Assessment of Agricultural Drought Vulnerability and Spatiotemporal Distribution Characteristics in Northwest China (Postprint)

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Abstract

Northwest China constitutes a critical agro-pastoral ecotone characterized by fragile ecological conditions and agricultural production that is highly sensitive to climate change. Investigating the spatiotemporal distribution patterns of agricultural drought vulnerability represents a key strategy for effective drought mitigation. Employing the IPCC assessment framework and accounting for the influence of evapotranspiration on soil water content, this study integrates multi-timescale drought indices into the indicator system to examine agricultural drought vulnerability and its spatiotemporal characteristics in Northwest China. The findings reveal that agricultural drought vulnerability in the region exhibited a declining trend during 2010–2020, with the most pronounced reduction occurring in 2010–2015. However, regional homogeneity diminished, manifesting a "bipolar" pattern. During 2015–2020, the vulnerability centroid progressively migrated toward southern areas, generating a "radiation" effect. Substantial transformations were observed in the cold and hot spot distributions of agricultural drought vulnerability. In 2010, hot spots clustered in southwestern Xinjiang, while cold spots were located in northern Xinjiang and Ningxia. By 2020, hot spots had relocated to southern Gansu and Qinghai, displaying an outward radiation phenomenon, whereas cold spots became predominantly concentrated in northern Xinjiang.

Full Text

Preamble

Agricultural Drought Vulnerability Assessment and Spatiotemporal Distribution Characteristics in Northwest China

Northwest China represents a critical agro-pastoral transition zone characterized by fragile ecological conditions and extreme sensitivity of agricultural pro-

duction to climate variability. Investigating the spatiotemporal distribution of agricultural drought vulnerability is essential for developing effective drought adaptation strategies. Based on the IPCC vulnerability assessment framework and accounting for evapotranspiration effects on soil moisture, this study integrates multi-timescale drought indices into the evaluation system to analyze agricultural drought vulnerability and its spatiotemporal patterns in Northwest China. Results indicate that agricultural drought vulnerability in the region declined from 2010 to 2020, with the most significant reduction occurring between 2010–2015. However, regional equilibrium weakened, manifesting a "polarization" phenomenon. The vulnerability core gradually shifted southward, creating a "radiation effect." Cold and hot spot patterns changed substantially: in 2010, hot spots clustered in southwestern Xinjiang while cold spots appeared in northern Xinjiang and Ningxia; by 2020, hot spots had migrated to southern Gansu and Qinghai, exhibiting outward radiation, whereas cold spots became concentrated in northern Xinjiang.

Keywords: Northwest China; agricultural drought vulnerability; IPCC assessment framework; entropy weight method; spatial hot spot detection analysis; drought index

Drought constitutes the most severe natural disaster affecting agricultural production in China, typically categorized into meteorological, agricultural, hydrological, and socioeconomic drought. Northwest China is a typical arid and semi-arid region and an important agro-pastoral transition zone. Rich in thermal resources, it possesses natural advantages for agricultural and pastoral development. However, influenced by topography and uneven water resource distribution, diverse farming systems have emerged—including rain-fed dryland farming and semi-irrigated agriculture—rendering regional agricultural systems highly sensitive to drought. Accelerated agricultural economic development has created structural mismatches between farming/pastoralism and natural resources, leading to water supply-demand conflicts, groundwater over-exploitation, soil degradation, and grassland deterioration, making it an ecologically vulnerable zone and climate-sensitive region. In 2020, varying degrees of agricultural drought occurred across the region, with moderate to severe drought in northern Ningxia, northeastern Gansu, and northern Shaanxi severely impacting agricultural production. To promote sustainable development of agriculture and pastoralism in Northwest China, the Ministry of Agriculture issued the *Northwest Arid Region Agriculture and Animal Husbandry Sustainable Development Plan (2016–2020)*, emphasizing ecological improvement alongside production increases and resource sustainability. In 2020, China's new western development strategy highlighted enhanced risk prevention capacity and coordination among economic development, population, resources, and environment, underscoring the importance of drought management. While short-term drought management focuses on monitoring drought indices, long-term strategies require drought risk and vulnerability assessment. The IPCC defines vulnerability as encompassing exposure to climate variability, sensitivity to climate impacts, and adaptive capacity. Existing research primarily addresses meteorological drought, with limited focus on agricultural drought. Under irrigation supplementation, climate drought does not necessarily translate to agricultural drought; only persistent climate drought causing soil moisture deficits leads to agricultural drought. Most studies overlook multi-timescale drought indices and evapotranspiration effects on soil moisture. In high-temperature, high-evaporation conditions, surface soil moisture depletes rapidly, creating negative pressure that transports groundwater upward to maintain soil moisture and crop water requirements. This study systematically investigates ecologically fragile Northwest China to clarify spatiotemporal distribution patterns of agricultural drought vulnerability and identify key vulnerability-driving factors, providing empirical support for regional drought risk planning and ecological security.

