Postprint: Study on Characteristics of Vegetation Changes at Different Successional Stages in the Xishawo Sandy Area, Minqin

Authors: Man Duoqing, Delu Li, Liu Mingcheng, Dekui Zhang, Tang Jinnian, Chen Fang, Fu Guiquan, Yang Xuemei, Ding Feng

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Abstract

Based on 60 years of observational research on ecological vegetation in the Minqin Xishawo sandy area, vegetation succession has primarily experienced four stages during the continuous decline of groundwater level: the degraded meadow and Tamarix community stage; the Tamarix community and Nitraria community stage; the Nitraria community and degraded Tamarix community stage; and the Nitraria community stage. This process is characterized by continuously decreasing plant diversity, significantly declining vegetation coverage, severe ecological degradation, and rapid desertification development. As rain-fed areas continue to expand, in years with higher precipitation, psammophytic and xerophytic herbaceous plants increase, resulting in increased species diversity and vegetation coverage, whereas in years with lower precipitation, the opposite occurs. Psammophytic and xerophytic shrub vegetation is relatively stable: annual precipitation exceeding 140 mm promotes the growth and development of shrub populations, 100–140 mm maintains growth, and below 100 mm leads to degradation. Most tree species used in artificial sand-fixation afforestation have degraded and died; Haloxylon ammodendron, as an exotic species with strong ecological adaptability, has developed into the largest artificial sand-fixation forest in the Minqin sandy area. High afforestation density and drought are the main causes of Haloxylon ammodendron forest degradation; according to vegetation carrying capacity, sustainability is enhanced after low-density afforestation. In recent years, with integrated watershed management and coordinated water allocation, the supply of ecological water in Minqin has increased, groundwater level has risen in some local areas, forming micro-wetlands, and past meadow vegetation has reappeared, with ecology developing positively; however, groundwater level decline is also slowing in most sandy areas, and desertification is still developing.

Full Text

Vegetation Change Characteristics of Different Succession Stages in the Xishawo Desert Area of Minqin

MAN Duoqing[1], LI Delu[1], LIU Mingcheng[2], ZHANG Dekui[1], TANG Jinnian[1], CHEN Fang[1], FU Guiquan[1], YANG Xuemei[1], DING Feng[1]

[1]Gansu Desert Control Research Institute, Minqin National Station for Desert Steppe Ecosystem Studies, Gansu Desert Plant Engineering Research Center, Lanzhou 730070, Gansu, China

[2]Gansu Endangered Animal Protection Center of National Forestry and Grassland Administration, Wuwei 733000, Gansu, China

Abstract

Through long-term ecological vegetation observation and research in the Xishawo desert area of Minqin over the past 60 years, we found that vegetation succession has undergone four main stages as groundwater levels have continuously declined: (1) degraded meadow steppe and *Tamarix* communities; (2) *Tamarix* and *Nitraria* communities; (3) *Nitraria* and degraded *Tamarix* communities; and (4) *Nitraria* communities. This process has been characterized by continuously decreasing plant diversity, significantly declining vegetation coverage, severe ecological degradation, and rapid desertification development. As rain-fed areas have expanded, xerophytic and psammophytic herbaceous plants proliferate in years with higher precipitation, leading to increased species diversity and vegetation coverage, while the opposite occurs in low-precipitation years. Desert-adapted shrubs remain relatively stable, with annual precipitation exceeding 140 mm promoting their growth and development, 100–140 mm maintaining basic growth, and below 100 mm causing gradual degradation. Most artificial sand-fixation tree species have degraded and died; *Haloxylon ammodendron*, as an introduced species with strong ecological adaptability, has developed into the largest artificial sand-fixation forest in Minqin. High planting density and drought are the main causes of its degradation, and sustainability can be enhanced through low-density afforestation according to vegetation carrying capacity. In recent years, integrated watershed management and coordinated water allocation have increased ecological water supply to Minqin, causing groundwater levels to rise in some local areas and forming micro-wetlands where past meadow vegetation has reappeared, showing positive ecological development. However, groundwater decline continues in most sandy areas, and desertification is still developing.

