Boundary and Change Analysis of the Northwestern Arid Desert Region: Postprint

Authors: Zulkar Helil, Zhao Tingning

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Abstract

Daily surface meteorological elements and monthly precipitation data from two periods (1980–1995 and 2010–2019) for Qinghai Province, Gansu Province, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region, Inner Mongolia Autonomous Region, and Tibet Autonomous Region were selected to determine the theoretical extent of the arid desert region in Northwest China. Based on the monthly precipitation in this region, the multi-year average precipitation was estimated, potential evapotranspiration was calculated using the Penman-Monteith formula, and the spatial distribution of the humidity index was obtained. Finally, overlay analysis of the multi-year average precipitation and humidity index was conducted to identify the boundaries of the arid desert region in Northwest China. The results indicate that the delineated extent of the arid desert region in Northwest China extends from the Kunlun Mountains in the south to the Altai Mountains in the north and to the Helan Mountains in the west, excluding parts of the northern foothills of the Tianshan Mountains, the Urumqi oasis, the Ili River Valley, and Tacheng. Through comparison of data from the two time periods in the study area, it was clarified that the change in the extent of the arid desert region in Northwest China was caused by a significant reduction in areas with low precipitation and potential evapotranspiration and a significant increase in areas with high humidity index, revealing a notable northward shift of the arid region boundary and a significant expansion of the semi-arid region area. By integrating the zoning results with mountain systems, the extent of the arid desert region in Northwest China was delineated down to the county/district level, providing data support for resource exploitation and utilization as well as site-specific ecological restoration in the region.

Full Text

Boundary Scope and Change Analysis of Arid Desert Area in Northwest China

Zulkar HAILILI, ZHAO Tingning, JIANG Qun' ou

College of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China

Abstract

Starting from the qualitative description of northwest arid desert areas, this study establishes a quantitative and precise boundary based on daily surface meteorological elements and monthly precipitation data from Qinghai Province, Gansu Province, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region, Inner Mongolia Autonomous Region, and Tibet Autonomous Region for the periods 1980–1995 and 2010–2019. The theoretical extent of the northwest arid desert area was determined, multi-year average precipitation was estimated based on regional monthly precipitation, and potential evapotranspiration was calculated using the Penman-Monteith formula to obtain the spatial distribution of the moisture index. Finally, through overlay analysis of multi-year average precipitation and moisture index, the boundary of the northwest arid desert area was identified. The results show that the northwest arid desert area extends from the Kunlun Mountains in the south to the Altai Mountains in the north and to the Helan Mountains in the west, excluding the northern foothills of the Tianshan Mountains, the Urumqi Oasis, the Ili River Valley, and parts of the Tacheng region. Comparison of data from the two study periods reveals that changes in the northwest arid desert area' s extent are primarily caused by significant reductions in regions with low precipitation and potential evapotranspiration, coupled with notable increases in areas with high moisture index. The arid zone boundary has clearly shifted northward, while the semi-arid zone area has expanded substantially. The zoning results, integrated with mountain systems, delineate the northwest arid desert area down to the county level, providing data support for resource exploitation and ecological restoration tailored to local conditions in the region.

Key words: Penman-Monteith formula; boundary identification; change analysis; northwest arid desert region

Regionalization is a method for expressing the regional distribution patterns of geographical phenomena and characteristics. Its primary function is to enable clearer identification of research objects, allowing regions with similar geographical features to be organically integrated under the guidance of zoning maps. This approach serves as the foundation for rational utilization of natural resources, ecological restoration adapted to local conditions, and formulation of various planning schemes. Classical regionalization methods mainly include "top-down" and "bottom-up" approaches. With scientific and technological development, key technical methods have evolved to include overlay methods, cluster analysis, and geographic information systems (GIS).

The northwest arid desert area is located deep in the inland northwest of China. Its macro-geomorphological pattern features large basins surrounded by high mountains, with alternating distribution of mountains and plains. Characterized by vast area, aridity and water scarcity, intense wind erosion, and extensive desert distribution, conservation, restoration, and sustainable management of this region must be based on its unique environmental characteristics, distinguishing it from other regions in China. Since the Industrial Revolution, global climate warming has affected atmospheric circulation processes, leading to significant variations in meteorological conditions in northwest China and consequent changes in the boundaries of the arid desert area. However, current research on the precise delimitation of the northwest arid desert area' s boundaries remains limited, hindering overall regulation of ecological restoration efforts in the region.

