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Historical evolution and the effects of ecological management in Tarim Basin, China

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The Tarim Basin, in northwestern China, is the largest continental basin in the world, and hosts desert landscapes as well as extensive oasis agriculture. Many horticultural products come from this basin. However, since the 1950s, frequent river flow interruptions have occurred in the lower reaches of the Tarim River. Thus, the natural ecology of the basin has undergone significant changes because of recent human economic and social activities. In particular, water resource development and utilization along with climate changes have had a significant impact on the area. To prevent further deterioration of the environment, the Central Government implemented a water conveyance project in 2000. Based on this project, Chinese scientists, together with those from overseas, have conducted extensive research on the historical evolution of the area, and the physiological and ecological responses of the natural vegetation around the Tarim Desert Highway. Progress has been made in the areas of environmental protection and ecological conservation.

Tarim Basin, historical evolution, vegetation recovery, Tarim Desert Highway, ecological water conveyance

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The Tarim Basin is located between the Tianshan and Kunlun mountains, in Southern Xinjiang, stretching over 1100 km from east to west and approximately 600 km from north to south. Its total area amounts to 1050000 km^2, with a desert area of 370400 km^2. The Tarim Basin is characterized by its abundant light and heat resources. Over the past several thousand years, humans have inhabited areas downstream along the Tarim River. Long-term anthropogenic activities have created a highly modified landscape within the basin [1–3].

The Tarim Basin hosts a multi-ethnic community. The Uygur constitutes the main region, and it consists of 42 counties, 56 agricultural and reclamation administrations, and nearly 1.33 million hectares of irrigated area. The total population is about 8.26 million, with 82.5% (6.81 million) composed of ethnic minorities. The basin sustains mainly farming and animal husbandry activities, and has become an important base for high-quality cotton and crops. In addition, the area is a base for horticultural products, such as Korla sweet pears, apricots, walnuts, muskmelons, pomegranates, and figs. The Tarim Basin has both abundant natural resources and fragile eco-environments. These environments contain unique natural and geographical characters with important water resources that support social and economic development, ecological construction and environmental protection in Xinjiang [4–7].

Since the 1950s, the natural ecosystem of Tarim Basin has undergone significant changes. These changes have been prompted by economic and social activities, especially with regard to water resource development and utilization,

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and climate changes. At the same time, a flood interruption hazard in the lower reaches of the Tarim River threatened this fragile system. As a consequence, the downstream Lop Nur and Taitema lakes dried up in 1970 and 1972, respectively. During this time, the groundwater levels dropped down to 8–12 m. As a result, the natural vegetation fed by groundwater experienced dramatic degradation. In addition, many herbs, including *Phragmites communis*, *Poacynum hendersonii*, and *Alhagi sparsifolia* died. Large areas of *Tamarix* and *Populus* decayed, wind erosion and desertification intensified, and biodiversity was severely reduced [8]. Numerous rivers have surface water contact with the Tarim River, such as the Chercheng, Keriya and Dina rivers, which were cut off from the main stream of the Tarim River before the 1940s. After the 1940s, the Kashigar, Kaidu-Konqi and Weigan rivers also were cut off gradually. At present, only three rivers are connected with the main stream of the Tarim River, the Hotan, Yarkant and Aksu rivers. The Konqi River diverts water from Boston Lake into the lower reaches of the Tarim River *via* pumping stations on the Kuta irrigation canal, which constitutes "four source rivers and one main stream" system [9]. The lower reaches of the Tarim River are now considered one of the most prominent ecological and environmental issues in western China, attracting the attention of ecologists within and outside China [10,11]. In order to prevent further deterioration of this environment, and in order to restore the endangered "Green Corridor" in the lower reaches of the Tarim River, the Central Government has implemented a water conveyance project. This project, which started in 2000, aims to elevate the groundwater level of both sides of the river.