Keywords: Minqin; Xishawo desert area; vegetation; succession; change characteristics

1. Study Area Overview

Minqin County, located in the middle and lower reaches of the Shiyang River Basin, has undergone dramatic ecological transformation. Historically dominated by rivers, lakes, marshes, and meadow steppes, the region has become highly desertified, with only remnant oases remaining. The ecological environment has changed significantly, with most vegetation shifting from aquatic, marsh, meadow, and mesophytic types to psammophytic, xerophytic, and hyper-xerophytic plants, resulting in substantially reduced biodiversity [1-2,7-11]. While multiple factors have driven vegetation evolution and desertification, climate change since the Quaternary, particularly the uplift of the Tibetan Plateau, has been the primary cause. Although historical periods have experienced alternating wet and dry phases, the overall trend has been toward increasing aridification [1-4,7-8]. Since the 1950s, population growth and continuous oasis expansion have increased water consumption, dramatically reducing water flow to the middle and lower reaches. Rivers, lakes, and wetlands have successively shrunk and dried up, groundwater levels have continuously declined, drought has intensified, vegetation coverage has decreased, and desertification has accelerated. Minqin has become one of China' s most typical examples of desertification development in inland river basins [1-2,7-11].

Previous research on the Shiyang River Basin' s middle and lower reaches has extensively investigated hydrological and ecological environmental changes, vegetation dynamics, and desertification processes [1-20]. Studies have examined correlations between regional vegetation degradation and desertification, relationships between groundwater decline and degradation of major herb and shrub species, thresholds for these processes, relationships between desert plant population reproduction, development, and decline with soil moisture, relationships between shrub dune degradation and soil moisture and their environmental significance, the "fertile island" effect of shrub dunes such as *Tamarix* and *Nitraria*, and changes in habitat factors for desert plant populations and communities [2-4,6-10,11-20]. However, research on vegetation change characteristics across different succession stages in Minqin' s desert areas over the past 60 years remains limited [1-20]. This study investigates ecological vegetation change characteristics across different succession stages in the hydrological-ecological process of Minqin' s Xishawo desert area to reveal vegetation succession patterns in typical desert regions of the Shiyang River Basin' s middle and lower reaches and further understand vegetation succession trends under similar habitat conditions in inland river basins.

The Xishawo desert area is located west of the modern Minqin oasis, representing a naturally evolved desertification zone following the sandification of Han and Tang dynasty ancient oases and their gradual eastward shift. The area extends from Shajingzi in the southwestern part of Minqin, through Liancheng and Gucheng in the central region, to the Qingtu Lake area in the northeast [Figure 1: see original paper]. Elevation ranges from 1290 m to 1400 m. The climate is characterized by scarce precipitation and dry conditions, with annual precipitation of approximately 110 mm concentrated in summer and autumn, mean annual temperature of 7.6°C, mean annual evaporation of 2643.9 mm, mean annual relative humidity of 45%, mean annual wind speed of 4.5 $m \cdot s^{-1}$, sand-driving wind speed of 2.4 $m \cdot s^{-1}$, mean annual gale days of 26.3 d, and dominant NW winds. Soils consist primarily of aeolian sandy soil, gray-brown desert soil, brown desert soil, oasis irrigation silt soil, desertified saline soil, and desertified gleyed saline soil. Natural vegetation is sparse, dominated by xerophytic desert plants including *Nitraria tangutorum*, *Tamarix ramosissima*, *Nitraria sphaerocarpa*, *Calligonum mongolicum*, *Kalidium foliatum*, *Artemisia sphaerocephala*, *Reaumuria soongorica*, *Oxytropis aciphylla*, *Caragana korshinskii*, *Haloxylon ammodendron*, *Lycium ruthenicum*, *Alhagi maurorum*, *Agriophyllum pungens*, *Halogeton glomeratus*, *Bassia dasyphylla*, *Peganum nigellastrum*, *Salsola ruthenica*, *Corispermum mongolicum*, *Suaeda glauca*, *Echinops gmelini*, *Salsola collina*, *Limonium aureum*, *Zygophyllum fabago*, *Stipa glareosa*, *Phragmites communis*, *Leymus secalinus*, *Achnatherum splendens*, *Typha orientalis*, *Polygonum sibiricum*, *Glycyrrhiza uralensis*, *Poacynum hendersonii*, and *Peganum harmala*. Over the past 60 years, hydrological and ecological changes have driven continuous vegetation succession and coverage decline, with intensifying desertification.