Previous studies generally define the northwest arid desert area as regions with annual precipitation $P < 200$ mm and aridity index $K > 16$, including the Junggar Basin, Tarim Basin, East Xinjiang Basin, Hexi Corridor in Gansu, Qaidam Basin in Qinghai, and the Alxa Plateau in western Inner Mongolia. Wu Lei et al. noted that the northwest arid desert area encompasses the vast region of the Hexi Corridor, Xinjiang, and western Inner Mongolia. Other research has identified the Helan Mountains as the boundary with significant precipitation differences between east and west. These studies primarily relied on qualitative descriptions to determine the northwest arid desert area' s extent, with some including all of Xinjiang and others using terrain to define boundaries without considering climate-induced azonal factors. While these approaches may not affect their specific research objectives, they create inconveniences for regional refinement and targeted ecological restoration in the northwest arid desert area.

To address this gap, the present study selected Qinghai Province, Gansu Province, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region, and Inner Mongolia Autonomous Region as the study area. Monthly precipitation, daily average atmospheric pressure, relative humidity, sunshine duration, temperature, and wind speed data were collected and analyzed through overlay analysis of precipitation and moisture index spatial distributions to quantitatively determine the boundary scope of the northwest arid desert area. This provides data support for regional refinement, resource exploitation, and ecological restoration tailored to local conditions, holding significant importance for economic development and scientific research in northwest China.

1.1 Data Sources and Processing

This study utilized meteorological data from 1980–1995 and 2010–2019, including monthly precipitation, daily average atmospheric pressure, relative humidity, sunshine duration, temperature, wind speed, and station altitude from meteorological stations in Qinghai Province, Gansu Province, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region, Inner Mongolia Autonomous Region, and Tibet Autonomous Region [Figure 1: see original paper]. To prevent interpolation errors from adjacent regions, meteorological stations in the Tibet Autonomous Region were included as supplementary data for spatial interpolation. Monthly precipitation data for both periods were processed using Excel to calculate multi-year average precipitation. Meteorological data were obtained from the China Meteorological Data Network (http://data.cma.cn/), and DEM data with 30 m resolution were acquired from the Geospatial Data Cloud (http://www.gscloud.cn/). Mountain ridge lines were extracted from the DEM to form the boundary framework for Qinghai, Gansu, Ningxia, Xinjiang, and Inner Mongolia.

1.2.1 Potential Evapotranspiration and Moisture Index

The United Nations Convention to Combat Desertification provides a global definition of desertification, identifying arid regions as continental areas where the ratio of annual precipitation to potential evapotranspiration is less than 0.05. Numerous methods exist for calculating potential evapotranspiration, including the Penman-Monteith, Thornthwaite, and Hargreaves formulas. The Penman-Monteith equation, recommended by the Food and Agriculture Organization of the United Nations in 1998, has been widely applied in China and demonstrated to be more suitable for Chinese conditions than other methods.

Given the limitations of earlier aridity calculation methods and the vast extent of the study area, a more rigorous approach was adopted by calculating potential evapotranspiration to determine the aridity index K, expressed as the moisture index $I = P/ET_0$, where ET_0 represents potential evapotranspiration calculated using the Penman-Monteith formula and P is precipitation. The specific calculation method is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_0 is the corrected potential evapotranspiration ($\mathrm{mm \cdot d^{-1}}$), R_n is net radiation at the surface ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), G is soil heat flux ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), T is mean daily temperature (°C) ($G \approx 0$ when calculating daily potential evapotranspiration), u_2 is wind speed at 2 m height ($\mathrm{m \cdot s^{-1}}$), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ is the slope of the vapor pressure curve ($\mathrm{kPa \cdot {}^{\circ}C^{-1}}$), and γ is the psychrometric constant ($\mathrm{kPa \cdot {}^{\circ}C^{-1}}$).

Climate classification criteria based on aridity index K and moisture index I are presented in .

1.2.2 Spatial Overlay Method

The spatial overlay method reduces arbitrariness and subjectivity while facilitating characterization of relationships and attributes among natural phenomena. This approach uses coincident boundaries or average positions as new zoning boundaries. In this study, annual precipitation $P < 200$ mm and moisture index $I < 0.2$ were established as the criteria for delineating the northwest arid desert area. Two spatial distributions were overlaid as thematic layers, and through overlay analysis, the qualitative scope of the northwest arid desert area was obtained.

