in wind velocity and significant effects in stabilizing shifting sands and mobile dunes.

9.3 Chemical measures for sand stabilization

The purpose of chemical sand stabilization is to provide a stable surface on the sand by spraying diluted cohesive chemical materials on the shifting sand surface. After treatment, water within diluted chemical materials quickly infiltrates into the deeper sand layer, while cohesive chemical materials remain in pores of the sand surface layer and congeal with sand particles to form a hard protective crust on the sand surface. Thus, air flows are restricted from contacting loose sand, and consequently, the sand surface is protected from wind erosion. This method can stabilize shifting sands in situ and cannot control sand particles within airflows. Chemical sand stabilization techniques are mainly used along communication lines and transport facilities in areas with highly mobile sands and around military bases and mineral and industrial sites in sandy deserts.

Chemical sand stabilization techniques have been used for 70–80 years; however, the chemical materials used today are much the same as those used during the 1930s and 1940s. Some chemical materials have been slightly improved upon with the addition of different compounds.

9.3.1 Asphalt emulsion for sand stabilization

Asphalts are black, organic, oil-based viscous material composed of 70–80% carbon, 10–15% hydrogen, 1–5% oxygen, 2–8% sulfur and 0.5–2% nitrogen, which are cohesive, waterproof (non-permeable and non-soluble) and resist corrosion. The physical and chemical properties of asphalt are more or less related to the proportion of oxygen, sulfur and nitrogen. The grade of asphalt is normally determined by its emulsible temperature (melting point), specific gravity and hardness.

Asphalt emulsion is composed of petroleum asphalt, emulsifier and water. Combined with emulsifier, it is a two-phased material diffused with asphalt into water. The asphalt particles are referred to as the diffusion phase, or internal phase, the water is referred to as the continuous phase, or external phase, and together this liquid is called oil-in-water emulsion. According to the electric charge of the liquid drops, the asphalt emulsion can be classified as a cation, anion, amphoteric ion or non-ion. According to the separation speed of asphalt from water upon touching sand particles, asphalt emulsion can be classified as quick separation, medium separation or slow separation.

The slow-separation asphalt emulsion, composed of HD-200/300 and HD-130/200 asphalts, is often used as a cohesive agent to temporarily stabilize the sand surface. The asphalt emulsion can remain on the sand surface for 2–3 years to control wind erosion and prevent denudation. Before spraying the asphalt emulsion, the sand surface should be watered to increase the depth of penetration of the asphalt emulsion. The depth to which asphalt emulsion will permeate into dry sand and wet sand is 10–15 cm and 20–30 cm, respectively. Asphalt emulsion will form a thin porous film (2–3 mm) on the sand surface. This film can be easily crimped and broken at the edges. Thus, the asphalt emulsion content should be no more than 10–15% while diluting the asphalt emulsion. Trampling by humans and animals should be avoided.

In addition, asphalt emulsion should be stored with a temperature not lower than 0 °C. To avoid dehydration, asphalt emulsion can be kept in an air-tight container. During long distance transport, 0.5 kg caustic soda should be added for every 10 tons of asphalt emulsion to avoid separation of the asphalt emulsion.

9.3.2 Asphalt compounds for sand stabilization

An asphalt compound is a type of dark-brown cohesive mixture containing asphalt or adhering oil, water and mineral powders (loess, loam soil, cement and lime). It is stirred in a cement mixer and can be directly sprayed onto the shifting sand surface with a mud pump.

9.3.3 Latex emulsion for sand stabilization

Latex emulsion is used to stabilize shifting sands by simply spreading over the sand surface. This latex emulsion can form a thin film with good elasticity. To stop shifting sands where wind velocity is approximately 6 $m \cdot s^{-1}$, 17.5 $g \cdot m^{-2}$ of latex emulsion should be used. When wind velocity is 10–12 $m \cdot s^{-1}$, the amount should be as high as 26.0–28.5 $g \cdot m^{-2}$.

9.3.4 Peat emulsion for sand stabilization

This method can be used in peat-rich areas of low-lying swamps among drylands. Treated peat emulsion can be used to stabilize shifting sands. The method to make peat emulsion is simple and can be widely used in peat-rich regions.

9.3.5 Adhesive agents for sand stabilization

This is an integrated method that has great potential to control shifting sand and is a simple method to agglomerate sand particles. Adhesive agents can be evenly sprayed on the sand surface to form a thin layer of integrated adhesive agents and underlying sand. The treated area should then be ploughed to break the agglomerated sand layer into small sheets that will withstand strong wind. These small sheets are effective at controlling wind and fixing sands. The latex can be used as the adhesive agent to create small sheets.

9.4 Hydraulic engineering measures to combat desertification

Hydraulic engineering usually involves various engineering works built to control and relocate surface water and ground water, to wisely use water resources, to alleviate potential flooding disasters and to promote local sustainable economic development. In recent decades, hydraulic engineering techniques have advanced rapidly, especially in arid and semi-arid regions in northern China where hydraulic engineering plays an important role in controlling water erosion and in mitigating and preventing blown sand disasters.

9.4.1 Storage and drainage engineering on slopes

Storage and drainage engineering on slopes refers to various water storage and drainage facilities constructed for controlling water erosion on slopes. The facilities function to harvest runoff on slopes for irrigation, to discharge surplus runoff, to protect slopes from erosion, to reduce sediment amount and to protect foothill farmlands. Storage and drainage engineering is usually designed and arranged together with constructed terraces and revegetation. The engineering should also be coordinated with the construction of irrigation channels, water ditches and road networks. At the same time, runoff interception ditches, drainage systems, canals, sedimentation ponds and water-storage ponds should be established.

9.4.1.1 Runoff-interception ditches on slopes

The purpose of runoff-interception ditches on slopes is to catch runoff on slopes. It shortens the slope length, cuts the runoff flow distance, reduces runoff erosion, harvests storm runoff on slopes and collects and transports the harvested runoff to a water storage dam or to irrigate farmland, forestland or grassland.

(i) Layout of the runoff-interception ditch

Runoff-interception ditches can be constructed on slopes less than 25° parallel with the contour and connected with drainage trenches perpendicular to the contour. The distance between ditches (distance on the slope) should be determined by the grade of the slope. The relationship between the grade of the slope and the inter-ditch distance is shown in Table 9.1.

Table 9.1 Slope grade and corresponding inter-ditch distance

SG	IDD	SG	IDD	SG	IDD
3	30	7	19	14–16	14
4	25	8	18	17–23	13
5	22	9–10	16.5	24–37	12
6	20	11–13	15	38–40	11.5

SG: Slope grade (%); IDD: Inter-ditch distance (m).

(ii) Design of the cross section of the runoff-interception ditch

The water volume (V) of each runoff-interception ditch can be calculated from the following equation:

$$V = V_w + V_s \tag{9.3}$$

Where V is the volume of the runoff-interception ditch (m^3); V_w is the runoff volume of one storm (m^3); and V_s is the soil erosion volume in 1–3 years (m^3). The metric unit for V_s should be calculated in cubic meters (tons) based on local soil bulk density.

In the above equation, V_w and V_s are respectively calculated:

$$V_w = M_w \times F \tag{9.4}$$

$$V_s = 3M_s \times F \tag{9.5}$$

Where F is the catchment area of the runoff-interception ditch (ha); M_w is the runoff modulus of one rainstorm ($m^3 \cdot ha^{-1}$); and M_s is the annual modulus of soil erosion ($m^3 \cdot ha^{-1}$).

The cross-section area of the runoff-interception ditch, A_1, can be calculated based on the value of V:

$$A_1 = V/L \tag{9.6}$$

Where A_1 is the cross-section area of the runoff-interception ditch (m^2); and L is the length of the runoff-interception ditch (m).

When the design of the cross-section is determined, the width and a safe height of the ditch dyke should be selected according to attributes of the building materials. The width of a small clay dyke should be no less than 0.3 m, and the safe height should be decided according to the volume of flow in the ditch. If the flow volume is less than 1 $m^3 \cdot s^{-1}$, the safe height should be 0.2–0.3 m, and if the flow volume is 1–10 $m^3 \cdot s^{-1}$, the safe height of the ditch dyke should be 0.4 m.

The runoff-interception ditch is normally built up in a half-digging and a half-filling manner as a trapezoid section. The bottom is 0.3–0.5 m wide, the depth of the ditch is 0.4–0.6 m, the inside slope is 1:1 and the outside slope is 1:1.5.

9.4.1.2 Drainage ditch on the slope

The drainage ditch on the slope is designed to drain surplus runoff, to control slope erosion and to reduce sediment transport. It is a ditch built on the two ends of the runoff-interception ditch or at the lower end of the runoff-interception ditch.

(i) Layout of the drainage ditch on the slope

The gradient of the drainage ditch on the slope can be determined by the location of the water storage pond or the natural water drainage route. When the location of the drainage outlet is at the foot of the slope, the drainage ditch can be perpendicular to the contour. When the location of the drainage outlet is on a slope, the drainage ditch can be built along the contour or crossing the contour. The ditch at the two ends of the terraced farmland should be built perpendicular to the contour and in the same direction as the road at the two ends of terraced farmlands. If the drainage ditch is made of clay or mud, drops should be set up at different parts.

(ii) Design of a drainage ditch on the slope

The cross-section of a drainage ditch on the slope is generally designed based on peak flow from an average rainstorm event. This can be calculated by the equation of uniform flow in the open channel as:

$$A_{\triangle} = Q/C \times (Ri)^{1/2} \tag{9.7}$$

Where $A_{\triangle}$ is the area of the drainage ditch cross-section (m^2); Q is the peak flow on the slope ($m^3 \cdot s^{-1}$); C is the Chezy coefficient; R is hydraulic radius (m); and i is the gradient of the drainage ditch.

i) Calculation of the Q value: The designed peak flow of a small catchment on the slope is calculated with a regional experience equation.

$$Q_P = KI^m F^n (F \geqslant 10\ \text{km}^2) \tag{9.8}$$

$$Q_P = C_p F^n (1\ \text{km}^2 < F < 10\ \text{km}^2) \tag{9.9}$$

$$Q_P = C_p F (F \leqslant 1\ \text{km}^2) \tag{9.10}$$

Where Q_P is the designed peak flow of an average rainstorm event ($m^3 \cdot s^{-1}$); K is an overall coefficient determined by ground surface slope, river network density, river course gradient, rainfall duration, watershed form and other elements; I is the net rainfall depth for an average rainstorm event (mm); M is an index relating peak flow to flooding flow; F is the catchment area of the slope drainage section (km^2); n is the decreasing index along with the increase of the catchment area; and C_p is the integrated parameter related to the given frequency.

ii) Calculation of the R value:

$$R = A_{\triangle}/x \tag{9.11}$$

Where x is the wetted perimeter of the drainage ditch (m), which refers to the total length of the water flow touching the ditch trough cross-section;

Rectangle cross-section: $$x = b + 2h \tag{9.12}$$

Trapezoid cross-section: $$x = b + 2h(1 + m^2)^{1/2} \tag{9.13}$$

Where b is the bottom width of the ditch (m); h is the water depth (m); and m is the coefficient of the inside slope of the ditch determined by the ditch depth and soil texture. This coefficient can be determined by referring to Table 9.2.

Table 9.2 The value of the coefficient (m) on the inside slope of the drainage ditch

Soil texture	Digging section			Filling section		
	(1)	(2)	(3)	(1)	(2)	(3)
Clay or loam soil	1.00	1.00	1.25	1.00	1.25	1.50
Slight loam soil	1.00	1.25	1.50	1.25	1.50	1.75
Sandy loam soil	1.25	1.50	1.75	1.50	1.75	2.00
Sandy soil	1.50	1.75	2.00	1.75	2.00	2.25

(1): Water depth <1 m; (2): Water depth 1–2 m; (3): Water depth 2–3 m.

iii) The C value: calculated with the Manning equation in most cases:

$$C = 1/n \cdot R^{1/6} \tag{9.14}$$

Where n refers to the roughness of the ditch, which is about 0.025 for earth ditches.

iv) The selection of the i value: The i value is determined by the topography and soil texture along the ditch, which is normally similar to the ground surface gradient. It is common to use 0.2–0.5.

The actual peak flow of the drainage ditch should be higher than the average peak flow, namely $Q \geqslant Q_{\mathrm{P}}$. Otherwise, the h, b, and i values should be readjusted, re-calculated and rechecked until the conditions are met.

9.4.1.3 Water-storage ponds

Water-storage ponds are built to make full use of runoff from slopes to mitigate effects of drought.

(i) Layout of water-storage ponds

Water-storage ponds are normally built at a low section or at the foot of a slope that is connected to the end of a drainage ditch or runoff-interception ditch to harvest runoff from the slope surface. The location and storage capacity of the ponds should be determined by the total volume of runoff harvested, the relationship between water storage and drainage and the eases of construction and water-use.

(ii) Water-storage pond design

The size, shape, area, depth and slope of the water storage pond can be designed according to the local landform and the total water-storage volume.

The total storage volume can be calculated according the following equation:

$$V = K(V_w + V_s) \tag{9.15}$$

Where V is the water storage of the pond (m^3); V_w is the runoff volume of an average rainstorm (m^3); V_s is the accumulated sediment volume (n years, m^3); and K is the safety coefficient (1.2–1.3). The values of V_w and V_s can be calculated according to the designed drainage volume and the sedimentation volume of the drainage ditch.

The intake and outlet areas of the ponds should be constructed of stone materials. The cross-section over which water flows can be checked by the equation of the rectangular broad-crested weir, namely:

$$Q = M \cdot (2g)^{1/2} \cdot bh^{3/2} \tag{9.16}$$

Where Q is the maximum flow volume of the intake or outlet ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$); M is the flow volume coefficient of 0.35; g is the gravity acceleration at 9.81 $\mathrm{m{\cdot}s}^{-1}$; b is the width of the broad-crested weir (m); and h is the water depth at the weir crest (m).

(iii) Sedimentation pond

To reduce the sediments in water-storage ponds, sedimentation ponds should be constructed at the upper part of the intake of water-storage ponds. The sedimentation pond should be rectangle shaped with a width two times wider than the drainage ditch and a length two times longer than its own width. The usual width of a silt-mud sedimentation pond is 1.0–2.0 m, the length is 2.0–4.0 m and the depth is 1.5–2.0 m. The intake and outlet of the sedimentation pond should be designed similarly to these of the water-storage pond and be made with stone materials.

9.4.2 Engineering in gullies and hilly valleys

Hydrological projects and facilities are built in valleys to stabilize valley banks, accumulate sediment, and control or alleviate flooding and debris flows. These facilities not only harvest runoff from rainstorms, control sediment accumulation and reduce soil erosion, but also slow down and reduce flood peaks and flood volume, increase water volume of a river and extend the life of the water-storage pond or dam.

9.4.2.1 Check dams

Check dams are normally constructed in small valley branches of a watershed, stream gully or canyon. The height of the dam is 3–5 m, and the sediment accumulation volume is less than 1,000 m^3.

(i) Types of check dams

Check dams can be classified depending on construction materials, permeability and duration of use. Classification based on construction materials includes earth dams, stone dams, *Salix* plantation dams, cement dams, reinforced concrete dams and wooden dams . Permeability includes permeable dams (stone and *Salix* plantation dams) and impermeable dams (earth and cement banks). Check dams based on duration of use include temporary dams (earth and stone dams) and permanent dams (cement and reinforced concrete dams).

(ii) Layout of check dams

Check dams should be small in size and widely distributed, starting at the upper part of the stream and then moving downstream. Check dams should be built one by one on the whole slope. A check dam should be located in the valley bottom with less than 5–10% gradient where the outlet is narrow and the upper stream is wider.