1 Physical and geographical background of the Tarim Basin

The Tarim Basin lies at the northern boundary of the Taklimakan Desert, and it includes nine water catchments. The catchments flow to the center from surrounding regions, as well as from the main stream of the Tarim River, Taklimakan Desert and the eastern desert region.

The climatic conditions of the Tarim Basin are classified as temperate, with a mean annual temperature of 10.6–11.5°C. The average temperature of July is 20–30°C, with a maximum of 43.6°C and in January of –10 to –20°C, with a minimum of –27.5°C. The accumulated temperatures of ⩾0°C range from 4100 to 4300°C. Average annual precipitation is 116.5 mm, with 200–500 mm in mountainous areas, 50–80 mm around the basin, and only 10 mm in the center of the basin. The temporal distribution of the precipitation has a strong heterogeneity, with more than 80% concentrated in summer (from May to October) and the remaining <20% in winter (from November to April) [12].

The Tarim Basin has a cultivated land area of 2.04×10^7 hm^2 and a surface water volume of 1.96×10^{10} m^3. With 2/3 of the total area of the region, the natural resources of Xinjiang, especially water resources, have not been well exploited and utilized. This lack of proper management has been caused by the rapid population growth and accelerated social development of the area over the past 50 years. The 321-km-long Tarim River has been interrupted for 30 years because of wasteland reclamation in the headstream and upper reaches. High water consumption also has occurred in the rolling lowlands of the middle reaches, where devastating effects of digging water holes to steal water have occurred. All these human activities have increasingly and dramatically degraded the natural vegetation of this "Green Corridor" [9,11,12].

2 Ecological environment and natural resource development in the Tarim Basin

2.1 Petroleum and natural gas exploration in the Tarim Basin

The Tarim Basin is not only the largest sedimentary basin in the world, but it also is an important strategic region for the petroleum industry in China. Many studies have indicated that the Tarim Basin is an important petroleum strategic area for China, and an important source of the West-East Gas Transmission, where 10 stratigraphic systems from the Sinian to the Quaternary have been found to be hydrocarbon bearing [13–21]. Jia and Wei [13] indicated that the structure of the Tarim Basin is responsible for its composite petroleum system, which includes multiple oil sources, abundant oil-bearing strata, and superimposed multi-stage formations. Zhou [14] showed that there were four periods of marine hydrocarbon accumulation and Wang [17] suggested that the early and late Hercynian periods were the most favorable times for hydrocarbon generation and accumulation in the Tarim Basin. Li [18] concluded that the early Hercynian, the late Hercynian-Indosinian, and the Himalayan were the three stages of hydrocarbon accumulation in the Manjiaer petroleum system, and the late Hercynian-Indosinian was the major stage for hydrocarbon accumulation.

The northern margin of the Tarim Basin (NMTB) has attracted attention because of its unique structure and position. The NMTB is made up of the Kuqa Depression (KD) and Tabei Uplift (TU). The KD is about 500 km in the E-W direction and 30–80 km in the S-N direction. From east to west, it is composed of the Yangxia, Baicheng and Wushi depressions [1]. The TU is an E-W trending arc-like structural belt, which is a superimposed structural unit after several tectonic movements. In recent years, Chinese geologists have carried out comprehensive geophysical explorations in the NMTB, and have obtained some important results. For example, 3D seismic prospects are of great assistance in locating oil and gas reservoirs [22]. For the NMTB, the 3D seismic technique has been invaluable for advancing understanding of Phanerozoic paleomagnetism and structural evolution [23], gravity field and deep structure of the crust [24], joint inversion of gravity and magnetism [25], and *Q* value and seismic converted waves [26]. Different viewpoints and approaches have been used to investigate lithospheric structure and geodynamics. Zhang et al. [27] conducted an analysis of the 2D velocity structure of the crust and upper mantle of the northern margin of the Tarim Basin by ray tracing and theoretical seismogram calculations. He et al. [28] analyzed the tectonic setting, litho-facies and palaeo-geography of the area, as well as depositional fill processes and superimposing and overlapping development in the Tarim region during the Ordovician. Shen et al. [29] surveyed the deformed terraces of the Boguzi River across the Artux anticline belt. Zhang et al. [30] built evolvement patterns of organic matter on the basis of source rock sedimentation styles and geothermal conditions, and concluded that hydrocarbon source rock evolvement was not associated with the types of sedimentation styles because burial time, depth, and the geothermal field also can affect source rock evolvement patterns.