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2. Research Methods

2.1 Study Area Selection Representative study sites were selected across different stages of desert vegetation succession in the Xishawo desert area: Shajingzi in the southwestern part (representing early succession stage), Liancheng and Gucheng in the central region (middle succession stage), and Qingtu Lake in the northeastern part (late succession stage) [Figure 1: see original paper].

2.2 Long-term Monitoring of Desert Vegetation Changes The Minqin Desert Control Comprehensive Experimental Station, located in the Shajingzi desert area, has conducted long-term ecological positioning monitoring and periodic investigations of desert ecological changes since its establishment in 1959, maintaining detailed records. Within the Shajingzi desert area, long-term positioning observations of representative plant communities have documented plant species, quantities, heights, crown widths, coverage, and other growth indicators. Multiple fixed observation wells monitor groundwater level changes, and the station' s standard meteorological station has recorded meteorological data since 1959. These records, combined with relevant literature, were used to conduct comparative analyses of ecological environment and vegetation changes in the Xishawo desert area over the past 60 years to understand vegetation succession processes.

2.3 Current Vegetation Community Investigation Current vegetation changes were assessed by measuring plant growth and development indicators within sample plots of representative plant communities across various study areas in the Minqin Xishawo desert region.

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3. Results and Analysis

3.1 Vegetation Succession Stage Division Over the past 60 years, as Minqin's modern oasis has continuously expanded and shifted eastward, agricultural water consumption has increased substantially, causing rivers and lakes in the Xishawo area to dry up and disappear, groundwater levels to decline continuously, and desertification to develop. Particularly since the 1970s, more than 6000 mechanized wells have extracted groundwater for irrigation in the Minqin oasis, causing the basin' s groundwater level to drop from 1-3 m to 10-30 m. Desert vegetation has gradually degraded, numerous species have disappeared, and succession has progressed from degraded meadow vegetation to extremely arid desert vegetation, with continuously declining vegetation coverage and severely developing desertification [6-7,9].

3.1.1 Vegetation Changes in Shajingzi Desert Area During Groundwater Decline In the 1950s–1960s, the groundwater level in Shajingzi desert area was 1-3 m, with extensive *Phragmites communis*, *Calamagrostis epigeios*, *Leymus secalinus*, *Achnatherum splendens*, *Poacynum hendersonii*, *Glycyrrhiza uralensis*, *Iris lactea*, *Cirsium setosum*, *Tamarix ramosissima*, and *Kalidium foliatum* meadow plants in inter-dune lowlands; *Tamarix* and *Nitraria* shrubs covering dunes; and *Agriophyllum pungens*, *Salsola collina*, *Limonium aureum*, and *Bassia dasyphylla* growing on sand-covered land. As groundwater levels declined and drought intensified, meadow vegetation fluctuated with precipitation and gradually degraded. Most shrub species survived by accessing groundwater, while shallow-rooted small shrubs such as *Kalidium foliatum*, *Alhagi maurorum*, *Oxytropis aciphylla*, *Artemisia sphaerocephala*, and *Lycium ruthenicum* have now degraded. *Tamarix* communities showed expansion trends in early stages, while *Artemisia sphaerocephala*, *Calligonum mongolicum*, and *Zygophyllum fabago* exhibited fluctuating growth with precipitation. From the 1970s–1980s to the present, vegetation types have remained similar, but *Nitraria* populations have become the largest in the desert area, with increasing activation of *Nitraria* dunes. Local expansion of *Nitraria sphaerocarpa*, *Ephedra przewalskii*, *Reaumuria soongorica*, and *Zygophyllum fabago* populations has also occurred (Table 1). Additionally, small communities of *Artemisia sphaerocephala*, *Calligonum mongolicum*, *Zygophyllum fabago*, *Limonium aureum*, *Phragmites communis*, *Stipa glareosa*, and *Allium mongolicum* are distributed across all stages, along with 1–2 year psammophytic and xerophytic rain-fed herbaceous plants whose growth and development fluctuate with precipitation [TABLE:1, TABLE:2].