(iii) Check dam design

Design indicators of a bank include dimensions, distance between dams and spillway.

i) Dimensions

Table 9.3 shows the dimensions of common types of earth and stone dams.

ii) Distance between dams

The height of and distance between check dams are two interrelated and limiting parameters. When the height of the bank is well designed, the top of lower check dam is level with the bottom of the next higher check dam. This design is used to determine the inter-distance and number of dams, which will help avoid water inundation at the bottom of the higher check dam and will also increase the stability of the dam.

Table 9.3 Dimensions of check dams in northern China

Types	Dimensions of dam sections			
	Height (m)	Dam crest width (m)	Upstream slope	Downstream slop
Clay dam	2.0	1.5	1:1.2	1:1.0
	3.0	1.5	1:1.3	1:1.2
	4.0	2.0	1:1.5	1:1.3
	5.0	2.0	1:1.8	1:1.5
Mortarless pebble check dam	1.0–2.0	1.0–1.2	1:0.5∼1:1	1:0.5
Mortarless block-stone check dam	1.0–3.0	1.0–1.2	1:0.5∼1:1	1:0.5

The distance between dams can be calculated by the following equation:

$$L = H/(I - I') \tag{9.17}$$

Where L is the distance between the dams (m); H is the height of the dam (m); I is the original gradient of the valley bottom (%); and I' is the gradient of the dam filled up with sediment (%). Usually, the gradient of coarse sands (with gravel or stone) is 2.0%, the gradient of clay is 1.0%, the gradient of loam is 0.8% and gradient of sandy soil is 0.5%.

iii) Spillway

To avoid destruction of the check dam by severe floods, a spillway for stone check dams should be made in the middle section at the top of the dam. The spillway for an earth dam should be built on hard earth or bedrock at one side of the dam. The spillways of the two nearby check dams should be built, if possible, in different locations of the dams.

9.4.2.2 Sediment storage dam

Sediment storage dams are normally installed in main valleys or large valley basins to block sediment, to reduce flooding and to control debris flow to downstream areas. The height of the dam should be over 5 m, and the sediment storage volume should be over 10–100 m^3.

(i) Types of sediment storage dams

i) Stone dam

Stone dams include mortarless stone dams and mortar stone dams. A mortar dam is a gravity dam with a simple structure and is one of the most widely used dams. It is trapezoid-shaped with an upstream slope of 1:0.5 and a downstream slope of 1:0.2. Mortarless stone dams are also trapezoid-shaped and are suitable for small flood gullies.

ii) Mixed dam

According to the materials used, mixed dams can be classified as earth-stone mixed dams and wood-stone mixed dams.

The dam body of an earth-stone mixed dam is filled in with earth, mud or clay, but the top and bottom of the dam is built with mortar stone. The dam is trapezoid-shaped. When the height of the dam is 5–10 m, the upstream slope is 1:1.5–1:1.75, the downstream slope is 1:2–1:2.5 and the width of the dam top is 2–3 m. To prevent water leakage from the dam body, clayey and waterproof layers should be built on the upstream slope of the dam, and drainage pipes should be installed at the foot of the downstream slope. An earth-stone mixed dam is used in regions where there are little stone materials but plentiful earth resources.

The dam body of a wood-stone mixed dam is built with a framework of wood pillars about 0.1 m in diameter, which is filled with stones and rocks. The top of the dam and upstream slope are always built with mortar stone to prevent them from being destroyed by floods. This dam is used in regions with rich timber resources.

iii) Arch-shaped dam

An arch-shaped dam is built with mortar stone or concrete, and the body is arch-shaped. The two sides of the dam are built on hard bedrock. Pressure from floods and sediment on the upstream side of the dam is mostly absorbed by rocks at the two sides of the dam body. The remaining pressure is transferred to the dam bottom. The arch-shaped dam has a high capacity to resist pressure because of the mortar stone and concrete building materials. Therefore, the thickness of the dam body can be slightly reduced. This dam uses less manpower and inexpensive building materials. It is estimated that about 25–30% building materials will be saved compared to constructing other types of similar-sized dams. This dam is suitable in regions with a narrow valley and riverbed and rocky side slopes.

iv) Grid-shaped dam

The grid-shaped dam is a new type of sediment storage dam that has been developed in recent decades. It has good permeability and can selectively block sediments. Constructing this dam uses less manpower and can save 30–50% on building materials compared with other dams. There are several kinds of grid-shaped dams, including concrete grid-shaped dams and metal grid-shaped dams.

(ii) Sediment storage dam height

Generally, the higher dam is the more sediment it accumulates. However, a higher dam body is more expense. Small sediment storage dams are 5–10 m high, medium dams are 10–15 m high and large dams are over 15 m high.

(iii) Sediment storage dam design

Dimensions. Table 9.4 lists dimensions of a mortar stone dam.

Stability calculation. There are many stresses acting on the body of the dam, such as the weight of the dam, sediment weight, water pressure and force of impact from mudslides and earthquakes . By calculating these acting forces, the most severe combination of acting forces is used to calculate stress and anti-sliding stability to guarantee that the dam is built to withstand these external forces.

Table 9.4 Dimensions of a mortar stone dam

Dam height (m)	Dam crest width (m)	Dam bottom width (m)	Upstream slope	Downstream slope
3	1.2	4.2	1:0.6	1:0.4
4	1.5	6.3	1:0.7	1:0.5
5	2.0	9.0	1:0.8	1:0.6
8	2.5	16.9	1:1	1:0.8
10	3.0	20.5	1:1	1:1.8

Calculation of spillway. The shape of the spillway is usually trapezoidal. The side slopes are 1:0.75–1:1. An arch shape is the best design for the debris flow gullies with rich solid materials.

Downstream energy consumption facilities. Water overflowing the top of the dam has a large amount of energy. It is possible that the base of the dam and the riverbed downstream can become severely eroded and deformed. Thus, solutions to dissipate this energy must be offered. These solutions include subsidiary dams (side dams) and aprons. Subsidiary dams are suitable for floods and debris flows in large and medium valleys. This energy-dissipation facility is composed of one subsidiary dam to reduce the energy of floods and debris flows. The top of the subsidiary dam should be 0.5–1.0 m higher than the bottom of the upstream sediment storage dam to guarantee that the height of sediments in the subsidiary dam is higher than the bottom of the main dam. The distance between the subsidiary dam and the main dam should be 2–3 times the height of the main dam. The apron is only suitable in small valleys or gullies and is normally built with mortar stone. Its length is 2–3 times the height of the main dam.

9.4.2.3 Silt storage dam for farmland formation

A silt storage dam is built in a valley to block sediment and form farmland. It is used to deter floods, block silt and level farmlands in line with objectives for the development of agriculture, forestry and fruit production. The silt storage dam is an important solution used in integrated rehabilitation of small watersheds.

(i) Structure of the silt dam

A silt dam is composed of the dam body, spillway and water release works (Fig. 9.5). The dam body is used to block floods, accumulate sediments and heighten the floodplain terrace. The spillway is used to drain and spread flood waters. When it overtops the designated water height, floodwater drains through the spillway to guarantee safety of the dam body and formed farmland. Water release works usually consist of vertical wells and horizontal pipes.

These structures are used to drain clear water from the dam.

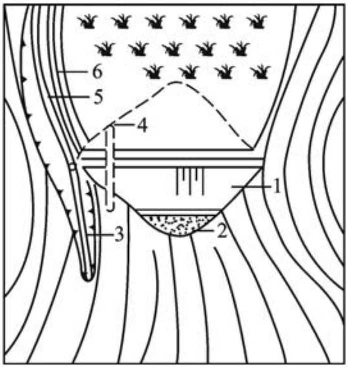

Fig. 9.5 Diagram of silt storage dam

1—dam body; 2—water drainage body; 3—spillway; 4—vertical well; 5—horizontal pipes; 6—flood prevention bank

(ii) Types of silt storage dams

Small silt storage dam: 5–15 m high; storage capacity is 10,000–100,000 m^3; catchment area is less than 1 km^2. This dam is normally built in small branch gullies and upstream of medium branch gullies.

Medium silt storage dam: 15–25 m high; storage capacity is 100,000–500,000 m^3; catchment area is 1–3 km^2. This dam is normally built downstream in large branch gullies or upstream of or in middle stream sections of main gullies.

Large silt storage dam: over 25 m high, storage capacity is 0.5–5 million m^3; catchment area is 3–5 km^2 or more. This dam is mostly built in the middle or downstream of main gullies or downstream of large branch gullies.

(iii) Dam system layout

The dam system refers to the construction of a series of silt storage dams along one valley. The density of dams should be determined by the precipitation, gully gradient, gully density, local conditions at construction sites and advantages and disadvantages of development. Three to five dams per km^2 is a suitable density in the hilly-gully region of the Loess Plateau, which has a gully density of 5–7 $km \cdot km^{-2}$ and a gully gradient of 2–3%. In the relic tableland gully region of the Loess Plateau, which has a gully density of 3–5 $km \cdot km^{-2}$, dam density is 2–4 dams per km^2. In earth-rocky mountainous regions, it is reasonable to construct 5–8 dams per km^2.

(iv) Locations of dam sites

Basic requirements for a good dam site location include high water storage and land formation capacity, low construction costs and good security. The following points should be considered when selecting dam sites: (i) the dam site should be placed in a narrow and deep gully with large water-storage capacity, and the bottom of the valley should be wide and level; (ii) topographic and geologic conditions adjacent to the dam site should be suitable for constructing the spillway; (iii) materials for constructing the dam should be easy to obtain and easy to transport to the dam site; (iv) the geologic structure of the dam site must be stable. Loose earth and landslides are unfavorable for dam construction; (v) the location of the dam site should not be in valley basins, bends, spring wells or waterfalls; and (vi) to reduce overflow costs, the overflow area of the dam should avoid villages, cultivated lands, transportation facilities and mineral sites.

9.4.3 Floodwater and debris flow discharge engineering

9.4.3.1 Floodwater and debris flow discharge ditch

Floodwater and debris flow discharge ditches can be classified into three different types, namely, digging-filling discharge ditch, lime-sand-clay mixed-earth discharge ditch and mortar stone discharge ditch. Selecting an appropriate discharge ditch is primarily based on the nature of the gullies. The digging-filling discharge ditch is the easiest to make and is suitable in debris flow gullies. The mixed-earth discharge ditch is suitable for high sediment-carrying flood gullies. The mortar stone discharge ditch is suitable to narrow river courses where flood scouring is strong and water flow is rapid. The design of the floodwater and debris flow discharge ditch must ensure smooth drainage without sedimentation or flood-scouring.

9.4.3.2 Sedimentation basin

The sedimentation basin is designed to block sediments and stones. The following points should be considered when designing and installing the basin: (i) it can be constructed in valleys where slopes are steep, slope erosion is serious and flood and debris flow are frequent; (ii) it can be built in gully sections with gentle slopes; (iii) the sedimentation basin cannot be installed in sections where deposition is severe and debris flow will potentially threaten farmland, settlements or livelihoods; and (iv) when the sedimentation basin is filled with sediments and stones, a new sedimentation basin should be installed at a new location.

The capacity of a sedimentation basin is based on the quantity of silt-mud that would occur in 1–2 floods per year. When designing the capacity of the sedimentation basin, the geologic and topographic conditions, angle of the slope and vegetation of the valley should be surveyed.

The simplest design of a sedimentation basin is a wide gully section. All gully slopes should be protected with stone materials. Horizontal mortar stone wings are needed at the intake and outlet of the sedimentation basin. The upper and low parts of the gully beyond the sedimentation basin should be maintained at their original heights.

9.4.4 Irrigation engineering

In the arid and semi-arid regions of northern China, an integrated irrigation system includes:

(i) Water storage facilities: Reservoirs, catchments, silt storage dams or water-storage ponds that block and store river water or runoff are water storage facilities.

(ii) Water intake facilities: Referred to as channel head facilities, water intake facilities draw water from a river or a reservoir, or they pump underground water according to the condition of irrigation water supplies.

(iii) Water channeling facilities: All levels of channel systems that transport and distribute water to cropland are included, such as the main trunk channel, trunk channel, branch canal, lateral canal and field ditch, as well as water troughs, sluice gates and tunnel and waterfall slopes. Underground pipe facilities for irrigation purposes is also a necessary part of water channel facilities.

(iv) Irrigation ditches in field patches: Irrigation ditches in field patches include the sub-lateral canal, irrigation trench, small facilities along the channel stops and the pipe and devices for water-saving irrigation. These ditches or devices are necessary to distribute water to cropland and guarantee plant growth.

(v) Flood control and drainage facilities: Flood control and drainage facilities refer to all types of spillways, sluice gates and drawing flood facilities that protect channel and canal systems during flood seasons. They also include on-site and underground drainage systems that drain surplus water in fields.

Water-storage facilities and flood control and drainage facilities have been introduced above. Three other facilities are introduced as follows.

9.4.4.1 Water intake facilities

(i) Water channeling facilities

i) Water channeling without a dam: Facilities include the intake gate, sluice gate, scouring sluice and water diversion dykes. These facilities are normally used at the middle and upstream areas of rivers where water volume is sufficient, water level is stable and the topographic conditions are unsuitable for constructing a dam. Hetao irrigating areas channeling water from the Yellow River in Ningxia and Inner Mongolia use this method.

ii) Water channeling with a dam: Facilities consist of a cross-river dam, an intake gate, a sluice gate and flood control dykes. The dam is generally installed at a section with a narrow river course and good geologic conditions that reduce the costs and workload and also increase the stability and safety of the dam facilities and structures. This method is frequently used to pump, channel and draw water at the upper and middle reaches of the river or in mountainous and hilly regions.

(ii) Water pumping facilities

Water pumping facilities are hydraulic facilities that pump irrigation water to regions where flood irrigation is limited or where flood-irrigation systems are not economical. They consist of a pumping station and its affiliated facilities.

i) Site selection for the pumping station

The site for the pumping station should meet the following requirements: ① open topography; ② a solid foundation; ③ available electricity, ④ a reliable water supply; and ⑤ convenient transportation in a settled area. High elevation and large irrigation areas need multi-stage water pumping. The height of each pumping station should be determined based on the minimum amount of power needed and then be readjusted and corrected according to topographic conditions.

ii) Designed water flow and pump-lift height

The designed water flow can be determined by tracking the maximum irrigation flow during a continuous time period (from 2–25 days) in the process of water consumption in an irrigation system. Generally, the maximum ration for each irrigation event can be used to calculate the designed water flow of the pumping station. The designed pump-lift height of the pumping station can be calculated by the average actual pump-lift height plus water loss in the pipelines and canals.

iii) Pump selection and its affiliated facilities

The following principles should be considered when selecting a water pump: ① meeting the requirements of the water flow volume and pump-lift height; ② ensuring efficient and reliable operation of the pumping station; ③ the economic investment; ④ the convenience of maintaining and managing the pump; and ⑤ the convenience of integrated utilization.

The engine should be selected first. In regions without sufficient electricity or those that lack electricity, an internal combustion engine should be selected. However, sometimes natural energy sources can be used to drive small water pumps, such as solar, wind turbine and hydraulic energy.

(iii) Underground water uptake facilities

i) Types of underground water uptake facilities

Underground water uptake facilities in soil erosion regions of northern China include pipe wells, barrel wells, Karez wells, radiating wells, multi-pipe wells and subsurface water interceptors.

The pipe well: The tube well is the most popular well used to pump water from underground. It can be used to exploit deep or shallow underground water. The pipe well is mainly composed of a series of pipes, and water is pumped by mechanical force. Thus, it is also called a motor-pumped well. The pipe well consists of a well-head, side-wall pipes, filter pipes and silt-up pipes. Different pipes made of different materials are suitable for different wells of various depths. The steel pipe is suitable for a deeper well, and iron pipe is suitable for a well with a depth of no more than 250 m.