The cratonic area of the Tarim Basin has an area of approximately 330000 km^2, which mainly consists of uplift in the southern and northern depression, central uplift and part of southwest depression in the northern Tarim Basin. Zhang et al. [31] conducted a comprehensive analysis of the main factors affecting hydrocarbon accumulation of cratonic areas in the Tarim Basin, summarized oil and gas accumulation laws of cratonic areas, and provided the basis for exploration of petroleum and gas fields in the future.

2.2 Ecological management and restoration

Current concerns for global warming have prompted efforts to arrest ecosystem degradation in the Tarim Basin. In addition, human activities have resulted in the continual reduction of available water resources, decimation of *Populus* fields and desertification. Thus, it is a pressing task for us to protect this ecosystem and the general environment of the Tarim Basin.

Because of water resource shortages, the lower reaches of Tarim River are faced with serious ecological degradation. The degradation trend is irreversible without ecological water conveyance. Before implementation of the drainage plan started in May 2000, the main perennial herbs remaining were salt meadow species, including *Phragmites communis*, *Glyzyrrhiza inflate*, *Poacynum hendersonii*, *Alhagi sparsifolia*, *Karelinia caspica*, *Inula ammophila*, and *Cynanchum sibiricum*. The annual halophyte grass, *Halogeton glomertus*, could be seen occasionally along the lower abandoned river channel. These herbs were mostly scattered, while others died off. Grassland conditions included a herb community of mainly xeric grass, super-xerophytic plants and halophytes, with decreasing diversity, reduced vegetation coverage (less than 10%), sparser grass distributions, low reed nourishing shoots (5–15 cm in height), declining net primary productivity (with yields down from 1200–2250 to 270–400 kg/hm^2, decreased availability of pastures (e.g. only 13.33 hm^2 of pasture could be used to raise sheep in Yingsu), and a gradual grassland transformation from lowland saline meadows to sandy desert grassland and mobile sand dunes [6]. In order to mitigate ecological degradation, the Central Government has spent 10.7 billion to implement an inter-basin water transfer project since 2000. Thus far, 2.3 billion m^3 of water have been diverted. The hydrological research group of the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, has conducted 11 consecutive years of uninterrupted field ecological surveys [1,2,8]. The investigations have expanded from 40 groundwater monitoring wells at 9 sections in the lower reaches to 92 wells at 84 sections concentrated in the middle reaches, including fixed plant sampling sites, groundwater tables, groundwater samples, soil samples, and plant samples. In addition, research on groundwater dynamic monitoring and physiological responses of plants provides theoretical support and technical guidance for the water conveyance project and ecological rehabilitation of the lower Tarim River.