2.1.1 Precipitation Changes

Considering the positive correlation between precipitation and altitude, and to prevent data anomalies, station altitude was used as a secondary dataset with the cokriging method for interpolation. Since precipitation in China decreases from southeast to northwest, a first-order trend removal was applied to the precipitation dataset to eliminate trend effects. The resulting spatial distribution of multi-year average precipitation shows that areas with precipitation $P < 200$ mm cover approximately 254.09 mm across the study area, exhibiting an increasing trend from northwest to southeast [Figure 2: see original paper]. Maximum annual precipitation occurs in Jiuzhi County, southern Qinghai, reaching approximately 700 mm, while minimum precipitation appears in Toksun County and Kashgar region, Xinjiang, at about 50 mm. The multi-year average precipitation for 2010–2019 increased by approximately 50 mm compared to 1980–1995, with the $P < 200$ mm boundary showing little change but the arid region precipitation boundary shifting northward, indicating gradual precipitation growth over time, particularly since the 1990s when precipitation anomalies were predominantly positive. This trend aligns with recent studies on precipitation spatiotemporal changes in Xinjiang, though the Helan Mountain rainfall boundary shows no significant change, with both eastern and western sides experiencing increased precipitation. This location serves as both the boundary between desert and desert grassland zones and between arid and semi-arid regions, representing China' s east-west climatic divide and the 200 mm precipitation isopleth. Precipitation in Qinghai and its western region slightly decreased, consistent with research on the Tibetan Plateau. Notable azonal characteristics emerged in the Ili River Valley, Urumqi Oasis, and other areas where precipitation exceeds 200 mm.

2.1.2 Potential Evapotranspiration Changes

The spatial distribution of multi-year average potential evapotranspiration was generated through data processing [Figure 3: see original paper]. The study area' s multi-year average potential evapotranspiration is approximately 1198.84 mm, showing an increasing trend from northwest to southeast. Low-value regions (600–800 mm) occur in the northeastern areas and southern Qinghai and Gansu, while high-value zones (1200–1500 mm) appear in western Inner Mongolia, the border region of Xinjiang, Gansu, and Qinghai, and southwestern Xinjiang. Maximum average potential evapotranspiration occurs in Subei County, Gansu, and Yiwu County, Xinjiang, exceeding 1500 mm, while minimum values appear in the northeastern region at approximately 600 mm. Azonal characteristics are evident in Xinjiang, particularly in the Urumqi Oasis at the northern foothills of the Tianshan Mountains, the Ili River Valley, and Tacheng region, where average precipitation exceeds 200 mm. Compared to 1980–1995, the multi-year average potential evapotranspiration for 2010–2019 decreased by approximately 200 mm, with low potential evapotranspiration areas shifting northward, particularly in the Ili River Valley region of Xinjiang, consistent with precipitation and moisture index distributions. The eastern, northern, and northwestern regions of Xinjiang show significant potential evapotranspiration increases.

2.1.3 Moisture Index Changes

The spatial distribution of multi-year average moisture index was generated, showing that the study area' s multi-year average moisture index is approximately 0.2 [Figure 4: see original paper]. The index exhibits an increasing trend from northwest to southeast, with maximum values (> 0.65) occurring in Jiuzhi County, Baima County, and the Liupan Mountain area of Ningxia, classified as humid zones. Minimum values (< 0.05) appear in Turpan, Naomaohu, Qiemo in Xinjiang, and Lenghu, Xiazaohuo in Qinghai, classified as arid zones. Azonal characteristics are evident in Urumqi, Fukang, and other regions with average moisture indices around 0.20, belonging to arid sub-humid zones. Compared to 1980–1995, the multi-year average moisture index for 2010–2019 increased, with the arid zone boundary shifting northward and semi-arid areas expanding significantly. Non-zonal semi-arid regions emerged in the Urumqi Oasis and Qitai County areas of Xinjiang.

2.2 Boundary Delineation and Verification of Northwest Arid Desert Area

Based on 2010–2019 meteorological data, spatial distributions of precipitation ($P < 200$ mm) and moisture index ($I < 0.2$) were overlaid to delineate the northwest arid desert area boundary, which was verified using national 30 m DEM mountain ridge lines to form China' s major mountain system distribution. The delineated northwest arid desert area extends from the Kunlun Mountains in the south to the Altai Mountains in the north and to the Helan Mountains in the west, encompassing the Tarim Basin, East Xinjiang Basin, Hexi Corridor, Qaidam Basin, and Alxa Plateau, with the Tianshan Mountains as the boundary in southern Xinjiang and the southern foothills of the Altai Mountains and Dzungarian Basin. This delineation aligns with Zhang Junying et al.' s research on major terrain features in the northwest arid desert area but excludes the northern Tianshan foothills, Urumqi Oasis, Ili River Valley, and parts of Tacheng Prefecture due to various topographic and hydrological factors in Xinjiang, such as oasis landforms surrounding the Dzungarian Basin, favorable climate conditions in the Ili River Valley, and numerous river systems along the northern Tianshan foothills.