The barrel well: The barrel well is a large-caliber, vertical pumping well and is 1–5 m or more in diameter. It is suitable for exploitation of shallow underground water with a depth of 6–20 m. It is particularly feasible to use a shallow barrel well with a large caliber in aquifer layers with poor permeability in mountain areas. The barrel well is built with mortar brick or stone, and some are built with reinforced concrete. The barrel well has a simple structure, is convenient to maintain and uses indigenous materials. Due to limitations in depth, the barrel well can draw a small amount of water from underground. If there is an increase of water in thick aquifer layers or phreatic water layers, drilling should continue, and pipes should be installed at the bottom of the barrel well into the deeper layer to draw the phreatic water. This kind of well is termed a pipe-barrel well.

Karez well: The Karez well is a popular well used anciently in the arid Xinjiang region of western China. The Karez well (also known as the qanat well) is characterized by a horizontal ditch stretching from piedmont aquifers to lowlands where underground water then flows spontaneously to the surface. The Karez well is normally built at piedmont alluvial-proluvial fan areas. It consists primarily of open canals, underground canals (corridors), vertical wells and cisterns. There is a vertical well every 20–30 m, and the vertical well and underground canals are linked. The wellhead is oblong and 1 m long and 0.7 m wide. There are several tens or several hundreds of vertical wells in each Karez well system. There are several tens of meters of open canal at the outlet of the underground corridor of the Karez well, and the cistern is constructed for storing water at the end of the open canal. The length of the Karez well is at least 3 km, and the maximum length is usually 20–30 km.

Radiating well: When the permeability of the aquifer layer is poor and the water-drawing volume is insufficient, horizontal water pipes should be installed in aquifer layers surrounding the original vertical well to increase the water-drawing area and volume. Because the pipes radiate horizontally into aquifer layers, it is termed a radiating well. The well consists of a vertical collector well and many horizontal radiating pipes. The lengths of the radiating pipes vary from several tens to several hundred meters, and they are usually 50–200 mm in diameter. Through the radiating pipes, underground water flows into a collector well. The radiating well has a large area for collecting water and a large capacity for drawing water. The water-drawing volume per individual well measures as high as 1 $m^3 \cdot s^{-1}$. This well is especially suitable for drawing water out of loess layers.

Multi-barrel well: The multi-barrel well is a new type of well that pumps underground water and combines special characteristics of the radiating well and the steel-pipe well. Several plastic pipes (30–40 mm in diameter) fitted with filter devices are equidistantly buried in aquifer layers in circles. They are linked with collecting water pipes in a radial pattern and are then connected with the water pump. Because of the short pipes, this well is suitable for exploitation of shallow water. This well is simple in structure, light weight, has considerable water-drawing volume and is cost effective. It is popular in sandy areas in the north of Shaanxi Province.

Subsurface interceptor: leakage has become a serious problem due to sand, gravel and stone sedimentation in medium and small river streams in rocky mountainous areas. At times other than the flood season, water flow is limited in these rivers. Most water infiltrates the soil and flows away under the riverbed. On these river courses, subsurface interceptors are constructed to retain underground water flow for irrigation purposes. This is termed a subsurface interceptor. A subsurface interceptor facility consists of an intake facility, water transporting pipes, collector wells (pools), checking wells and intercepting walls (intercepting dams).

ii) Distance and number of irrigation wells

When the exploitation and recharging volumes of underground water are basically balanced, the water-pumping volume of the individual well and the irrigation area determine the distance between irrigation wells. The radius of the irrigation circle is used to decide the distance between wells. The distance (D) between wells can be calculated with the following equation:

$$D = (667QtT\eta/m)^{1/2} \tag{9.18}$$

Where Q is the water-pumping volume of an individual well ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$); η is the effective utilization coefficient of irrigation water; m is the quota of irrigation water; t is the number of irrigation hours of the well per day; and T is the number of required days for completing one irrigation cycle for the controlled irrigation area.

In regions with insufficient water supplies, when the recharge volume of the underground water cannot meet irrigation requirements, the number of wells and the distance between wells in a unit area can be determined according to the allowable exploitation modulus of aquifer layers and the water pumping volume of each well. The number of wells in a unit area can be calculated by the following equation:

$$N = \varepsilon/QtT \tag{9.19}$$

Where N is the average number of wells per km^2; ε is the allowable exploitation modulus ($\mathrm{m}^3 \cdot \mathrm{km}^{-2} \cdot \mathrm{a}^{-1}$); Q is the water-pumping volume of each well ($\mathrm{m}^3 \cdot \mathrm{h}^{-1}$); t is the working hours of the well per day; and T is the annual number of working days of the well.

The distance between wells (D) is:

$$D = 1\ 000(1/N)^{1/2} = 1\ 000(QtT/\varepsilon)^{1/2} \tag{9.20}$$

9.4.4.2 Water channeling facilities

Water-transporting canals for irrigation can be divided into several types based on topographic condition and the number of acres requiring irrigation. They include main canals, branch canals, lateral canals, field ditches and sub-lateral canals. To meet requirements necessary to transport and distribute water, a water distribution system also consists of a bifurcation gate, check gate, sluice gate, aqueduct, cascade, inverted siphon, water scale and other affiliated facilities. These should be installed and constructed along the water-transporting canals. At present, in arid and semi-arid areas that have characteristically low water supply and high losses from leakage, a mixed water-transport system should be gradually adopted. Main and branch canals should use open canals, and lateral canals and field ditches should use pipeline.

(i) Selecting canal and ditch systems

Main canal: The typical design is composed of a main canal installed along a contour and a branch canal vertically installed along a contour line and separated at the lower side of the main canal. Another design has the main canal vertically installed along the contour, when topography is backbone-shaped with laterals slanting toward the two sides. The branch canals are separated from the two sides of the main canal.

Branch and lateral canals: These canals draw water from main canals and redistribute it to the end users. Installation of branch and lateral canals should allow easy distribution of water, convenient irrigation, unblocked drainage, proper cultivation and sound cropland management. The distance between branch canals should be 2,000–3,000 m. In irrigated areas of plains, the natural landscape should determine the amount of acreage lateral canals can irrigate. The average irrigated land area is 200–300 ha and can be as high as 466.7–666.7 ha in some regions. But in mountainous areas, the amount of irrigated land varies, as do the length and distance between lateral canals. These distances should be fixed according to the landscape and topography and be based on site-specific needs and conditions.

(ii) Canal section design

A U-shaped canal is a popular open canal with low leakage. It is characterized by high hydraulic efficiency, smooth and rapid flow of water and high capacity to transport both water and sediment. Compared with the trapezoid canal, loss from transporting water in the U-shaped canal is reduce by 3.7% per km. Compared with the earth canal, loss due to water leakage in the U-shaped canal is reduced by 97% per km.

The trapezoidal canal is also another open canal with low leakage. It is characterized by high hydraulic efficiency, rapid water flow, even distribution of water, ease of restoration after freeze-thaw processes, less farmland occupancy and low costs of manpower and materials. The design of this canal is suitable for large and medium low-leakage canals or channels.

(iii) Facilities associated with canals and ditches

i) Facilities for regulating and allocating water volume

The accessory facilities constructed on the irrigation canal for regulating the water table and distributing water flow volume include the check gate, bifurcation gate and sluice valve (sluice gate). The bifurcation gate is a facility that draws water from the main canal to the branch canals. The sluice valve is installed at the intersection of the branch canal and lateral canals and controls and distributes the volume of water flow.

ii) Crossed facilities

Crossed facilities are the specific water-channeling devices, such as a tunnel, aqueduct, inverted siphon and culvert, built to cross streams, valleys, transport lines and roads or even over a hill ridge (using an inverted siphon).

iii) Waterfall related facilities

These facilities, including the declivity and cascade, are constructed at the center of a waterfall.

iv) Water discharge facilities

These facilities, including the spillway discharge dam and discharge sluice gate, are built for clearing remaining water in the canal when the irrigation system is under threat of damage.

v) Sediment-washing and sediment-accumulating facilities

These facilities are built at the head of the canal or in a channel system to reduce sediment accumulation within the canal system. They include the sediment-washing gate and sediment-accumulating sedimentation ponds.

vi) Water-measuring facilities

These are measuring devices installed along the canals to accurately control water drawing at different levels and to charge water fees. They include water gauges, water-measuring troughs, water measuring valves and water meters.

(iv) Low-pressure water pipe system

A low-pressure, water-transporting pipe system can be used to replace a water-transporting open channel. With a certain amount of pressure, water is led and distributed to crop fields via bifurcation gates and water pipes. The maximum working pressure of the water pipe is generally no more than 0.2 MPa, and the pressure at the farthest outlet of the pipe is 0.002–0.003 MPa. The low-pressure water pipe irrigation system is characterized by ① large water volume at the outlet and rapid water transporting; ② low leakage and evaporation; ③ high water use coefficient; and ④ no limitations due to topographic conditions. At present, the low-pressure, water-transporting pipe system is widely used in well-irrigated areas in China where ground water is the main water source.

9.4.4.3 Irrigation ditches in field patches

Irrigation ditches in field patches refer to the end water transporting facilities that are distributed within fields. It includes all fixed or temporary irrigation ditches and accessory facilities at various levels within the field patches. The field ditches usually run parallel with the road and at right angles to the higher-class canals. Crop fields should be kept square-shaped and similarly sized for convenience in cultivation.

In plains, the irrigation area of the field ditch is normally 33.3 ha, and the distance between field ditches should be 300–600 m. In mountainous or hilly irrigated areas, because of small distances between and irrigation areas of lateral canals, sub-lateral canals can be opened along lateral canals. Installation of a field canal is unnecessary.

9.4.5 Runoff-harvesting engineering

Runoff-harvesting engineering is a kind of micro-water conservation project, which is effective at harvesting, storing and using surface runoff in arid, semi-arid and other regions without sufficient water supplies. Runoff-harvesting engineering normally consists of the runoff-harvesting system, water transporting system, water purification system, water storage system and irrigation system (Wu, 2002; Li et al., 2005; Wu and Feng, 2009).

9.4.5.1 Runoff-harvesting system

The main component of a runoff-harvesting system is a micro-catchment with a treated or untreated surface. The untreated micro-catchment is a naturally-formed or built area with high runoff rate and low infiltration rate, such as villages, settlements, yards and roads. The treated micro-catchment refers to man-made ground specifically for runoff collection (Li et al., 2005).

(i) Treatment methods of catchment surfaces

First, existing natural or man-made landscapes and topography, such as asphalt roads, house roofs and household yards, and original slopes can be chosen to harvest runoff. If existing areas are unable to collect enough runoff to meet needs, new artificial harvesting areas should be constructed as subsidiary harvesting areas. Common materials used to treat artificial runoff harvesting surface include concrete, cemented tiles and plastic films. At present, new materials, such as HEC soil-solidified agent, anti-infiltration films and cloths are widely used for harvesting runoff. The results of different materials vary widely in collecting surface rainwater and runoff. They should be carefully selected considering topographic conditions and the surrounding landscape. Table 9.5 and Table 9.6 show the runoff harvesting efficiency of different treatment materials in Gansu, Ningxia and Inner Mongolia.

(ii) Preparation of the micro-catchment

Concrete micro-catchment: Before construction, the surface of the micro-catchment should be watered, and the top 30 cm of soil should be turned over and then compacted. The bulk density should not be lower than 1.5 $t \cdot m^{-3}$. On areas without other special requirements, concrete can be directly applied to the ground. On areas with additional special requirements, such as threshing ground or roadways, concrete should be paved with the project design.

Roof tile micro-catchment: House roofs are usually used as micro-catchments. The water-harvesting efficiency of cemented tile is 1.5–2 times higher than that of machine-made or hand-made earth tiles. The harvested runoff is often used for garden irrigation or for domestic use. A slanted earth slope can also be constructed simulating a house roof, and cemented tile can be used as the water-harvesting surface. Tiles should be tightly cemented to eliminate water leakage.

Table 9.5 Runoff harvesting efficiency of catchment treated by different materials in Gansu and Ningxia ($m^3 \cdot m^{-2}$)

Mean annual rainfall (mm)	Con	CeT	CeS	PlF	MMT	CLT	CLS	APR	OrS
400–500	0.80	0.75	0.53	0.46	0.50	0.40	0.25	0.68	0.08
	0.79	0.74	0.25	0.45	0.48	0.38	0.23	0.67	0.07
	0.76	0.69	0.41	0.3	0.39	0.31	0.19	0.65	0.06
300–400	0.80	0.75	0.52	0.46	0.49	0.40	0.26	0.68	0.08
	0.78	0.72	0.46	0.41	0.42	0.34	0.21	0.66	0.07
	0.75	0.67	0.40	0.34	0.37	0.29	0.17	0.64	0.05
200–300	0.78	0.71	0.47	0.41	0.41	0.34	0.20	0.66	0.06
	0.75	0.66	0.40	0.34	0.34	0.28	0.17	0.64	0.05
	0.73	0.62	0.33	0.28	0.30	0.24	0.13	0.62	0.04

Con: Concrete; CeT: Cement tile; CeS: Cement soil; PlF: Plastic film; MMT: Machine-made tile; CLT: Clay tile; CLS: Compacted loess soil; APR: Asphalt paved road; OrS: Original slope.

Table 9.6 Runoff harvesting efficiency of catchment treated by different materials in Inner Mongolia ($m^3 \cdot m^{-2}$)

Mean annual rainfall (mm)	Waste slope	Hard road	Mixed soil road	Cemented road	Plastic film
200	0.066	0.077	0.088	0.091	0.103
250	0.074	0.086	0.099	0.105	0.116
300	0.103	0.120	0.137	0.145	0.161
350	0.109	0.127	0.145	0.154	0.170
400	0.137	0.160	0.182	0.194	0.214
450	0.215	0.250	0.286	0.304	0.336

Sheet stone (or gravel) cemented micro-catchment: Different cementing methods should be adopted depending on the sizes and shapes of the stones or gravel. If stones are sheet-like and regularly shaped, they can be placed horizontally on a compacted 30 cm thick surface. If stone or gravel materials are small and irregularly shaped, they can be vertically paved or inserted into soil. The gravel layer should be at least 5 cm deep.

Earth micro-catchment: In rural areas, an earth road can be used to harvest runoff after it is smoothed and leveled. If natural sloping areas are used to harvest runoff, the slope surfaces should be wetted, turned over to a depth of 30 cm and compacted. The bulk density should be higher than 1.5 $t \cdot m^{-3}$.

Plastic film micro-catchment: There are two methods using plastic films to harvest water, namely exposed and hidden methods. The exposed method directly covers the plastic films on a well–prepared, sloping land surface. A heating iron is used to connect 10 cm of overlapping plastic film, or 30 cm of overlapping film should be folded to limit water infiltration along connected seams. The hidden method applies plastic film on a smoothed, compacted surface, which is then covered with 4–5 cm of mud or fine sand. The mud should be evenly applied and compacted. Fine sand should be evenly paved on the slope surface and compacted. The compacted surface should not be trampled. Appropriate locations of the micro-catchment should be stabilized with bricks, stones and wood materials.

9.4.5.2 Water-transporting system

The water-transporting system refers to the ditches, canals or water blocking ditches that transport runoff harvested from the micro-catchment into the water purification system.

The design and installation of water-transporting system differs because of differences in topographic condition, micro-catchment locations and surface treatment materials. If the distance from the runoff harvesting system to the water-storage system is relatively long, permanent canals or ditches such as U-shaped or rectangle-shaped cemented ditches should be installed. If highways and roads are used as runoff harvesting sites, the affiliated drainage ditches along the highways and roads can be used to connect with the water transporting ditches or canals to bring the water to the storage dam. These drainage ditches should be treated with measures to reduce infiltration. During water-collecting periods, these ditches or canals should be cleaned periodically to remove litter and sediments. When using a mountain slope as a runoff-harvesting site, runoff-interception ditches should be built along the contour every 20–30 m, and the runoff flowing distance on these slopes should be as short as possible to reduce infiltration. The runoff-interception ditch can be made with soil, and the gradient of the slope should be 1:30–1:50. The runoff-interception ditch should also be linked with the water-transporting ditch at a right angle. The U-shaped or rectangle-shaped canals should be built with cement or with brick and stone materials.