Through the water conveyance project, vegetation began to grow well along the river bank. Today, new types of herbaceous vegetation, such as *Glyzyrrhiza inflate*, *Alhagi sparsifolia*, *Poacynum hendersonii*, and *Phragmites communis*, can be found along the coast in some parts of the Tarim Basin. With the rise in groundwater levels, some xerophytic arbors and bushes have been brought back to life. *Populus* populations, with their unique root sprouting and bud germination systems, also have been restored. According to recent surveys, vegetation now covers more than 90% of the downstream areas. The number of live plant species has increased from 3–4 to more than 10 after the water conveyance. At the same time, vegetation in other areas has showed different responses to changing groundwater levels. Within a certain range around the river, there is a close relationship between apparent responses of vegetation and distance from the river channels. Within a distance of 150 m away from the river, herbaceous vegetation has regerminated, with species increasing significantly, and some local trees and shrubs have shown more clear responses to the rising groundwater level. In the 150–350 m range, the main characteristics of shrubs and *Populus* indicate an increase in coverage and crown changes. In the range of 350–700 m, groundwater level has risen by 1–3 m, which can only meet the growth demands of some adult *Populus* and *Tamarix*. Beyond 700 m, there has been little change in vegetation coverage, species diversity, species richness or crown of *Populus euphratica*. Thus, the desertification within a certain distance from the river channel has been reversed, which has produced some positive effects in protecting the eco-environment of the “Green Corridor” [32].

It has been urgent and timely to implement integrated environmental management strategies in the Tarim Basin. This management system is focused on guaranteeing eco-water to prevent further deterioration of the eco-environment of the Tarim River. In combination with previous studies, many ecologists have evaluated the spatiotemporal effects of the eco-water conveyance in terms of occurrence and ecological characteristics of riparian forest vegetation. These studies provided a theoretical framework for subsequent water conveyance projects [33,34]. The book *Eco-hydrological Research in Tarim Basin* provides a summary of ecological hydrology studies in the Tarim Basin over the past 10 years [35]. The book analyzes the composition, changes and sustainability of hydrology and water resources in the Tarim Basin. It also discusses oasis development and oasis agriculture-hydrological processes under the constraint of water resources. It reveals the responses and adaptation strategies of desert riparian forest vegetation to environmental stress, and proposes concrete countermeasures to policy makers.

Large-scale ecological restoration projects using artificial recharging of groundwater are rare throughout the world. However, without such studies, it is difficult to identify the change brought about by such an unprecedented ecological engineering experiment, and its future ecological trends. Huang and Pang [36] began a systematic study in 2005 on the isotope hydrology of the water cycle and ecology of the Tarim Basin. The results have provided a scientific basis for assessing the effects of water diversion on relieving ecological deterioration, as well as the optimization of water diversion methods. Ye et al. [37] studied the income of farmers and herdsmen and the local economy after the water conveyance project started, using a combined method of random sampling surveys, door-to-door household surveys and statistical data. Results showed that the ecological water conveyance project improved the eco-environment, as well as raised the income of the local people. Chen et al. [38], Xu et al. [39] and Guo et al. [40] studied the ecological benefits of emergent water conveyance and groundwater changes after the start of the water conveyance project. Physiological responses of plants to groundwater changes after the emergent water conveyance were studied from the viewpoint of ecology and physiology by Yan et al. [41], Li et al. [42], Zhuang et al. [43], Wei et al. [44], Zeng et al. [45], Fu et al. [46], Shan et al. [47], Chen et al. [48] and Guo et al. [49] mainly with respect to photosynthesis, respiretion, water potential, biomass, chlorophyll, soluble sugar, Pro, MDA, SOD, POD, CAT, ABA, CK, IAA, and cell microstructure and ultrastructure. These studies aimed to identify a reasonable amount of water for conveyance.

2.3 Research on the Tarim Desert Highway

The Taklimakan Desert is the second largest desert in the world, with an area of approximately 3.38×10^5 km^2. More than 82% of its area is covered by active sand dunes. It is probably the most arid area throughout Eurasia, and it is known as "the sand dune museum of the world" for its great variety of dune morphologies. It is also called "the Dead Sea" because animals and plants are rarely seen there. The desert part of the Tarim Desert Highway is located between latitude 37°–42°N and longitude 82°–85°E. It is 562 km long, and runs across the Taklimakan Desert from the north at No. 314 National Highway in Luntai County to the south at No. 315 National Highway in Minfeng County. It includes 446 km across the desert, and it has been the longest highway crossing a desert in the world since it opened to traffic in 1995. Generally, about 50% of its mobile dunes are in areas with highly complex longitudinal sand ridges. As a result, landforms along the Tarim Desert Highway are dominated by highly complex sand ridges and broad flat inter-dunes.