3.1.2 Vegetation Changes in Liancheng and Gucheng Desert Areas During Groundwater Decline The habitats and vegetation succession in Liancheng, Gucheng, and Shajingzi areas have been similar over the past 60 years, though groundwater decline in Liancheng and Gucheng has lagged slightly behind. The different succession stages have also been similar (Table 1). The area has mainly experienced: (1) Degraded meadow steppe and *Tamarix* shrub communities, with herbaceous plants dominant and numerous *Tamarix* shrubs and dunes distributed within; (2) *Kalidium foliatum* community stage, where *Kalidium foliatum* populations expanded rapidly, gradually replacing *Tamarix* populations, with *Tamarix* and *Nitraria* shrub dunes distributed alternately and vegetation coverage declining [6-7,9,12-15]; (3) *Nitraria* community stage, where by the 1990s–2000s, groundwater levels had dropped to 3–5 m, most shrub populations had degraded, and *Tamarix* had largely disappeared from the desert area, existing only in high groundwater areas such as oasis edges and river/lake shores, with *Nitraria* dunes widespread and *Nitraria sphaerocarpa* dunes interspersed, though later some *Nitraria* showed obvious degradation symptoms; and (4) *Nitraria* and degraded *Tamarix* community stage, followed by *Nitraria* and *Reaumuria* community stage, forming aeolian landforms dominated by *Nitraria* shrub dunes, with *Tamarix* communities existing only at oasis edges and high groundwater areas [TABLE:1, TABLE:3].

3.1.3 Vegetation Changes in Qingtu Lake Area During Groundwater Fluctuation During the Han dynasty, Qingtu Lake had a water area of 4000 km^2, which reduced to 1300 km^2 by the Ming and Qing dynasties and 400 km^2 in the early liberation period, before completely drying up in 1959. With the disappearance of water bodies and wetlands and continuous groundwater decline, vegetation severely degraded, and the Badain Jaran and Tengger deserts converged on Qingtu Lake, creating Minqin' s largest wind-sand passage with severe desertification [1-2,7]. In the 1950s–1970s, the area still had some water bodies with groundwater at 0–3 m, dominated by *Phragmites* and gramineous meadow vegetation with numerous *Tamarix* shrub dunes, and *Kalidium foliatum* in saline areas. As water bodies disappeared and surface drought intensified, meadow vegetation gradually degraded, becoming dwarfed and sparse, with thinning herb layers, sandification in some areas, and invasion by psammophytic, xerophytic, and halophytic herbs and shrubs, leading to development of *Tamarix* and *Nitraria* shrub dunes. By the 1980s–1990s, groundwater levels had dropped to 4–7 m or deeper, surface desertification was widespread, most meadow vegetation had disappeared, and the area was dominated by *Tamarix* and *Nitraria* shrub dunes with psammophytic and halophytic plants, leaving only drought-tolerant *Phragmites* and *Leymus* sparsely distributed. Since 2010, artificial ecological water replenishment has created a 25.16 km^2 water area with groundwater at 0–3 m, forming dense *Phragmites* populations, increasing meadow plant species, gradually restoring plant diversity, and causing psammophytic plants to retreat, with *Tamarix* shrub and *Kalidium* communities at wetland edges showing complete reversal of desertification and positive ecological development .