9.4.5.3 Water purification system

All harvested runoff must be filtered and treated before it is transported to a water storage pond or dam. Filtering or treatment removes and collects silts and other wastes. The purification devices often used in front of the water pond or dam are sedimentation ponds and filter fences.

(i) Sedimentation ponds

The sedimentation pond is normally built about 3 m away from the water storage dam. At the same time, favorable micro-landforms should be fully used to deposit sediments in runoff and floods. Sedimentation ponds should be built in a rectangle shape. The volume is determined by both the amount of sediment in the runoff and the requirements for sediment accumulation. Normally, the optimum size of the sedimentation pond should be 0.6–0.8 m deep with a length-width ratio of 2:1. A rectangle-shaped sedimentation pond that is 2–3 m long, 1–2 m wide, 1.0 m deep and with a pond bottom 0.8 m lower than the intake can accumulate 3 m^3 of silt-sand sediments.

(ii) Fences to block wastes

No matter which sedimentation pond is used, fences should be installed in front of the pond intake. These fences block large debris and litter carried in runoff and floods. The structure of the fence is simple and can be made of iron wires or a metal plate drilled with holes. In less-developed regions, the fence can be made of bamboo strips, wood or willow branches and wickerwork.

9.4.5.4 Water storage system

Frequently used water storage facilities include water storing ponds, water cellars, water-retention wells and dams. Due to differences in landscape, topographic condition, economic potential, construction technique and local building materials, water storage systems differ in shape, pattern and structure. However, the water cellar is the most popular water storage facility in drylands of China.

(i) Types and structure of water cellars

The water cellar is a facility frequently used for storing runoff and rainwater and is a key type of rainwater storage system. Water cellars can be classified according to their shape. They can be cylinder-shaped, ball-shaped and bottle-shaped. They can also be divided according to the anti-infiltration materials use such as red-clay, concrete and cement.

The selection of water cellar types should be based on local topography, soil texture, surface treatment methods and purpose of water use. Table 9.7 shows the types of water cellars used in regions with different soil textures.

Table 9.7 Types of water cellars in regions with different soil texture

Soil condition	Types of water cellar	Volume of water cellar (m^3)
Red soil or loess soil with dense texture	Traditional water cellar	30–40
	Improved cemented water cellar	40–50
	Water pit	60–80
Loam soil with medium texture	Cemented bowl-shaped water cellar	50–60
	Concrete water cellar	50–60
Sandy soil with loose texture	Unsuitable for water cellar; suitable for water storage pond	100

At present, the following water cellars are widely used because of their ease of construction, simple structure and reliable designs.

Concrete ball-shaped water cellar: This type of water cellar is characterized by a simple structure, safety and reliability, longevity, even force distribution, similar internal and external pressures and convenient management. It is suitable for various topographic conditions and soil types. However, it requires high quality building materials and accurate construction techniques.

Concrete cylinder-shaped water cellar: This type of water cellar has a simple structure and long durability and is easy to implement and convenient to maintain. It is suitable for regions with dense soil texture. A reinforcing steel bar should be used at the connection between the cellar wall and the cellar bottom to improve structural strength and to avoid collapse.

Red-clay water cellar: This is a bottle-shaped, traditional water cellar that is popular in rural areas. It is made of and compacted with red clay. Usually, the cellar wall is 8–10 cm thick, and the bottom is 30 cm thick. This cellar is inexpensive and durable. It is characterized by low infiltration and leakage and good stored water quality. However, the construction process is complex and labor intensive. It is suitable for regions with loess and red soil with good soil texture. It is widely used for storing water for people and domestic animals.

(ii) Determining volume of water cellars

In addition to sound technical and economic principles, water harvesting projects must also determine the proper water volume. This is an important element in the development of a water harvesting project. The main factors limiting the volume of a water cellar include topography, landscape and soil texture. In regions with red clay and loess soil, the volume of the water cellar can be large, but in regions with sandy soil and fine loess soil, the volume must be smaller to prevent collapse of the water cellar under pressure.

Generally speaking, the volume of a concrete, ball-shaped water cellar should be limited to 20–40 m^3. The volume of a cylinder-shaped water cellar with a thin concrete wall should be limited to 40–60 m^3. The volume of a red clay water cellar should be limited to 15–50 m^3.

(iii) Layout of water cellars

The layout of water cellars in northwestern China are briefly introduced as follows.

i) Loess ridge and tableland areas

Topographic features: Undulating ridges and tablelands are often found. The land surface is level and covered with dense vegetation. Ridges and tablelands are terraced crop fields or natural rangelands where fewer erosive gullies have been formed.

Layout of the water cellar: Most ridge-top or tableland areas are rural roads or traffic lines, and asphalt-covered or compacted earth road surfaces are optimal locations to harvest runoff or collect rainwater. The location of a water cellar should be installed along the two sides of the road according to local topography or landscape. Experiences in Fengchuan Village of Haiyuan County in Ningxia provide good examples of harvesting runoff. Water-collecting and runoff-harvesting ditches and pools have been installed along the two sides of the highway on a mountain ridge of the village. Rainwater and runoff are collected and transported and stored in the water cellars constructed at the middle of the mountain slope. After a few weeks, the stored water is drawn to irrigate crop fields at the foothill using gravity irrigation.

ii) Hill-front trenched area

Topographic features: Many gullies are distributed in steep hills and converge at the outlet of small watersheds. Converged water spreads toward the outlet forms trenched geomorphology. Roads are built or formed along the trench, and the areas at the two sides of the trench are mostly crop fields.

Layout of water cellars: The water cellars are often installed along the two sides of the road or trench, and water-channeling ditches or canals should be built to lead rainwater or runoff to the water cellars sector-by-sector. Meanwhile, sedimentation facilities should be built in front of the water cellars due to heavy soil erosion and high sediment concentration within runoff. When the water cellar is filled with runoff or rainwater, the cellar intake should be immediately closed. A runoff-harvesting and irrigation pilot project in Nihao Village of Qiying Township of Guyuan County in Ningxia has been successful in constructing runoff harvesting and water cellar irrigation practices in hill-front trenched areas.

iii) Gentle slope area

Topographic features: Foothill terraces, tablelands and trench terraces with gentle slopes and flat landscapes. The loess hilly areas are mostly dissected by gullies, and denudation is severe with wide and deep gullies. Gentle slopes are mainly used for crop cultivation and intercropping of crops and forage (agroforestry practices).

Layout of water cellars: In this area, runoff is produced after soil is saturated. Paths in crop fields are the main sites for harvesting runoff. Water cellars should be installed along the two sides of the field paths. The number of water cellars, or water cellar distribution density, should be determined by the runoff volume from field paths.

iv) Water cellars along roads

In most rural areas of China, different grades of road or highway (such as a province-highway, prefecture-road and county-road) pass through different landscapes and topographic features such as ridges, floodplains, slopes and plains. The changing topographic features should be fully considered during design and installation of water cellars. The site of the water cellar is usually set in a crop field along the road, while water-drawing canals and sedimentation ponds should be well connected to the water cellars.

v) Water cellars near yards

In rural areas, households are widely separated, and houses are mostly one-story buildings surrounded by threshing ground, vegetable gardens and cropland. The yard, threshing ground and house roof can all be used as runoff harvesting sites. Such small-scale runoff-harvesting sites not only meet the needs of domestic water consumption and the growth of the yard plants, but also meet cropland irrigation needs through the installation of a water cellar outside the yard. The 121 project that was popularized in Gansu Province is the best and most successful practice for harvesting runoff in yards (Gao et al., 2005).

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10 Optimized Sustainable Eco-production Paradigms in Drylands

Longjun Ci, Xiaohui Yang and Xinshi Zhang

Drylands in China can be divided into five natural or semi-natural regions based on physical and socioeconomic features, e.g., the mountain-basin system in arid desert regions, the Loess Plateau region, the Inner Mongolia Steppe region, the Inner Mongolia agropastoral transitional region and the Ordos Plateau region (Fig. 10.1). The first three regions are biogeological regions that are relatively independent. The Ordos Plateau region is a special biogeological region that is separate from the Loess Plateau region, and the

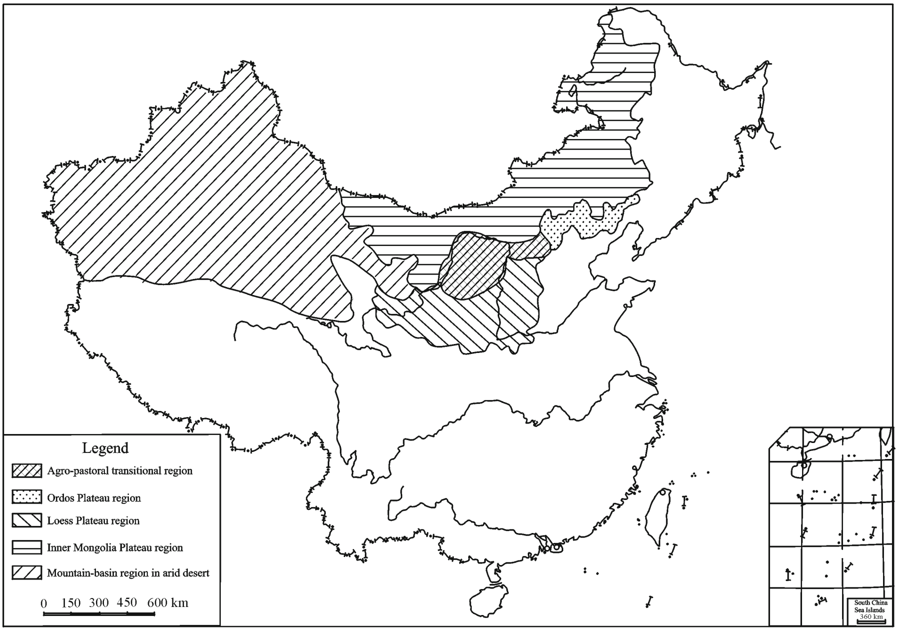

Fig. 10.1 Distribution map of five natural or semi-natural regions in the drylands of China (Yang et al., 2008, with permission from authors)

agropastoral transitional region is a land-use based, semi-natural region rather than a biogeological region.

In this chapter, four sustainable eco-production paradigms are established. The Inner Mongolia steppe and agropastoral transitional regions are combined into one pattern. Here, a sustainable eco-production paradigm refers to the integration of ecosystem management, regional landscape patterns and geologic functional belts to optimize ecological functions, production potentials and economic benefits based on the replicate complex of the regional landscape and its energy and material flows (Zhang, 2000; Zhang and Shi, 2003; Ci et al., 2007). In these paradigms, different functional belts are determined and used in consideration with regional biogeophysical processes, biogeochemical cycles and biogeosocial relations.

10.1 Three-circle eco-production paradigm in drylands

Three-circle paradigm is the first eco-production paradigm we generalized in Ordos Plateau, then the paradigm was expanded to the whole drylands at different scales, and a large area of degraded landscapes in drylands have been restored based on this paradigm. Here, we give descriptive introduction to this paradigm at regional and local scales.

10.1.1 Physical geography background for the three-circle eco-production paradigm

10.1.1.1 Geographical belt features of bioclimatic zones

Bioclimatic patterns of drylands follow patterns of geographical belts (Ci and Wu, 1997). The northwest-southeast direction in China is controlled by the Mongolian-Siberian anticyclone and has bioclimatic zones with circles or rings encompassing extremely arid, arid, semi-arid, dry sub-humid and humid climates. Bioclimatic types differ among deserts, sandlands and their peripheral regions. For example, the Taklimakan Desert and its peripheral sandland is a warm-temperate arid desert; the Gurban Tonggut Desert and its peripheral sandland is a temperate arid desert; deserts in the Qaidam Basin are cold-temperate deserts; a high-elevation cold desert is located north of Tibet; the Ordos Plateau and its sandland is a temperate sandified grassland; and the Horqin Sandland, Hulun Buir Sandland and other sandlands in eastern China are located in the temperate steppe zone.

According to the UNCCD, bioclimatic zones for desertification-prone zones include arid, semi-arid and dry sub-humid areas, other than polar and sub-polar regions, in which the ratio of annual precipitation to potential evapotranspiration falls within the range of 0.05–0.65 (Ci, 1994; INCD, 1994). Correspondingly, the bioclimatic zone of China was classified using the Thornthwaite Method with 10 years of meteorological data collected from 1914 stations (Ci and Wu, 1997; Thornthwaite and Mather, 1957; Zhang, 1989). Extremely arid zones include the Taklimakan Desert and some deserts in northwestern China. Arid areas are distributed throughout China from the Tianshan Mountains in the north, to the Pamler Plateau in the west, to Helan Mountain in the east, and to the Kunlun and Qilian Mountains in the south, as well as the northwestern part of the Qinghai-Tibetan Plateau. Semi-arid areas consist of typical steppe and desert steppe in the east and high and cold steppe and desert in the Qinghai-Tibetan Plateau. Most of northern Xinjiang is semi-arid, including desert and semi-desert. Dry sub-humid areas include the Hulun Buir Plateau in the north, the border between typical steppe and meadow steppe in the east, the north part of the Loess Plateau and north edge of the Qinghai-Tibetan Plateau and the border around the Qaidam Basin to the southwestern part of the Qinghai-Tibetan Plateau.

10.1.1.2 Concentric-circle rules in drylands

Drylands around the world are mainly distributed within the Tropic of Cancer and Tropic of Capricorn, which are controlled by the subtropical high. In China, the lifting of the Qinghai-Tibetan Plateau, resulted in drylands with complex and diverse ecological relationships and geologic boundaries.

(i) Concentric circle patterns — geological basis for constructing large, regional three-circle paradigms

The famous Russian geologist, Vladimir Obruchev, gave a classic concept of concentric aeolian deserts in China and Mongolia after his field survey in 1895. In his theory, the Mongolia-Siberian high-pressure anticyclone is the strongest and most frequent desert wind system in mid-Asia and is the driving force of the rocky Gobi Desert, desert and Loess Plateau geological patterns (Zhang, 1992). The basic processes forming these systems are as follows. ① Gravel or rocky desert (Gobi): In the center of the anticyclone area, the climate is arid and cold in winter and extremely arid in summer. Fine particles, such as sand and dust formed through weathering, are transported to other regions with strong winds, leaving behind gravel and stone. ② Deserts or sandlands: At the edge of the anticyclone area, the ground surface is covered with less xerophytes and hyper-xerophytes. Finer dust is removed by winds, and coarse particles are redistributed with blowing and accumulating processes to form deserts or sandlands. ③ Loess soil: In the periphery of the anticyclone area, dust-carrying air flow is hindered by mountains or meets humid air flow. Dust and sand precipitate and accumulate to form loess soil. The Loess Plateau is the dust precipitation belt at the periphery of arid areas.

(ii) Interfaces between mountains, basins and deserts (sandlands) — geological basis for constructing small, local three-circle paradigms

Deserts and sandlands in China are mainly located in basins surrounded by mountains or plateaus. For example, the Taklimakan Desert, which is the largest mobile desert in the Tarim Basin, the Gurban Tonggut Desert in the Junggar Basin, the Mu Us Sandland in the Ordos Plateau and the Otindag Sandland in the Inner Mongolia Plateau have similar geologic patterns.

10.1.2 Structure of the three-circle eco-production paradigm

The three-circle eco-production paradigm is an optimized ecological management and design paradigm based on the spatial pattern of arid ecosystems and landscapes and their mechanisms of energy and material flow. It is based on the Mu Us Sandland of the Ordos Plateau but follows rules of natural geographic belts with geographic cycles in drylands in general (Zhang, 2000). This kind of landscape forms heterogeneous ecosystems through redistribution of water, energy, material and salt and includes differences among ecosystem components, productivity, biogeochemical cycles, biogeophysical processes and biogeosocial relationships (human activities). It also includes relationships among ecosystems and material and energy exchange and flow at the landscape scale.