The Tarim Desert Highway traverses the Taklimakan Desert from north to south, and is the lifeline for oil and gas exploitation, traffic and economy in Southern Xinjiang. Plants and surface runoff are scarce in the area, which poses a serious threat to the traffic security of the Tarim Desert Highway.

The area along the desert highway is extremely arid and dry, with little precipitation and strong winds, leading to intensive sand blown activities and a great variety of sand dune types, relatively few soil types, low vegetation coverage, and the mobile sand-dominated land surfaces. Consequently, the wind-blown sand character is one of the most severe challenges to the Tarim Desert Highway. To ensure the long-term safe operation of the Tarim Highway, a physical sand protection system has been constructed to protect the highway from damage by strong winds. A shelterbelt structure includes a sand-binding forest belt, sand-obstructing forest belt + sand-binding forest belt, sand-obstructing forest belt + sand-binding forest belt, and reed sand-obstructing fence + sand-binding forest belt [50]. To ensure the long-term safe operations of the Tarim Highway, the ecological project of shelter forests along the Tarim Desert Highway was initiated in 2003, and was concluded in 2005. The shelterbelt covers an area of 3128 hm^2, with 436 km in length and 72–78 m in width [51]. The shelterbelt has three layout patterns, including the four-belt pattern in the inter-dunes and small dunes, the two-belt pattern in the high-complex sand dunes or ridges, and the three-belt pattern in the transition areas between the high-complex sand ridges and the inter-dunes. The plant species in the area are *Callignonum*, *Tamarix* and *Haloxylon ammodendron*, which were intercropped with a distance of about 2 m and a row spacing of about 1 m. Since the completion of this project, groundwater has been used for drip irrigation in the Tarim Desert Highway shelterbelt. The water consumption of 1.8×10^7 individual shelterbelt plants promotes the important concept of shared water resources. The Tarim Desert Highway shelterbelt has become a 436-