3.2 Precipitation Effects on Vegetation Changes

3.2.1 Intra-Annual Precipitation Effects on Seasonal Vegetation Changes Sample plot observations show that in Minqin Xishawo desert area, vegetation begins greening in late March when soil thaws and moisture rises. Annual and perennial herbs germinate explosively, with new shoots reaching 3–9 cm by late April. In May, soil moisture is good and temperatures suitable, allowing rapid vegetation growth and significantly increased coverage. However, as temperatures rise rapidly and precipitation becomes scarce during the dry season (Figure 2), drought intensifies, evapotranspiration increases, and soil moisture declines. From mid-to-late June through July, many annual herbs die from drought, perennial herbs and shrubs show reduced growth, some shoots wither, and vegetation coverage declines. July-September is the rainy season with significantly increased precipitation and suitable temperatures, causing annual herbs to germinate explosively again, grow rapidly, and increase biomass, while perennial herbs and shrubs continue growing relatively stably, with vegetation coverage continuously increasing until reaching maximum species diversity and coverage by late September. Afterward, temperatures drop, vegetation withers and sheds leaves, and coverage declines to its minimum in winter. Annual herbs are seasonal vegetation that fluctuates with precipitation amounts—in high-rainfall years, herbaceous species diversity, quantity, and biomass increase significantly, raising desert vegetation coverage, while low-rainfall years show the opposite pattern. Shrubs and perennial herbs also fluctuate with precipitation but remain relatively stable in desert areas [Figure 2: see original paper].

3.2.2 Interannual Precipitation Fluctuation Effects on Desert Vegetation Changes Located in the middle and lower reaches of the Shiyang River Basin, Minqin has a typical arid continental climate with scarce precipitation. Historically, ecological vegetation relied primarily on surface water and groundwater. Since the 1970s, surface water disappearance and groundwater decline have caused meadow vegetation to degrade and disappear, replaced by xerophytic plants. By the 1990s, most xerophytic shrubs had degraded, with previously widespread meadow shrubs such as *Tamarix*, *Kalidium foliatum*, and *Lycium ruthenicum* having largely degraded and disappeared [6-7,9,15]. These species cannot survive on natural precipitation alone without groundwater access, while some shrub populations have gradually developed adaptation mechanisms to arid environments. Investigation reveals that *Artemisia sphaerocephala*, *Calligonum mongolicum*, *Zygophyllum fabago*, *Nitraria tangutorum*, *Reaumuria soongorica*, and *Ephedra* species previously relied on groundwater but have sequentially degraded with falling water tables. However, they also show recovery growth in good precipitation years and subsequent years, with several consecutive good precipitation years promoting population expansion, while poor precipitation years reduce biomass and several consecutive low-precipitation years cause obvious degradation or even death. As rain-fed ecological areas expand, desert plant population dynamics fluctuate with annual precipitation amounts. Annual precipitation exceeding 140 mm promotes population growth and development, with better growth in higher precipitation years; 100–140 mm maintains normal to general growth; and below 100 mm shows degradation trends. In recent years, increasing precipitation trends in northwest China will effectively promote rain-fed shrub vegetation growth (Table 5, Figure 3, Figure 4) [TABLE:5, FIGURE:3, FIGURE:4].