10.1.2.1 Large three-circle paradigm

The large three-circle paradigm is designed at the national scale, which is the landscape pattern for sand control, sand-dust storm alleviation and optimized eco-production models at the macroscopic scale. It consists of three components including arid desert, steppe and agropastoral transitional circles.

(i) Arid-desert circle

The outer circle is the arid desert belt, which includes the Gobi Desert along the national boundary with Mongolia in Xinjiang, the Hexi Corridor of Gansu, western Inner Mongolia, Junggar Desert, Badain Jaran Desert, Tengger Desert and Qubqi Desert. Loose sand cover in these areas provides rich source materials for large sand-dust storms. Likewise, sandlands formed because of vegetation destruction between deserts and oases and farmland along desert edges. Denuded oases during winter and spring also provide sand materials for large sand-dust storms. Hence, emphases in desertification control and sustainable development should be placed on natural vegetation protection, sound land-use management, setup of vegetation shelterbelts along rivers, roads and irrigated channels, and windbreaks and sand control vegetation belts near deserts.

(ii) Steppe circle

The transitional circle is located at the temperate steppe belt in northern China, which includes five of six grassland provinces in China undergoing conversion to sandlands. Grasslands in Inner Mongolia, Xinjiang, Qinghai and Gansu account for 94% of grasslands in drylands, in which 70–80% of the area is degraded. Conversion of grassland to sandland is a major type of grassland degradation, which provides dust material for large sand-dust storms. Therefore, pen-raised livestock and artificial grassland development will be helpful in restoring natural grasslands and reducing expansion of deserts.

(iii) Agropastoral transitional circle

The inner circle is the agropastoral transitional area, or forest-steppe transitional belt. The modern agropastoral transitional area is located at both sides of the northeast-southwest diagonal in China. Annual precipitation is about 400–450 mm. Ecosystems here are unstable due to their transitional features. In addition, they are under dual pressure from natural forces and human activities. Ecosystem processes are dominated by positive feedback mechanisms involved in desertification. Hence, ecosystem instability and fragility are increasing, and conversion to sandland is becoming serious. For instance, in the hilly mountains of Duolun and Zhangbei counties, Hebei Province, continuous drought, over-reclamation, overgrazing and excessive fuelwood collection result in deteriorating environmental conditions. Large, black sand-dust storms are formed as thick, black, wind-blown soil is loosened by over-cultivation and overgrazing of the meadow steppe in the Hulun Buir Steppe. Hence, raising pen-fed livestock with artificial grassland should be advocated, and transforming farmland into forest and grassland (Grain for Green) should be implemented to increase surface cover to combat desertification and improve the quality of people's lives.

10.1.2.2 Small three-circle paradigm

The small three-circle paradigm is a local eco-production paradigm to combat desertification and enhance agricultural development. It is also a basic element of the large three-circle paradigm. Ecological restoration and combating desertification within one geographical unit, one small watershed or one oasis can be accomplished with the small three-circle paradigm. The following are two examples of small three-circle paradigm in Beijing and the Ordos Plateau.

(i) Small three-circle paradigm in Beijing

The Beijing region is a forest-steppe bioclimatic zone with an annual average precipitation of about 500–600 mm. Due to drought and extensive human activities, conversion of soil to sand is a serious problem. In spring, a large amount of sand-dust is transported to Beijing from northwestern China and Mongolia with the Mongolian-Siberia anticyclone. Muddy rains or sand-dust storms are formed in Beijing, which negatively influence Beijing's environment. Hence, sand control projects in and around Beijing have been initiated, and a small three-circle paradigm was accordingly submitted to assist in this project.

The sand control system in Beijing consists of three ecological circles. The first circle for water conservation and soil erosion control covers the hilly and mountainous areas of Yanshan Mountain. The second circle for windbreaks and stabilizing sand covers the piedmont fluvial plain. The third circle for urban greening covers transition areas between suburbs and downtown Beijing.

Outer circle: water conservation and soil erosion control

The Yanshan Mountain in north Beijing and Taihang Mountain in west Beijing are important regions for water conservation. Water in the branches of the upper reaches of the Haihe River and Guanting and Miyun Reservoirs originates from these mountainous regions. Vegetation in these mountainous regions formerly consisted of coniferous forests, such as *Picea koraiensis* and *Larix gmelinii* in higher mountainous zones (>800 m a.s.l), and deciduous-broadleaf forests, such as pine-oak mixed stand or *Quercus liaotungensis* in lower mountainous zones. These stands have been replaced by secondary shrubs or bushes dominated by *Ziziphus acidojujuba*, *Lespedeza bicolor* or *Vitex negundo*. Biodiversity has declined, and soil erosion is severe. Therefore, the following measures should be taken. ① Regenerate highly-efficient water conservation forests by enclosing vegetation and revegetating with coniferous trees, oak-dominated broadleaf-deciduous forest or coniferous-oak mixed forest in the middle mountains. ② Convert cultivated land into forest or grasslands in lower mountains. Fruit tree belts including *Diospyros kaki*, *Ziziphus jujuba*, *Castanea mollissiwa* (chestnuts), *Pyrus* spp. (pears) and *Prunus* spp. (apricots) are planted on gentle-sloping terraces. Landscape or timber forests consisting of *Ginkgo biloba*, *Acer* spp., *Fraxinus velutina*, *Magnolia denudata*, *Quercus liaotungensis*, *Quercus dentata*, *Gleditsia sinensis*, *Koelreuteria paniculata*,*Pistacia chinensis*, *Pinus bungeana*, *Pinus armandi*, *Platycladus orientalis* and *Sabina chinensis* can sometimes be planted. Shrub belts of *Caragana* spp. can be planted on south slopes for soil and water conservation, and shade-tolerant leguminous grasses can be intercropped with fruit trees for soil and water conservation and to increase soil fertility.

Transitional circle: windbreaks and sand stabilization

This transitional circle lies in the suburban counties of Beijing and is the alluvial plain of the Haihe River and its tributaries and the main agricultural cultivation area in Beijing. Due to long-term agricultural cultivation, natural vegetation has almost complete disappeared. The soil surface is bare in winter and spring. Strong airflow in early spring results in severe wind erosion. This is especially true along dry river courses and alluvial plains. Conversion to sandland is serious, and areas with low productivity are becoming the main source of locally blown sand in Beijing.

This region is managed to control wind erosion. Windbreaks and a combination of trees, shrubs and grasses should be setup to form an artificial savanna-like landscape. Following the implementation of the project to transform farmland into forestland or grassland, this circle will be planted with forests (protection, timber and landscape forests), gardens (orchards, vineyards, seedling nurseries and flower gardens), grasslands (artificial or natural) and farmlands (cropland, melon field, herb nursery and forage land). The ratio of these four land-use types is about 3:3:2:2. Grasslands consist of two categories. Artificial grasslands include legumes and graminoids, which can be used as a base for pen-raised animal husbandry (cow, beef cattle and goat farms) in suburbs combined with artificial forage lands. Natural green grasslands function to beautify the landscape.

The aforementioned ratio of land uses is based mainly on local annual precipitation. In temperate climates, forest zones occur where annual precipitation is no less than 800 mm. Areas where annual precipitation is less than 800 mm cannot be covered entirely by forests without supplemental water. A forest coefficient of 0.33 is the area coefficient assigned to forests from an economic viewpoint. In Beijing, annual precipitation is about 500 mm. The maximum forest cover rate (*MFC*, without irrigation or other supplementary water sources) is: MFC=500/800=0.625, which is multiplied by the forest area coefficient. The planned forest cover is: PFC=0.625×0.33=0.21, or 21%.

Due to the large area of this circle in Beijing (about 60% of the total land area), this temperate savanna-like landscape pattern will be the dominant landscape in the paradigm.

Inner circle: urban greening

The inner circle is downtown Beijing. The greening circle consists of trees, grasses, water bodies and canals and also a core circle for city greening, beautification and purification. The scientific design in this circle is the prudent arrangement of buildings, roads and highways, squares, community gardens, parks, sidewalk trees, lawns, flower gardens, roof gardens, climbing plant covered walls and water bodies (channels, canals and lakes). An urban landscape system integrating protection, greening and aesthetics will be formed.

(ii) Small three-circle paradigm in the Ordos Plateau

i) Geomorphological features in the Ordos Plateau

The Ordos Plateau, located at 37°38′–40°52′ N and 106°27′–111°28′ E, is surrounded by the Yellow River on the north, west and east and abuts the Loess Plateau on the south (Shi, 1991). It has an elevation of 1,100–1,500 m above sea level, and the climate is arid and semi-arid, temperate and continental. Three terrains on the Ordos Plateau are distinguished as follows (Fig. 10.2).

Hard ridge: Purple, horizontal Cretaceous sandstone and grey-green Jurassic sandstone several thousand meters thick form the base and backbone of the Plateau. Called a hard ridge locally, the rock is usually covered by sandy gravel loam of different depths or a rock mass with a thin soil layer. The relative height of the ridge is generally 30–50 m. The northwestern part of the Plateau is 1,500–1,600 m in elevation, which gradually descends to 1,300 m in the southeast.

Soft ridge : In the lower part of the plateau, a gentle-inclined terrace is formed by the thick Quaternary and Tertiary fluvial or alluvial deposit layer and is usually deeply eroded and cut by surface runoff. It is called the soft ridge locally and forms the second terrace of the area.

Quaternary fluvial and lacustrine deposit plain: The plain is the alluvium of the interior drainage, which interchanges with the ridge. The alluvium in the plain consists of fine sand, silt and bog deposits. The plain is flat and broad but is usually characterized by poor drainage capacity and various degrees of salinity.

The largest surface characteristics on the Plateau, occupying three-fourths of the total area, are sand dunes and sand flats that widely cover the various ridges, flats and even fluvial terraces. The sand originates from local fluvial and lacustrine deposits, weathering products of sandstone and the sand interlayer in loess deposits. The main geomorphological types of sand are moving sand dunes, semi-fixed sand dunes, fixed sand dunes and undulating sand flats. Large moving crescent dunes can be up to 10–30 m high. Semi-fixed and fixed sand dunes, which are usually lower than 10 m, are covered by sagebrush (*Artemisia ordosica*) and are referred to as "Bala" locally. Owing to long-term overgrazing, cutting and cultivation, the historic vegetation on the sand dunes is almost extinct. Fig. 10.2 gives a detailed illustration of a vegetation transect and its associated topography, parent rocks, materials and typical soils on the Ordos Plateau.

ii) Ecological principles for paradigm establishment and revegetation

According to research results and requirements for local economic development, the following ecological principles should be matched or considered during paradigm establishment and revegetation (Zhang, 1994).

First, water and bioclimatic conditions are key

Water is the major limiting factor for plant growth in arid and semi-arid areas. Moisture and heat conditions vary greatly among different bioclimatic zones. The three-circle, eco-production paradigm should be designed for each bioclimatic zone. First, the region is classified into site types. Second, each type is designed following the criteria of the three-circle, eco-production paradigm. Third, suitable, high-quality plant species are selected. Fourth, soil for afforestation or grass-sowing is prepared.

Second, selection of shrubs as dominant species to enrich local biodiversity

Selection of suitable, high-quality plant species is necessary for successful ecological functioning. Dominant plant life in arid and semi-arid areas consists of sand- and drought-tolerant shrubs due to diverse geomorphological conditions, high sand content and low soil moisture. Shrubs are characterized by multi-branching, lignified stems and small, dense crowns, which are adapted to strong, blown sand areas and easily form sparse green spots on the surface of barren sandland. The root system of shrubs is more horizontally or vertically distributed and the ratio of roots to stems is higher than those of trees. Hence, shrubs are better able to stabilize the sand layer and take up more water than trees in rocky habitat. In addition, the root system of shrubs can grow into rock cracks to reach deeper soil water and form a dense shrub community. Some shrub species are also good for forage. Leguminous shrubs are especially good because they have symbiotic rhizobium, which allow them to grow well in poor soil and increase soil fertility. Therefore, shrub species play a significant role in regulating environmental factors and soil moisture,

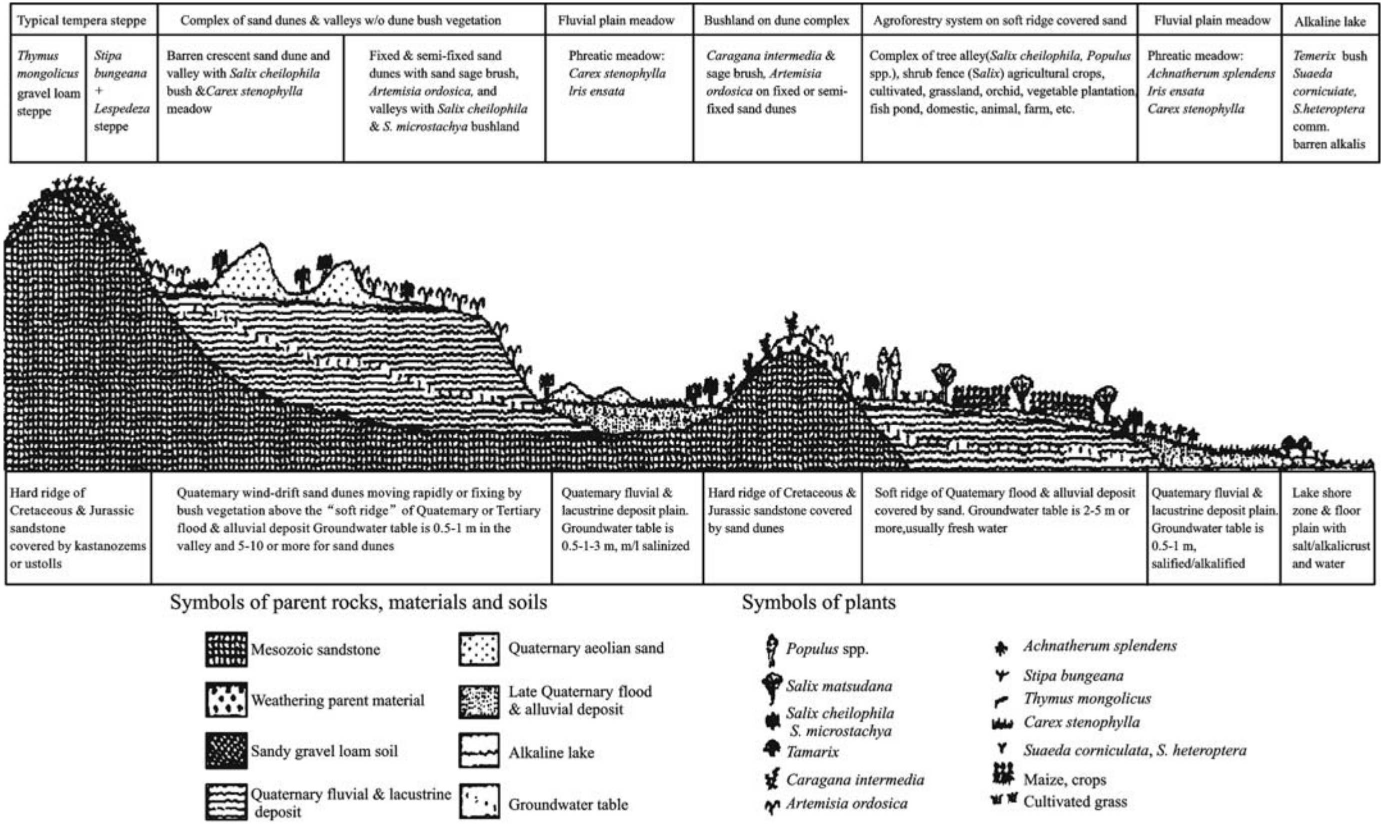

Fig. 10.2 Schematic transect of vegetation and associated topography, parent rocks, materials and typical soils on Ordos Plateau (Ci, 1997, with permission from author)

interactions among wind, water and sand materials, relative equilibrium of plant communities and balances between livestock and forage.