1.1 Study Area Overview

Northwest China, located in the Eurasian continent within the Central Asian arid zone, is characterized by dry climate, water scarcity, sparse vegetation, and fragile ecological conditions. The region comprises Shaanxi, Qinghai, Ningxia, Xinjiang, and Gansu, covering 32.11% of China's total land area. As an important agro-pastoral transition zone and specialty agricultural production area, it primarily cultivates fruits, cotton, and melons while raising cattle and sheep. Water resources are severely limited, with total annual water supply accounting for only 14.89% of the national total. Agricultural development foundations are weak and vulnerable to drought, with agricultural water consumption comprising 25.34% of regional water resources in 2020. Rural economic development lags behind the national average, with rural per capita net income in 2020 falling below the national average, limiting farmers' capacity to cope with drought disasters.

1.2 Index System Construction

Based on the IPCC vulnerability assessment framework and considering drought formation mechanisms in Northwest China, this study establishes an evaluation index system ensuring scientific rigor and data availability (Table 1). **Exposure** represents the degree to which agriculture is subjected to drought variability. Under an expanded water resources concept, "green water" (precipitation directly utilized by ecosystems) serves as a natural water supply source that can effectively mitigate meteorological drought. Given the region's high temperatures and strong evapotranspiration, this study incorporates multi-timescale drought indices (monthly, seasonal, and annual) to reflect precipitation use efficiency and meteorological drought characteristics, while accounting for effects of antecedent precipitation, water supply-demand balance, and evapotranspiration on agricultural drought. **Sensitivity** reflects agricultural susceptibility to drought stress under external pressures, with water resource pressure sources comprising: (1) agricultural water pressure from population and farming/pastoral activities, and (2) land pressure from multiple cropping indices, chemical inputs, and output value. **Adaptive capacity** indicates the region's ability to prevent, withstand, and recover from drought disasters, with indicators selected from macro-environmental and micro-agent perspectives: regional agricultural production infrastructure represents fundamental adaptive capacity guarantees; farmer production inputs represent subjective initiative for adaptation; and grain yield per unit area reflects output-level resilience to drought.

1.3 Methods

1.3.1 Entropy Weight Method

Current weight assignment methods fall into subjective (e.g., Analytic Hierarchy Process, Delphi) and objective (e.g., entropy method) categories. The entropy weight method assigns weights based on the relative variation degree of each indicator, overcoming information overlap and enhancing objectivity for multi-indicator comprehensive evaluation. The formula is:

$$Z_j = \sum_j \theta_j x_{ij}$$

where Z_j is the agricultural drought vulnerability index, θ_j is the indicator weight, and x_{ij} is the standardized indicator data.

1.3.2 Agricultural Drought Vulnerability Function

Using the TOPSIS method, exposure (EI), sensitivity (SI), adaptive capacity (AI), and agricultural drought vulnerability (DVI) are classified into low, moderate, high, and extreme levels via natural breaks classification. Since higher exposure and sensitivity increase vulnerability while higher adaptive capacity reduces it, the vulnerability function is established as:

$$DVI = f(EI, SI, AI)$$

1.3.3 Spatial Hot Spot Detection Analysis

Spatial hot spot detection analysis (Getis-Ord G_i^*) identifies local spatial clustering of significant hot or cold spots. Using ArcGIS 10.1, this method visualizes spatial distribution patterns of agricultural drought vulnerability hot and cold spots. The formula is:

$$G_i^* = \frac{\sum_j w_{ij}(d) X_j}{\sum_j X_j}$$

$$Z(G_i^*) = \frac{G_i^* - E(G_i^*)}{\sqrt{VAR(G_i^*)}}$$

where G_i^* is the hot/cold spot detection statistic, $Z(G_i^*)$ is the standardized statistic, $E(G_i^*)$ and $VAR(G_i^*)$ are the expected value and variance, $w_{ij}(d)$ is the spatial weight, and X_j is the agricultural drought vulnerability index of region j. When $Z(G_i^*)$ is significantly positive, region i is a hot spot of high-value clustering; when negative, it is a cold spot of low-value clustering.