The boundary was refined to the county level according to administrative divisions [FIGURE:5, FIGURE:6]. In Xinjiang, the area includes southern Xinjiang south of the Tianshan Mountains, parts of Tacheng Prefecture, the Ili River Valley under Ili Kazakh Autonomous Prefecture, and Changji region surrounding the Urumqi Oasis at the northern Tianshan foothills. In Inner Mongolia, it covers western regions including Alxa League, Bayannur City, and Wuhai City, comprising Ejin Banner, Alxa Left Banner, Alxa Right Banner, and parts of Urad Rear Banner and Urad Middle Banner. In Qinghai, it includes the northwestern Haixi Mongol and Tibetan Autonomous Prefecture, covering Golmud City, Delingha City, and parts of Ulan County and Dulan County. In Ningxia, it comprises northwestern Shizuishan City and Yinchuan City, including Helan County, Xixia District, Yongning County, and Qingtongxia City. In Gansu, it covers the extensive Hexi Corridor region, avoiding the northern foothills of the Qilian Mountains.

2.3 Analysis of Boundary Changes in Northwest Arid Desert Area

Comparative analysis of meteorological data from 1980–1995 and 2010–2019 reveals significant changes in the study area. Precipitation increased substantially, the arid zone boundary shifted northward, and the arid area decreased, with notable azonal characteristics emerging in the Ili River Valley and Urumqi region. Potential evapotranspiration distribution also reflects the northward shift of the arid boundary, with lower ET_0 areas appearing in the Ili River Valley. The moisture index showed overall growth, primarily through expansion of semi-arid and arid sub-humid zones, with semi-arid azonal regions appearing in the Urumqi area.

Vector boundaries of the northwest arid desert area were extracted from both periods for comparison [Figure 7: see original paper]. Overall, the northwest arid desert area shows a decreasing trend. The southern boundary has shifted northward, primarily along the southern Qilian Mountains foothills and Qinghai Lake region, where three areas have transitioned from arid desert to non-arid desert zones due to improved climate conditions. The eastern boundary remains largely unchanged, with only slight westward movement in Ningxia. The most significant changes occurred in the Ili River Valley, northern Tianshan foothills, and Urumqi Oasis, correlating with recent climate changes including increased precipitation in northwest China since 1961, decreased potential evapotranspiration in Xinjiang, and overall moisture index growth, resulting in expanded semi-arid and sub-humid arid zones, reduced arid zone area, and evident northward shift of the arid boundary with azonal regions exhibiting non-arid desert climate characteristics.

3 Conclusions

1) Through overlay analysis of precipitation and moisture index spatial distributions, combined with China' s mountain system distribution and previous qualitative research, the northwest arid desert area boundary has been delineated at the county level: southern Xinjiang south of the Tianshan Mountains, parts of Tacheng Prefecture, the Ili River Valley, and Changji region surrounding the Urumqi Oasis in Xinjiang; western Inner Mongolia' s Alxa League, Bayannur City, and Wuhai City; northwestern Qinghai' s Haixi Mongol and Tibetan Autonomous Prefecture; northwestern Ningxia' s Shizuishan City and Yinchuan City; and the extensive Hexi Corridor in Gansu Province. This provides data support for regional refinement, resource exploitation, and ecological restoration tailored to local conditions.

2) Changes in precipitation, potential evapotranspiration, and moisture index in the border regions between Qinghai and Gansu and in the Ili and Urumqi regions of Xinjiang have caused corresponding boundary changes in the northwest arid desert area. These changes result from reduced potential evapotranspiration and increased precipitation at the Qinghai-Gansu border, and the formation of valley and oasis landforms with increased precipitation and moisture index in the Ili and Urumqi regions.

3) Since 1961, increased precipitation in northwest China, decreased potential evapotranspiration in Xinjiang, and overall moisture index growth have led to expanded semi-arid and sub-humid arid zones, reduced arid zone area, and evident northward shift of the arid boundary with azonal regions exhibiting climate characteristics untypical of arid desert areas.

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