km-long green corridor, which plays an important role in road protection from wind and sand coverage. However, with the decline in the sand-proof effect and the subsequent rapid development of wind damage, the soil moisture of shelterbelts and the capacity of irrigation water have become the focus resent research [52,53]. Zhou et al. [54] investigated the contents of salt and water in soil, and concluded that salt does not aggregate in soils, and that the trends in water and salt contents are attributed to climate, soil texture, and irrigation. Huang et al. [55] conducted a field experiment to study water and salt movement in soil after the basin was irrigated by saline groundwater in the center of the Taklimakan Desert. Soil water potential, soil water content and EC values of soil solutions at different depths along the soil profile were obtained within different periods after irrigation suspension. Xu et al. [56] conducted useful investigations on the choice of irrigation technology for the shelterbelts, and implementation and application of the irrigation system. Wang et al. [57] analyzed the variation of soil moisture, as well as its regularity over the irrigation cycle, along the shelterbelts at different sites and planting years. This author also discussed the dynamics for soil moisture variations. Results showed that there is an apparent temporal variation of soil moisture within a typical irrigation period in shelterbelts, and soil water storage varies linearly with number of days after irrigation. Xu et al. [58] studied stem sap flow, water status and water consumption of shelterbelt plants with a stem sap flow gauge, and discussed the problem of shelterbelt water saving in terms of the present irrigation pattern. On the basis of the groundwater level and hydrologic data, Fan et al. [52] analyzed temporal and spatial fluctuations of groundwater levels in combination with measurements of groundwater/surface water inter-conversion theory and groundwater dynamics. In addition, Lei et al. [59] reported a comprehensive study on the eco-environmental effects of the shelter forest along the Tarim Desert Highway, including the effects on aeolian environment, soil, micro-climate, biodiversity, and groundwater. In their opinion, the sand disaster-prone environment along the Tarim Desert Highway can be classified into four grades based on fuzzy mathematics. This approach is expected to provide significant insights into the prevention and control of damage induced by windblown sand, a better understanding of spatial variation in aeolian environments, and the formation of windblown sand disaster [60]. Wang et al. [61], Xu et al. [62], Wang et al. [63] and Huang et al. [64] evaluated the ecological benefits of the Tarim Desert Highway from the sand-proof system and the sand-resistance characteristics of sand breaks. These authors also investigated plant roots, the physico-chemical characteristics of soil, water and salt movement, and groundwater changes in the Tarim Desert Highway shelterbelt irrigated by saline water. Zhou et al. [65] studied the relationship between the shelterbelts and their environment. More importantly, a decision analysis was introduced into the research on the stability of the Tarim Desert Highway shelterbelt. On this basis, the analysis was able to select barrier factors affecting the shelter system stability to set up a comprehensive index system, and to apply the ecological stability concept related to ecosystem management. The research showed that, currently, the Tarim Desert Highway shelterbelt system is in a relatively fragile state and that climate is a major influencing factor. However, we can improve the environmental quality of the desert highway system and increase stability through artificial measures. Soil quality changes, soil microbial distributions, and the relationship between soil enzymes and soil organic matter were studied by Jin et al. [66] and Zhou et al. [67]. Zhao and Zhou [68], Dong et al. [69], Liu et al. [70], Wang et al. [71] and Lei et al. [59,60] probed into the features of sand materials and environmental implications, sand disaster, the formation and evolution of the wind-sand environment, disaster differentiation patterns and the formation mechanism of disasters. Based on temperature and humidity measurements of the shelterbelt micro-climate on both horizontal and vertical scales, and in order to investigate its ecological function, Wang et al. [72] expounded on the micro-climate effect of temperature and humidity on shelterbelts systems of the desert highway.

3 Perspective and proposal

As part of the process of the ecological rehabilitation of the Tarim Basin, the lower reaches of the Tarim River have been investigated since the 1970s when the area first began to dry up. However, a seasonal cutoff occurs in the middle reaches, with a decrease of available water. The phenomenon has become more serious in recent years, and the problem will pose a serious threat to the natural euphrates poplar forests widely distributed in the middle reaches. Thus, it is important that future studies are focused not only on ecological restoration and reconstruction of the lower reaches, but also on the ecological protection of the middle reaches.

With regard to the water shortage in the basin, it appears that there are two major reasons for this problem: (1) along with the gradual increase of irrigated areas in the headstreams and the upper reaches, a large amount of water has been consumed in the runoff utilization areas, leading to decreasing flow into the mainstream, and (2) water resources are used irrationally. Thus, the key to solve ecological problems in the Tarim Basin involves harmonizing the water distribution among the headstream, mainstream and different sections of the Tarim River. This process will require establishment of a water-efficient economic model.

Numerous studies have been conducted on the distribution of desert riparian forest, habitat and ecology, species composition and groundwater. Such studies provide a scientific basis and technical guidance for the restoration and reconstruction of natural forest vegetation. However, studies on the vegetation restoration of the Tarim River "Green

Corridor" are mainly focused on the responses of plants to groundwater level, and are lacking on zoology and soil microbiology. It is well known that a complete ecosystem consists of plants, animals and microorganisms, and that relationships and interactions among the three components must be taken into account for the recovery of vegetation in the Tarim Basin.

Current studies have shown that, although the ecological water conveyance project has to some extent alleviated environmental deterioration, it cannot change the general degradation trends seen in the area. Further research should be conducted on monitoring and testing the work of previous studies. On the basis of the initial achievement of the water conveyance, we should establish a special monitoring system for the entire Tarim Basin. This system will require the use of 3S technology, and should be focused on water resource utilization and water environment monitoring to achieve appropriate levels of water allocation and eco-environment protection.

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