The role of shrubs in three-circle paradigm establishment should be better understood. In addition, Poplar species planted in northern China should be carefully selected.

Third, scientific arrangement of various protection forest systems

A protection forest system is an important component of the three-circle paradigm. Research shows that protection of forested systems in arid and semi-arid areas must have the following features: ① a comprehensive and integrated system; ② a narrow shelterbelt and small network size is the main component of a protection forest system; ③ the shelterbelt has good spatial structure with a combination of trees, shrubs and grasses to better utilize light and water; ④ multiple species should be mixed to prevent disease and pest damage; and ⑤ a protection forest system should be matched to roads, rivers, irrigated systems, etc (Ci, 1980).

Fourth, semi-fixation principle for sandland management

Vegetation cover is low in sandy areas limited by water. When revegetating these regions without irrigation, the supply of groundwater and lateral runoff must be considered in advance. Therefore, to keep the water balance in the sand, vegetation cover in sandy areas should be no more than 25%, less than 30% and less than 40% in western, central and southeastern areas of the temperate steppe zone of China, respectively. In highly mobile sandy areas, non-biological measures should be used to enhance successful revegetation. Non-biological materials should be non-pollutant, non-toxic and have no harmful effects on the environment.

(iii) Structure of the small three-circle paradigm in the Ordos Plateau

The following optimized, eco-production paradigm framework, referred to as three-circles, was constructed based on the particular geomorphological features of the Ordos Plateau (Fig. 10.3).

Inner circle: Irrigated oases on plain deposits

The first circle is the efficient and integrated productive farming circle on floodlands characterized by thin sand cover (<30–40 cm) and medium depth to a water table (about 50 cm). This circle accounts for 10% of the total area. This is intensive, cost-effective farming with a high investment and includes: ① oasis agriculture, planted with maize, millet and sunflower; ② artificial forage plantation and natural grassland improvement, seeded with highly-palatable forage such as Sudan grass, smooth brome, triticale, *Leymus* spp., alfalfa, sweet sorghum, fodder maize and sugar beet. For small, degraded grass floodplains, seasonal or rotation grazing is applied for female or young livestock, and livestock can be excluded from heavily-salinizing *Achnatherum splendens* floodplains or heavily-alkalinizing *Iris pallasii* var. *chinensis* floodplains; ③ orchards, apples, grapes, almond trees and cherries are planted; ④ shelterbelts, a broad and highly-protective tree-shrub-grass belt is planted to protect the oasis. Small network shrub belts are planted around or within

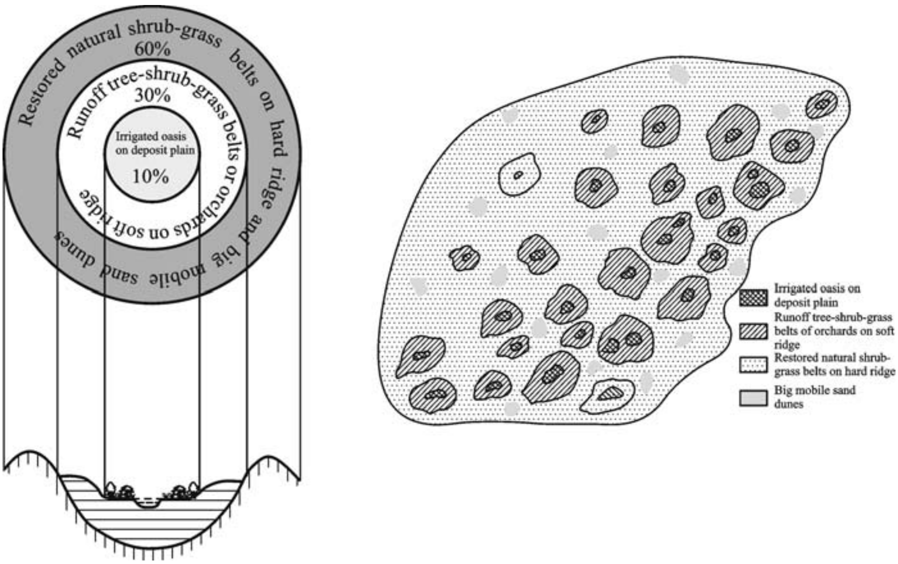

Fig. 10.3 The 3 circle eco-productive paradigm on Ordos Plateau (Zhang, 2000; Ci et al., 2007, with permission from authors)

cultivated land, rangeland and orchards; ⑤ emphasis on pen-raised livestock, fodder ensilage and animal processing is expanded; and ⑥ fishery and poultry farms are properly developed.

Transitional circle: Runoff tree-shrub-grass belts or orchards on soft ridges

The second circle is the runoff-harvesting, tree-shrub-grass circle on soft ridges, which accounts for 30% of the total area. Without irrigation, extensive agricultural development is impossible, but integrated protection and moderating exploitation are alternatives. In soft ridges and terraces with an even landform and deep soils, semi-artificial, rain-fed grassland is established by planting two to three rows of *Caragana intermedia* or *Salix psammophila* shrub belts and inter-rows of *Melilotus suaveolens*, *Medicago sativa*, and *Astragalus adsurgens* leguminous forbs. Banded shrub belts are planted in uneven or sloping positions. In some sloping ridges with good runoff-harvesting condition, small orchards or cash trees can be planted using run-on water. A degraded *Artemisia ordosica* community can be seasonally grazed with some ancillary improvement. Briefly, in this circle, the community or landscape vegetation cover should be determined in accordance with the water supply capacity.

Outer circle: Restored natural shrub-grass belts on hard ridges and large mobile sand dunes

The third circle, which accounts for 60% of the total area, is the shrub-grass shelter circle on hard ridges and moving sand dunes. It mainly serves as a windbreak and for stabilizing sand, for soil and water conservation, and as a water source for the other circles. In this circle, the *Stipa* spp. steppe, a main vegetation type on hard ridges, is degraded due to overgrazing. Hence, artificial shelterbelts can be established with shrubs such as *Caragana intermedia* and *Hippophae rhamnoides* in the relatively dry west and *Pinus sylvestris* var. *mongolica* in the humid east. Light rotation grazing can be implemented after restoration of the grass layer. On large, mobile sand dunes, some pioneer species, such as *Artemisia ordosica* and *Artemisia sphaerocephala*, are seeded to gradually stabilize the dunes. On sand dunes with high soil moisture, grasses and small shrubs can be planted on the lower part of the dunes' windward side. This will gradually level the dune and enhance conditions for either re-colonization by other species or active planting.

10.2 Mountain-basin paradigm in arid deserts

Mountain-basin systems are the most typical landscape in arid deserts of China. Here, we introduce a generalized mountain-basin paradigm in arid deserts and give an example named "Green Bridge System" from the north foot of Tianshan Mountain, Xinjiang.

10.2.1 Mountain-basin paradigm in arid deserts

In arid deserts of China, mountain-basin systems are formed from a series of geo-physiologically concentric circles, typically including a mountainous region, piedmont-tilted plain and basin region (Fig. 10.4).

Mountainous region: In the outer circle, the tectonically uplifted mountainous region consists of an alpine belt, forest/grassland belt and desert belt. The majority of the mountains greater than 3,000–4,000 m in altitude include glaciers and snow and ice covered mountain tops. More precipitation occurs in mountainous areas, which provides rich surface and ground water to the basin region. Alpine or subalpine forest is characterized by rich biodiversity, high stand productivity and strong water conservation. Alpine or subalpine meadow, mid-mountainous grassland and fewer steppe deserts have relatively high herbaceous cover.

Piedmont-tilted plain (alluvial fan): Piedmont-tilted alluvial fans are linked together in a skirt-like manner and constitute the transitional circle, the upper part of which is mostly Gobi or gravely desert characterized by a thin soil layer and deep water table that is difficult to utilize. The middle part is characterized by a thick soil layer and shallow water table, which can be used for irrigation. Some natural forests occur such as *Ulmus pumila* or *Populus euphratica*. The lower part is the fan edge belt, which has a very shallow water table (0.5–1.5 m) and heavy soil salinization. The area is covered with

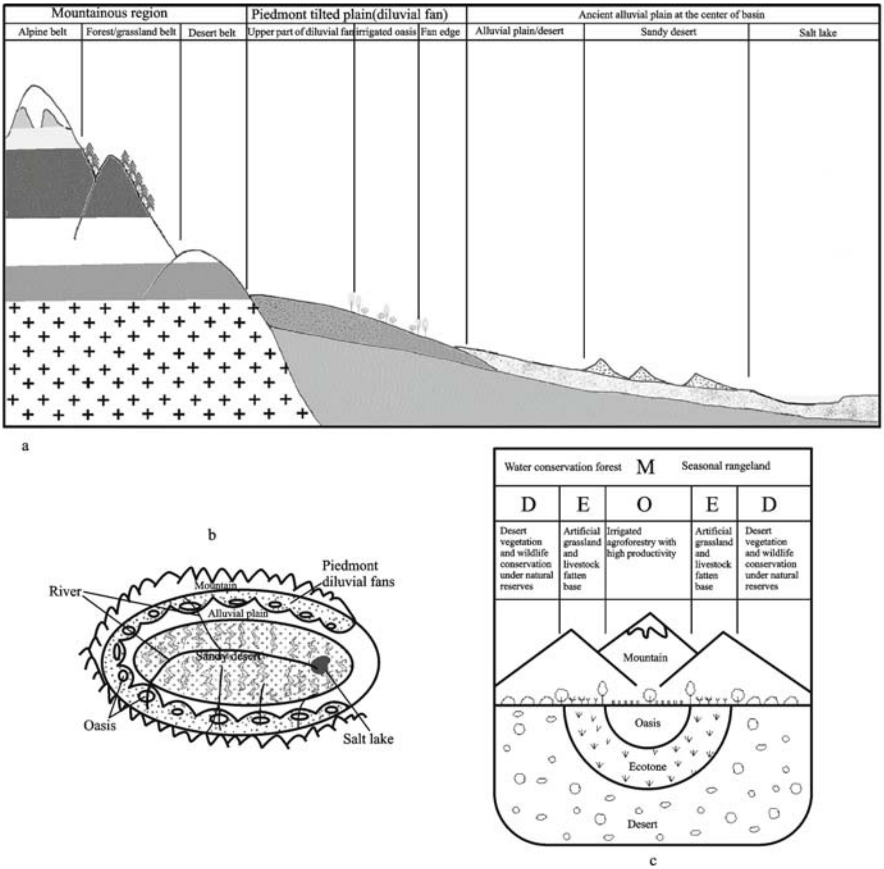

Fig. 10.4 Sketch map of geo-physiological features and mountain-basin paradigm in arid desert (Zhang, 2000; Zhang, 2001, with permission from authors)

salt-tolerant plants such as *Tamarix* spp., *Populus euphratica*, *Halimodendron halodendron*, *Achnatherum splendens*, *Karelinia caspica*, *Alhagi sparsifolia* and *Phragmites communis* or halophytes including *Halostachys caspica*, *Halocnemum strobilaceum*, *Kalidium foliatum* and *Suaeda physophora*.

Basin region: The majority of the basin is ancient alluvial-lacustrine plain with a large proportion of sandy-loamy desert covered with *Reaumuria soongarica* and *Calligonum mongolicum*. Sandy desert with sand dunes or sand dune chains is located at the center of the basin, and salt lakes, playas or salty deserts are scattered at lower elevations.

This mountain-basin system is driven by water. Water melting from glaciers or falling in the form of precipitation flows down into the basin as surface runoff and subsurface water flow. Surface runoff converges into rivers and is used for oasis irrigation. The subsurface water flow infiltrates deep into the soil in the upper part of the piedmont-tilted plain and then is close to or emerges above the ground surface at the fan edge, resulting in soil salinization and saturated conditions. Subsurface water also infiltrates deep into the soil layer in the alluvial plain and converges into low-elevation salt lakes. This sustainable mountain-oasis-ecotone-desert system (MOED) consists of four basic utilization belts based on water movement as follows (Zhang, 2001).

Mountain belt: An alpine sub-belt covered with ice or snow serves as the main source of water from precipitation and melting ice. The alpine-subalpine forest belt consists mainly of sparse forests, young forests and clear-cut forests resulting in deforestation. The ability of the alpine-subalpine forest belt to conserve water should be restored with long-term exclosure, while timber harvesting should be transferred to the basin. The mountain meadow (grassland) sub-belt can be grazed in summer and autumn, and the desert sub-belt can be grazed in winter and spring. However, most rangelands in these two sub-belts have become degraded from severe overgrazing. Sustainable livestock numbers and sensible rangeland management should be implemented, and animal husbandry should be transferred from the mountain to the basin. In addition, beautiful scenery in the arid mountain belt provides the opportunity to develop eco-tourism (Li and Han, 2001).

Oasis belts: The oasis has abundant solar and heat energy during the growing season. Hence, this belt has high productivity, and irrigated agro-forestry consists mainly of food crops, cash crops, forage crops, cash trees and fast-growing and high-production forests. These areas also serve as sites for breeding and reproduction industries and settlements and are the center of economic, cultural and communication development (Shen et al., 2001).

Oasis-desert ecotone belt: The diluvial fan edge belt where groundwater is close to or emerging above the soil surface is called an oasis-desert ecotone belt. It is not suitable for agricultural development because of severe soil salinization. This belt can be exploited as artificial grassland that can be up to 30 times more productive than natural grassland and can support 15 sheep units/ha. To support forage production from neighboring oases, it can be developed as a livestock fattening base that receives young livestock from mountain regions. The ecotone belt also protects the oasis from wind-blown sand and moderates the local climate (Xu, 1995; Zhang, 2001).

Desert belt: The desert belt should not be cultivated unless there are guaranteed water sources for irrigation, as well as a high-quality irrigation-drainage system. Grazing activities are also unsuitable in the desert belt. Here, grazing animals should be excluded to restore and conserve natural desert vegetation. Some wild desert ungulates, such as *Gazella subgutturosa*, *Saiga tatarica mongolica*, *Equus hemionus* var. *mongolica*, *Equus przewalskii* and *Camelus bactrianus*, and other wildlife, such as *Canis lupus*, can be reintroduced, and sound wildlife breeding and hunting practices can be developed (Zhang, 2001).

The four above-mentioned belts constitute an eco-economic chain of sustainable desert-oasis development, which guarantees a sound pattern of agricultural development. Sustainable development forms optimum transformation and flow of energy and material, prevents and reverses land degradation processes and will be a sustainable desert eco-production paradigm for a long time to come.

10.2.2 Green Bridge System — an example from the north foot of Tianshan Mountain, Xinjiang

The north foot of Tianshan Mountain is a key section of the new Asia-Europe land bridge. It is a political and cultural center as well as a developing economic center. The Xinjiang economic belt on the north foot of Tianshan Mountain has been listed as a priority development area. Ecological and environmental improvements as well as the sustainable social and economic development of this region have a direct bearing on Xinjiang's economic development and the smooth implementation of China's Great West Development Strategy.

The mountain and basin areas of the north foot of Tianshan Mountain are linked together by energy flow as well as exchanges of materials, values and cultures. This area has become the support system for the region's ecology and society, and it contains the most precious natural resources in the surrounding arid area. However, following a series of human disturbances such as drastic population increase, a poor agriculture and animal husbandry structure, poor land management, a degraded environment, water shortages, pesticide pollution, etc., the ecological status of the mountain-basin system has become fragile and degraded. Industry and agriculture production, and thus people's lives and means of subsistence, have been negatively impacted. Sustainable ecological, economic and social development has been seriously impeded. The former development method of simple oasis enlargement can only continue to destroy environmental conditions.