3.3 Characteristics of Artificial Sand-Fixation Afforestation Vegetation Since the mid-1960s, aerial seeding of *Artemisia sphaerocephala*, *Nitraria tangutorum*, *Iris lactea*, and *Sophora alopecuroides* in the Shajingzi desert area helped restore vegetation and stabilize shifting sand. Subsequent large-scale afforestation with *Haloxylon ammodendron*, *Elaeagnus angustifolia*, *Hedysarum scoparium*, *Tamarix ramosissima*, *Calligonum mongolicum*, and *Caragana korshinskii* effectively stabilized moving dunes and protected the oasis [3,6-7,9]. However, as vegetation coverage increased, water demand rose, groundwater levels declined, and soil water balance was disrupted. By the 1990s, large areas of artificial *Elaeagnus angustifolia* (44,000 hm^2 died), *Haloxylon ammodendron* (35,000 hm^2 died), *Artemisia sphaerocephala*, and *Tamarix* forests had degraded, with shifting sand reappearing. The most extensively planted species was *Haloxylon ammodendron*, with planting densities of 1 m $\times$ 1 m to 2 m $\times$ 4 m. Early growth was good, but middle-to-late stage degradation was severe, with greater density causing more severe degradation and self-thinning [6-7,9,12-15]. Long-term water balance research shows that the carrying density of artificial *Haloxylon ammodendron* under rain-fed conditions in Minqin is 450–500 plants $\cdot$ hm^{-2}, similar to natural *Haloxylon* forests in the Gurbantunggut Desert. Recent low-density afforestation at 2 m $\times$ 2–3 m spacing with row spacing of 3–5 m approaches natural carrying capacity, enhancing stability and sustainability. Due to its strong adaptability, low seedling and afforestation costs, mature technology, and easy operation, *Haloxylon ammodendron* windbreak forests have become Minqin’ s largest artificial forest population. High planting density and drought are the main causes of degradation, but natural regeneration occurs after self-thinning in some areas, significantly influencing the growth and succession of natural vegetation.

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4. Discussion and Conclusion

Minqin is a typical desertification development area in China’ s inland river basins, and the Xishawo desert area represents a historical microcosm of Minqin’ s desertification. Over the past 60 years, excessive water resource development and utilization have caused significant environmental changes. With surface water disappearance and groundwater decline, desert vegetation succession has experienced four main stages: groundwater depth 1–3 m (dominated by degraded meadow and *Tamarix* communities), 3–5 m (*Tamarix* and *Nitraria* communities), 5-7 m (*Nitraria* and degraded *Tamarix* communities), and >7 m (*Nitraria* communities). Vegetation has shifted from aquatic, marsh, meadow, and mesophytic types to psammophytic, xerophytic, and hyper-xerophytic types, with massive species loss, significantly reduced biodiversity, continuously declining vegetation coverage, strengthening rain-fed characteristics, and forming a process of severe ecological degradation and rapid desertification development [6-7,12-15,17,20,23].

As soil drought deepens and rain-fed areas expand, precipitation has the greatest impact on xerophytic and psammophytic herbaceous plants. In high-precipitation years, these herbs grow explosively, increasing species diversity, biomass, and vegetation coverage, while low-precipitation years show the opposite pattern. Desert-adapted shrubs remain relatively stable, with annual precipitation >140 mm promoting growth, 100–140 mm maintaining normal growth, and <100 mm causing degradation. Most artificial sand-fixation tree species have degraded under drought conditions. *Haloxylon ammodendron*, with strong ecological adaptability as an introduced species, has developed into Minqin’ s largest artificial sand-fixation forest. High planting density and drought are the main causes of degradation, but sustainability increases with low-density afforestation according to vegetation carrying capacity, enabling natural regeneration and development.

In recent years, increased ecological water allocation to Minqin, well management, and farmland reduction measures have caused groundwater levels to rise in some local areas, forming micro-wetlands centered on water bodies that reproduce past meadow steppe ecological landscapes, playing a positive role in curbing desertification and ecological restoration. However, groundwater decline has only slowed in most desert areas and even shows rising trends, though impacts on ecological restoration remain limited in the near term, desertification continues to develop, and desert ecological recovery will be a relatively slow process.

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Note: Figure translations are in progress. See original paper for figures.