To counter these effects, a new system called the Green Bridge System was implemented in the northern part of Tianshan Mountains. This system is a new, optimized eco-production paradigm based on field studies and a series of seminars. Green Bridge refers to the new industry belt established on the fan edge belt and oases that serves as an artificial forage and timber forest base that builds an eco-economic bridge between mountainous regions and deserts. On one side of this bridge, 60% of the animal husbandry and 100% of the timber forests were transplanted from the mountainous region to the new industry belt. This was done to rehabilitate the mountainous forests and grasslands for water conservation and soil erosion control. In the Junggar Desert, located on the other side of this bridge, grazing activities and farming cultivation were prohibited, thus establishing a nature reserve to preserve the wildlife gene-base and encourage wild ungulate breeding(Fig. 10.5). Implementation of the Green Bridge System will play an important role in the ecological security of this mountain-basin system. It will also aid the economic belt development on the northern slope of Tianshan Mountain. The sustainable social, economic and environmental development of Xinjiang will help stabilize national border areas.

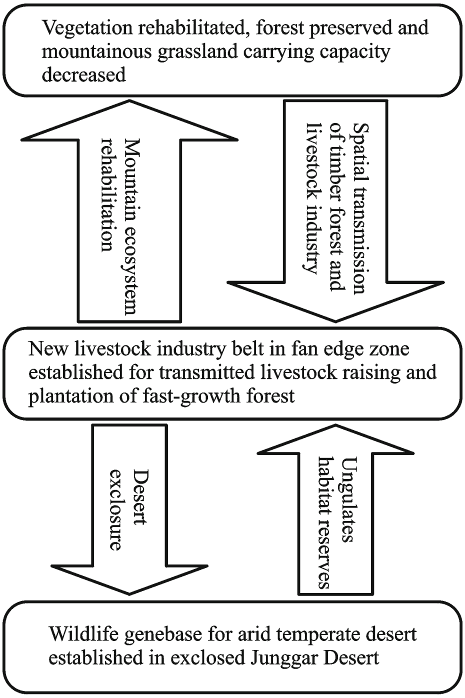

Fig. 10.5 Sketch map for Green Bridge System in Xinjiang

10.2.2.1 Modification of the oasis industry structure on the north foot of Tianshan Mountains

(i) Main existing problems

The north slope of Tianshan Mountains is characterized by large changes in altitude, complex landform, variable climate, multiple ecosystems, rich biodiversity and productive farming and animal husbandry. In the past, unsound agricultural policies and population pressures allowed large areas of grassland to be exploited for farmland. Plantation output value accounted for more than 75% of the total output value. Animal husbandry still follows the traditional nomadic grazing system. Seventy percent of livestock is grazed in the mountainous areas, and the rest are loosely grazed in the farmlands and desert. Forests in the plains were created to protect farmlands and played an auxiliary role in agriculture production. Special forest areas (fruit trees) and forage crops make up 16% and 4%, respectively, of the total land area. Cotton crops, the economic pillar industry in this region, cover large farming areas and have been seeded continuously for more than 8–10 years. This kind of simple planting structure results in a reduction in biodiversity, rampant disease and pests, weak resistance to market fluctuations and an unstable oasis ecosystem. These factors seriously cumber sustainable ecological, economic and social equilibrium and development in this region.

(ii) Thoughts and measures for modification

i) To establish multiple and complex planting structures in the oasis

Forage and forest (fruit tree) areas should be enlarged. The proportion of crops, forests (fruit trees) and grasslands in the oasis on the northern foot of Tianshan Mountains should be modified from 8:1.6:0.4 to 5:2:3. The total production output value of animal husbandry should occupy more than 60% of the total agricultural production output value.

ii) To construct forage bases in farming areas

Forage production is the material basis for modern animal husbandry and guarantees the transformation from a traditional grazing system to modern, industrial animal husbandry. Top-quality grasses and livestock corn feed should be planted in large farming areas. Simultaneously, cotton-grass rotation or an intercropping system should be implemented. Leguminous forbs, such as *Medicago sativa*, should be selected. These forbs will help control disease and pests, restore soil fertility, reduce the amount of pesticides and fertilizers needed and will also provide forage for livestock. Using forbs in combination with reusing crop straw, will basically meet livestock forage needs. Manure from livestock is returned to the farmland. This non-polluting treatment is an optimized production chain that enhances good farming practices.

iii) To develop unique fruits and cash crops

This area, characterized by rich sunshine and high variability between day and nighttime temperatures, has high plant photosynthesis and sugar accumulation and is famous for its melons and fruits. At present, the red industry, consisting of tomatoes, safflowers, wolfberries and carrots, forms the industrial base and is the predominant resource and production base for the region's famous and high-quality products, such as seed melons, grapes, watermelons, muskmelons, licorice and hops. This industry should be developed to capture a greater market share. Cotton agriculture, as the pillar industry in this region, should be modified to plant species that are in demand internationally and domestically. They should also develop specialty and top-quality cottons.

10.2.2.2 Rehabilitation of mountainous vegetation on the north slope of Tianshan Mountains

The mountains north of the Tianshan Mountains provide a source of water for the whole mountain-basin system. Melting water from alpine glaciers and accumulated snow and rainfall supply Xinjiang rivers and groundwater. The volume of water from annual mean precipitation for the region is 2.43×10^{11} m^3, of which 84% occurs in mountainous areas. The mountainous forest-grassland belt, located at the lower part of the large precipitation zone, plays a significant role in water conservation, hydrological regulation and soil erosion control. This belt also has rich biodiversity and high productivity and can be used for biological resource conservation and civilization.

(i) Ecological status of the mountain vegetation

In last 60 years, about 40×10^6 m^3 of timber have been harvested from the mountainous region, occupying one-fourth of the total forest volume in Xinjiang. This mountainous ecosystem has been seriously degraded. According to incomplete statistics, existing stands are mostly sparse, clear-cut or young forests because of high-intensity harvesting. The decrease of forest area has resulted in weather extremes, severe soil erosion, low water conservation and a high frequency of natural disasters. At present, the runoff ratio of the flooding period to low runoff is increasing. Some small rivers dry up in the low runoff period, sediment in the river increases, and correspondingly, erosion also increases. As one of the main mountainous forest areas in the region, the Tianshan Mountains face the same problems. Results of a remote sensing investigation in 2000 show that the grassland area in Xinjiang of about 4.8×10^5 km^2, is decreasing by 1.38×10^5 ha·a^{-1}. Over 70% of the livestock products come from the natural grassland. Grasslands on the north slope of the Tianshan Mountains, which represent the largest mountainous grasslands in the region, have been degraded because of summer and autumn overgrazing in the recent decades. The area and productivity of winter and spring grasslands are very low and degraded. This obvious disequilibrium between summer and autumn grassland and winter and spring grassland leads to a loss of ecological function.

(ii) Measures of ecological conservation

The mountainous forest-grasslands and desert in the northern part of the Tianshan Mountains have been nomadic rangeland for several thousand years. These lands have been severely degraded, and existing livestock numbers exceed the land's carrying capacity. In the mountainous forest-grassland belt, if existing artificial young forest is well managed and protected, at the end of this century, near-mature forest (120–150 years) will be restored to its water conservation and soil erosion control capacity. A basic, slightly-selective cutting regime for enhancement of reforestation and stand health can be applied. Livestock numbers should be reduced and a sound grazing system implemented in mountain grassland and low-mountain desert areas. With 10–20 years of rehabilitation, grassland productivity, soil nutrients and soil and water conservation are expected to be gradually restored.

Hence, mountainous timber forest and grassland animal husbandry should be evenly distributed to rehabilitate overused mountain ecosystems and to restore ecological functions of the mountain and its water supply. The main function of the mountain in the future is oriented toward water conservation and summer and autumn rangeland with a reasonable amount of livestock.

To maintain the ecological services, the majority (60–70%) of animal husbandry in mountainous forest, meadow grassland and desert should be transferred to the oasis and fan edge belt. This will establish a new ecological industry belt for timber forestry and artificial grasslands and will also form an intensive ecological industry chain that will rehabilitate mountain and desert vegetation, solve the problems of timber and grassland shortage and improve the regional environment.

10.2.2.3 Establishment of a new industry belt on the oasis and fan edge belt of the northern slope of the Tianshan Mountains

(i) Existing problems

The majority of natural or artificial oases on the northern slope of the Tianshan Mountains, especially those used for traditional agriculture, are surrounded by deserts. The oasis agricultural system is characterized by a simple and unstable structure, single crop agriculture and low productivity with unwise irrigation and land reclamation. Large land areas with secondary soil salinization are formed on the oasis edge, which results in a salty desert. The fan edge belt lies on the lower edge of the diluvial fan. Because of clayey soil and groundwater near or above the ground surface, primary salinization is widespread. Natural vegetation is salinized meadow, shrubbery and halophytes in the salty desert and boggy herbaceous plants around spring outflow sites. The fan edge belt is normally unsuitable for cultivation due to soil salinization. Though millions of hectares of land have been reclaimed as farmland in recent decades, the majority of these lands have been abandoned because of secondary soil salinization. The primary and secondary soil salinization areas on the northern slope of the Tianshan Mountains account for approximately 16% of the entire region.

(ii) Establishment of pen-raised animal husbandry and related industry development

Xinjiang is one of the main animal husbandry areas in China. At present, animal husbandry in northern Xinjiang includes grazing in natural grassland and raising livestock in agricultural areas. Management rests on the primary stage, and an optimum industry chain has not yet been formed. Currently, livestock numbers are around 50 million. Production types and management ideas must be completely transformed from the traditional and extensive seasonal nomadic mode to intensive, cost-effect, pen-raised animal husbandry. A national livestock production base should be established based on artificial grassland. The animal husbandry industry should be developed as a key supporting industry for the economic development of northern Xinjiang (Fig. 10.6).

Development of the forage industry guarantees the strategic transfer of animal husbandry in mountainous areas and desert. Crop rotation and intercropping between cotton and leguminous plants, such as *Medicago sativa*, should be extended into the oasis to enhance herbivore animal husbandry. The fan edge belt is unsuitable for agriculture and forestry, but some salt-tolerant plants or halophytes such as *Populus euphratica*, *Alhagi pseudalhagi*,

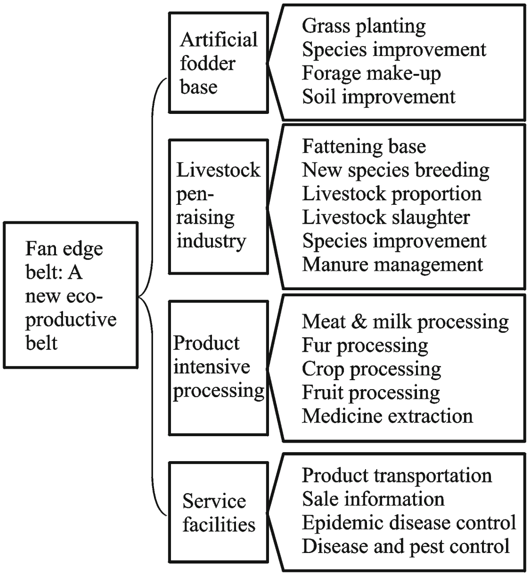

Fig. 10.6 Sketch map of industry belt on oasis and fan edge belt

Halocnemum strobilaceum, *Halostachys caspica*, *Achnatherum splendens* and *Melilotus suaveolens* can grow well. These plants can be planted as an artificial forage base and ecological barrier for oasis development.

It has been estimated that the area of fan edge belt on the northern slope of the Tianshan Mountains was about 1.08×10^6 ha, and the arable land area with channel water projects or water-saving irrigation projects was about 4.86×10^5 ha. At present, there are 1.14×10^6 ha of farmland from Urumqi to Jinghe on the northern foot of the Tianshan Mountains. Based on population analysis and the land resource carrying capacity, a single agricultural structure can be modified, i.e., 4.57×10^5 ha can be used for a grass-sowing base. It was estimated that $1–1.5\times10^6$ ha of artificial grassland can be established in the oases and fan edge belts of the northern slope of the Tianshan Mountains. It has also been measured that the yield of *Achnatherum splendens* planted in the abandoned land of the fan edge belt is up to $15–18\times10^3$ kg·ha^{-1} and that the yield of maize silage sown in an oasis is up to $12–15\times10^4$ kg·ha^{-1}. In addition to supplements from the agriculture ecosystem, it has been calculated that $0.6–0.7\times10^3$ kg fodder is needed for each sheep. Artificial grassland in a fan edge belt can support 22.5–27 sheep·ha^{-1}, and artificial grassland and fodder land in an oasis can support 45–180 sheep·ha^{-1}. Hence, the new ecological industry belt on the northern slope of the Tianshan Mountains can carry about 30 million sheep, or approximately 60% of the total livestock of Xinjiang or about 100% that of northern Xinjiang. The ratio of livestock between mountainous areas and deserts can be modified from 7:3 to 3:7. A highly productive, good-quality and cost-effective animal husbandry base can be established. Pen-raised and fattened animal husbandry, supported by an artificial grassland and fodder base, will become the supporting industry in this region.

(iii) Development of modern, pen-raised animal husbandry and integration of regional agriculture and animal husbandry

In mountainous areas, productivity for traditional nomadic animal husbandry is very low. The herder's lifestyle is difficult to change, and increasingly, overgrazing results in grassland degradation, especially in winter and spring grazing in low mountain areas. Hence, the only way to change local animal husbandry is with a strategic transfer from grazing in natural grassland to pen-raised livestock in an agricultural area. In other words, traditional nomadic animal husbandry in mountainous areas is transferred to modern, pen-raised animal husbandry in artificial grassland and fodder base oases. In the future, oasis agriculture should emphasize forage production and pen-raised animal husbandry, and grassland should be managed using agricultural methods. Forage production in agricultural land is advantageous not only to stabilize animal husbandry but to increase the overall health of the agricultural ecosystem.

Due to the shortage of winter and spring grazing land in pasture areas, a great deal of commercial livestock can be transferred to agricultural areas from pasture areas before winter and then sold after 3–4 months of fattening. This will alleviate grazing pressure on mountainous areas and deserts and will also restore grassland productivity and ecological functions. In addition, organic manure is provided for agricultural production the following spring. Establishing a new industry belt can replace ineffective, destructive grazing activities with artificial grassland that has higher ground cover and better ability to stabilize sand, control soil salinization and protect oases.

(iv) Prolonging the ecological industry chain and establishing a corresponding service system

During an increase of animal husbandry production, out-of-region sales for livestock products such as skin, feather, meat and milk, is an important production chain with many economic benefits. However, thorough processing of primary livestock should be developed locally to realize local profits. The animal husbandry production process has various products that can be produced locally, such as skin, feather, meat and milk. Viscera and blood can also used for biochemical products and medicinal materials. Local production will significantly increase animal husbandry profits by multiples of tens or hundreds. In addition, local institutions, such as good species breeding bases, livestock fattening bases, veterinarian stations, epidemic prevention stations, mechanical cultivation stations, disease and pest control and related service systems, should be further strengthened. Transportation, food processing, finance, information and consultation services should also be expanded.

10.2.2.4 Resource care for biodiversity in the Junggar Desert

(i) Ecological status

The desert in the Junggar Basin covers an area of 4.55×10^4 km^2. Because of unwise human activity and modern agricultural development, biological processes of the desert ecosystem in the Junggar Basin have been degraded. Effects include biodiversity loss, shrinking metapopulations, simplified food chains and trophic levels and fragile and unstable ecosystems. Habitat destruction has resulted in endangerment and extinction of many wild animal species.

(ii) Implications for biodiversity conservation

The Junggar Desert consists of a number ecosystems including typical natural and artificial desert vegetation, salt-desert vegetation, desert wetland (e.g., Manas Lake) and desert fresh and salt-water lakes (e.g., Ulungur Lake and Ebinur Lake). These ecosystems are the ecological barriers for oases and desert steppes in the northern part of the Tianshan Mountains. They are also the biological resource base for sustainable ecological and economic development in northern Xinjiang.

The Junggar Desert has the richest plant species resources of any temperate desert in the world. It is located at the joint and transitional belt between the Central Asian Desert Irano-Turanian flora and the North Asian Mongolian Gobi flora and also includes Tethyatc xerophytic flora. The desert vegetation includes the typical desert plant community and typical salt desert community, as well as abundant ephemeral plants. The Junggar Desert is also the distribution zone of precious medicinal plants such as *Cistanche deserticola*, *Ephedra sinica* and *Capparis spinosa* . An abundance of lichen species in the sand dunes on the southern edge of the Junggar Desert forms a 1–3 cm thick biotic crust that stabilizes mobile sand dunes.

The Junggar Desert is a natural rangeland for wild ungulates. Many large, wild, herbivorous ungulates, such as *Gazella subgutturosa*, *Saiga tatarica* var.*mongolica*, *Equus hemionus* var. *mongolica*, *Ovis ammon darwini*, *Equus przewalskii* and *Camelus bactrianus*, have adapted to the harsh environmental extremes of high summer temperatures, cold winters and a shortage of water. They can effectively utilize desert plants, and their feeding habits are adapted to plants that are high in fiber and salinity.

The Junggar Desert is also a precious wildlife gene bank in the arid temperate zone. Many special plant species and genotypes have evolved during natural selection and adaptation throughout the area's long-term geologic history. These include many that are drought-tolerant, tolerant of high-temperatures, resistant to low-temperatures, tolerant of radiation or have high photosynthetic efficiency or special secondary metabolic compounds (perfume oil, alkaloid). Internationally, wild plant gene resources in drylands is listed as the first focus of international biodiversity conservation and the most important resource for agriculture, food, medicine and industrial materials in the 21st century. Hence, the rich biological resources of the Junggar Desert may help determine the region's development potential.

(iii) Urgent need for establishing biodiversity conservation

Principles of biodiversity conservation in the Junggar Desert state that extensive desert grazing at the expense of the natural environment should be forbidden by local or national policies. Petroleum extraction should avoid disturbing or destroying the desert ecosystem as much as possible, and a seedbank or gene bank of desert plants should be established.

The former Soviet Union has propagated *Saiga tatarica mongolica* successfully in the Central Asian Desert, and the U.S. has restored America's bison which had gone extinct in the fields of the Great Plains. In recent years, a few institutions in China have successfully reintroduced *Equus przewalskii* and *Saiga tatarica mongolica*, which were bred and brought from overseas. Therefore, it is suggested that the Junggar Desert nature reserve should be established with a focus on biodiversity conservation. Wild animal breeding farms should be established and systematically designed in the Junggar Desert to breed wild ungulates that will be released to reestablish wild animal populations. Afterward, moderate ecotourism and range game land can be developed. The ecological security of the Junggar Desert will not only be advantageous to the sustainable social, economic and environmental development of the northern slope of the Tianshan Mountains and the surrounding Xinjiang area, but it is also important for biological resource conservation of temperate arid zones all over the world.

10.2.2.5 Artificial fast-growing and highly-productive forests

Timber needs in Xinjiang increase from year to year because of economic development and increases in standard of living. For example, the amount of timber needed in 2001 was 35×10^4 m^3. However, timber production was reduced to 8×10^4 m^3in 2001 from 28.2×10^4 m^3in 1997 due to implementation of a national natural forest conservation project. The rest of the needed timber, 27×10^4 m^3, was imported. Hence, planting artificial fast-growing and highly-productive forests in plains will alleviate pressure on the timber supply and will help to improve the environment of the oasis edge.

Planting artificial fast-growing, highly-productive forests in plains would provide economic benefits for agriculture, forestry, animal husbandry and their related industries. At present, the proportion of agriculture, forestry and animal husbandry in oasis agriculture is about 8:1.6:0.4. The proportion of forestry is relatively low. In Xinjiang, where timber is in short supply, timber prices and their indirect costs are equal to the cost of cotton or grass needed for raising livestock. Therefore, a part of the artificial fast-growing, highly-productive forest can be planted during the period of industry structure modification and reforestation of protective forests in the oasis. In addition, the loamy desert plain boasts rich land resources and high solar radiation, which has great potential for growing this kind of forests. By introducing fast-growing and high-quality timber species with intensive management, timber can be harvested in 6–7 years with a timber volume of 180–225 $m^3 \cdot ha^{-1}$. This timber can be used to produce high or medium density boards for a good profit. Accordingly, in sites with enough regional surface water and a partial groundwater supply, water needed for forestry irrigation is 9,000 $m^3 \cdot ha^{-1}$. Through many years of planting, 16,700–20,000 ha of fast-growing, high-quality forest can be planted in the oasis, fan edge zone and loamy desert areas of the Junggar Desert. 2,000 – 2,670 $ha \cdot a^{-1}$ could then be rotationally cut, and 36–50$\times10^4$ m^3 of timber could be provided. In addition, the Ili Valley has abundant water and soil resources. More than 133,000 ha of fast-growing, high-quality forest could be planted, which would form the largest artificial timber forest base in Xinjiang. 20,000 ha of forest per year could be cut, which would provide 360$\times10^4$ m^3 of timber and meet the paper pulp and timber needs in Xinjiang. Therefore, timber forests can be transferred from mountainous areas to plains.

10.2.2.6 Necessary strategies for implementing the Green Bridge System

- Traditional nomadic grazing activities in mountainous area must be changed to decrease livestock in mountainous areas by 60%. Animal husbandry must be transferred from the oasis to the fan edge belt to allow mountainous grasslands to recuperate and rehabilitate.
- Cost-effective artificial forage bases must be established in oases and fan edge belts to provide feeding sites for livestock that are usually grazed in mountainous grassland in the short-term. An organic system between mountainous grasslands and feeding sites in farming areas must be formed to enhance sustainable animal husbandry on the northern foot of the Tianshan Mountains.
- During the implementation of new productive belts and ecological conservation practices, advanced technology must be applied and increasingly extended. These technologies include crossbreeding, fine livestock raising, precise processing, and environmental protection, etc.
- The ratio of farmland to grassland to forest in a newly-built oasis should be 5:4:1, and the ratio in an old oasis should be modified to 5:3:2. This will ensure oasis stability as well as sustainable social and economic development.
- The Junggar Desert, as a whole, should be established as a nature reserve for a valuable gene base of natural vegetation and as a breeding base for wild desert ungulates.
- A series of ecological compensatory policies, similar to policies for transforming cultivated land to forest, should be enacted to transform cultivated land to grassland or grazing-free grassland for revegetation. Economic compensation or other preferential treatment should be provided for local minority herders. Preferential and encouraging policies should be enacted for enterprises which invest in the forage industry, pen-raised animal husbandry, thorough processing of animal husbandry products

and other service trades.

10.3 Other eco-production paradigms

In addition to two typical paradigms introduced above, two other paradigms, i.e. integrated animal husbandry paradigm in the Inner Mongolia Steppe and agropastoral regions and small watershed based paradigm on the Loess Plateau, have been established and will be introduced as follows.

10.3.1 Integrated animal husbandry paradigm in the Inner Mongolia Steppe and agropastoral transitional regions

The Inner Mongolia Steppe is located on a flat, undulating plateau characterized by two typical geomorphological units. The lower unit, with an elevation of 960–1,000 m, consists of first class and second class terraces and is covered with zone-typical steppe vegetation such as *Stipa grandis*, *Leymus chinensis* and forbs. The higher unit, with an elevation of 1,200–1,400 m, consists of first-class and second-class terraces and is a meadow steppe covered with *Stipa baicalensis* and xerophytic and mesic forbs. At the plateau level, incised river valleys form lower terraces, floodplains and wadis with good moisture condition, as well as a few large sand dunes or sand belts distributed on the plateau surface. The agropastoral transitional region is not a biogeological region. It is a land-use based transitional region along the eastern and southernmost edge of the Inner Mongolia Steppe and is one of the most serious desertification-affected regions due to excessive human activity. Considering the close interactive relationship between the Inner Mongolia Steppe and agropastoral transitional regions, we establish the two-in-one integrated eco-production paradigm as follows (Fig. 10.7).

In the Inner Mongolia Steppe, the basic development framework is designed as grazing rangeland, mowing grassland and artificial grassland. In the first and second terraces, enclosed rotation grazing rangeland should be established. In the third and fourth terraces, where the meadow steppe exists and grass cover is abundant, mowed natural grassland is suitable but limited by longer distances from water points. In the valley and floodplain where runoff water can be used, artificial grassland with high production capabilities can be developed. On sand dunes or sand belts, sand stabilization shelterbelt systems should be established with shrubs or trees, and some rain-fed forage plants can be planted within the shelterbelt system.

However, because of widespread rangeland degradation, small areas of artificial grassland development, high livestock numbers and frequent spring drought and winter snow disasters, an intra-regional disequilibrium has formed

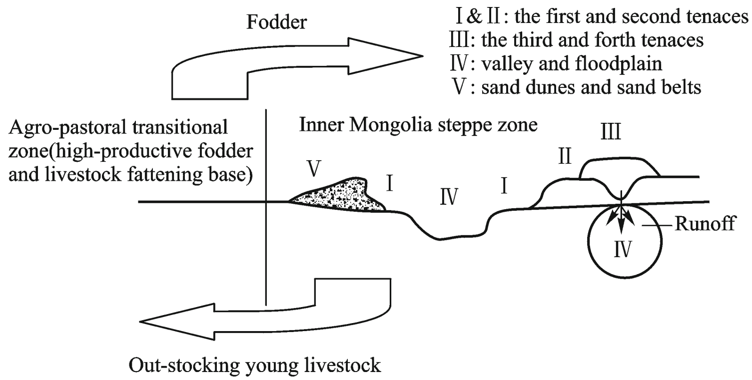

Fig. 10.7 Sketch map of Inner Mongolia Steppe and agro-pastoral transitional region (Yang et al., 2008, with permission from authors)

in the development framework, which is difficult to change. Therefore, the agropastoral transitional region is combined to form an integrated eco-production paradigm. With better physical conditions, high-producing, artificial forage bases can be established in the agropastoral transitional region. This forage can be transported to the steppe in the winter. A livestock feeding base can be established to receive young livestock from the steppes each autumn to fatten the livestock and increase profit. Only mother, newborn and breeding livestock are raised in the steppe during the winter. Thus, an integrated animal husbandry paradigm in the Inner Mongolia Steppe and agropastoral transitional region is formed as enclosed rotation grazing rangeland, mowed natural grassland, artificial grassland, high-productive forage and livestock feeding base (Fig. 10.7) (Zhang, 2000).

10.3.2 Small watershed-based paradigm on the Loess Plateau

The Loess Plateau covers 626,800 km^2, or 6.5% of the national territory, and is famous for its ancient civilization and severe soil erosion (Chen et al., 1988; Tang and Chen, 1990; Yang et al., 2005b). The climate is warm, temperate, and semi-arid with a mean annual precipitation of 350–700 mm. More than 70% of precipitation is distributed between the months of July and September. Deposited with aeolian soil from the periphery of the Gobi, deserts and other sandlands, the majority of this region is covered with deep, loose, loamy soil with relatively even soil textures that gradually become finer moving from north to south (Sun and Ding, 1998). Loess physiognomy, with an altitude of 800–1,800 m and evolving from aeolian processes in the Cenozoic and from severe water erosion associated with historical human activity, can be divided into two types. The first is the loess deposition type that primarily includes loess Yuans (a large flat surface with little or no erosion), ridges and hills characterized by ancient highlands formed from original deposit surfaces incised from gully erosion. The second is the loess erosion type that consists of various gullies. When water flows toward a gully bottom, soil erosion gradually increases. Gully erosion accounts for more than 80% of soil erosion in a watershed (Kang et al., 2003). Considering the arrangement of landscape elements, runoff and sediment redistribution, a small watershed-based paradigm is designed as follows(Fig. 10.8).

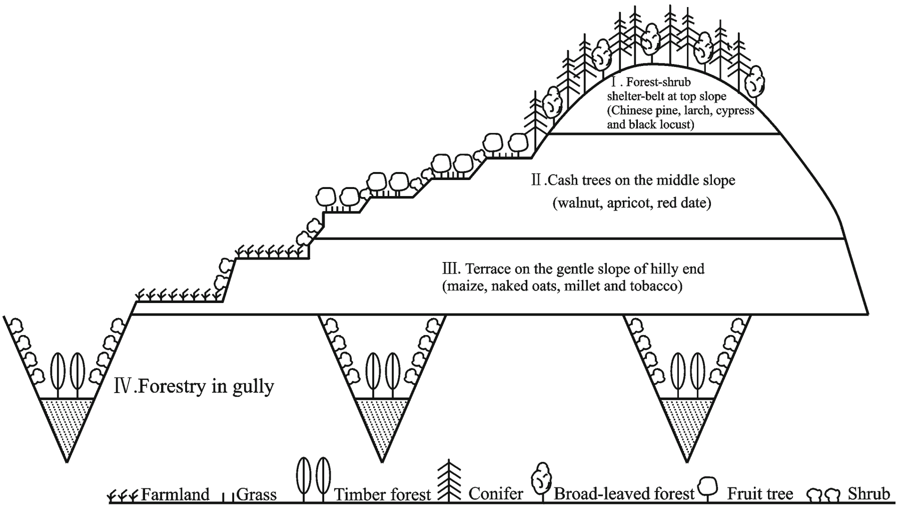

Fig. 10.8 Sketch map of small water-based paradigm on Loess Plateau (modified from Tang and Zhang, 2003, with permission from authors)

Tree-shrub-grass shelterbelt at the hilltop: This belt lies at the top and upper part of the loess ridges and hills. Combined with non-biological measures such as diversion ditches, this belt is established mainly as a soil and water conservation belt to stop headward gully erosion. Trees or shrubs should be planted with horizontal ditches, and grasses should be sown between the rows. The grasses and shrubs act together as livestock forage (Fu, 1989).

Cash tree belt with intercropped forage grass on the middle of the hill slope: Cash trees, especially dry fruit trees, can be planted at the middle of the hill slope. Tree density should be low, and water-harvesting techniques should be applied. Leguminous forbs, such as trefoil, can be sown on the micro-catchment area (Li et al., 2005; Yang et al., 2005a), and some shrub species, such as *Caragana intermedia*, can be planted at the brim of the runoff ditch.

Terraced farmland belt at the hill foot: On gentle slopes at the foot of the loess hill, terraces, which are traditionally used on the Loess Plateau (Lu and Stocking, 2000a), are built for rain-fed agriculture. Grain crops, cash crops or rotation grass-crops are planted on level or anti-slope terraces. On ridges of the terrace, one or two rows of shrubs can be planted to protect the terrace from floods or erosion from rainstorms.

Gully forestry: On gentle gully slopes, shrub belts are planted along contour lines as buffer zones and soil and water conservation zones. Silt-trapping dams are built at the bottom of the gully (Chang et al., 1996; Lu and Stocking, 2000b). Fast-growing, high-production timber, such as Poplar, is planted in sediment land formed by silt-trapping dams. Because of possible flooding, the newly-formed land is not suitable for agricultural development.

Drylands cover a large proportion of China's territory, and physical conditions in different regions are diverse and complex and are characterized by poverty and fragile physical conditions. For these reasons, economic and environmental development should be synchronously implemented. Hence, new dryland development paradigms are needed for sustainable regional development (Reynolds et al., 2007). We do not expect that the four above-mentioned eco-production paradigms include all possible types, but these paradigms cover the main biogeographical regions of China and provide theoretical frameworks and practical models for sustainable dryland development in China. These paradigms are helpful in making regional development plans and aid in government decision-making. At present, these paradigms have been applied in dryland development, which is partly or completely combined with national ecological projects. More detailed designs for specific regions based on these frameworks will be made in the future.

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