1.4 Data Sources

The study covers 84 prefecture-level cities and autonomous prefectures in Northwest China. Due to data limitations, ten cities in Xinjiang (Shihezi, Aral, Tumxuk, Wujiaqu, Beitun, Tiemenguan, Shuanghe, Kokdala, Kunyu, and Huyanghe) were excluded. Data sources include: (1) meteorological data (temperature, wind speed, precipitation) from NOAA's FLDAS-10 km resolution dataset, with outlier processing; (2) statistical data from the *China City Statistical Yearbook* (2011–2021), provincial statistical yearbooks, and water resources bulletins.

2.1 Spatiotemporal Evolution of Agricultural Drought Vulnerability Indices

2.1.1 Exposure Analysis

From 2010 to 2020, exposure levels fluctuated frequently, with the exposure center shifting from northwest to southeast. Between 2010–2015, overall drought exposure decreased regionally, with the mean value dropping from 0.32 to 0.29, and the spatial pattern of "high west, low east" gradually intensifying. From 2015–2020, exposure increased overall, with the mean rising from 0.29 to 0.33, and the center shifting from western to southern regions. Provincially, only Xinjiang showed significantly increased exposure, with the mean rising from 0.32 to 0.37, as dry climate intensified drought exposure. Exposure in Gansu, Ningxia, and Qinghai decreased by 13.45%, 8.20%, and 13.86% respectively. At the prefecture level, 13 regions upgraded from moderate-high to extreme exposure, primarily due to climate aridity, while 51.35% of regions maintained their exposure level and 17.65% experienced upgrades, reflecting how climate warming exacerbates agricultural drought conditions.

2.1.2 Sensitivity Analysis

From 2010 to 2020, sensitivity levels gradually decreased, forming a spatial pattern of "high east-west, low central." Between 2010–2015, the regional mean sensitivity dropped from 0.51 to 0.42, with 12 extremely sensitive regions downgrading to high sensitivity and 17 highly sensitive regions downgrading to moderate sensitivity; only 15% of regions experienced sensitivity upgrades. From 2015–2020, the mean sensitivity further decreased from 0.42 to 0.35, with 36 regions downgrading sensitivity levels. Provincially, sensitivity rankings from high to low were: Shaanxi, Ningxia, Xinjiang, Qinghai, and Gansu, with reductions of 7.86%, 12.37%, 5.19%, 15.47%, and 12.05% respectively. Central

Gansu and Qinghai maintained low sensitivity due to urbanization reducing agricultural population pressure. Eastern Xinjiang's high sensitivity stemmed from high agricultural population ratios, multiple cropping indices, and primary industry value shares, creating strong agricultural dependency and drought sensitivity. The region's large crop sown area—driven by both food security needs and livestock feed demand for meat, eggs, and milk—intensified water resource shortages and sensitivity.

2.1.3 Adaptive Capacity Analysis

From 2010 to 2020, adaptive capacity gradually strengthened but regional imbalance intensified, with high-adaptation areas concentrated in western and northern regions and low-adaptation areas in central-southern areas. Between 2010–2015, the regional mean adaptive capacity index increased from 0.21 to 0.30, with 15 regions upgrading from high to extreme adaptation and 12 downgrading from low to moderate adaptation. Provincially, rankings from high to low were: Xinjiang, Shaanxi, Ningxia, Gansu, and Qinghai, with improvements of 41.72%, 42.16%, 38.22%, 43.06%, and 30.80% respectively, benefiting from western development infrastructure investments. From 2015–2020, the mean index rose from 0.30 to 0.37, but the growth rate slowed. Only 24 regions (28.92%) upgraded adaptation levels, while 71.15% maintained previous levels, indicating that future development must focus on motivating farmers toward intensive land production, machinery and fertilizer inputs, and improved resource use efficiency.

2.2 Overall Spatiotemporal Evolution of Agricultural Drought Vulnerability

Agricultural drought vulnerability in Northwest China showed a declining trend from 2010 to 2020. The most significant reduction occurred between 2010–2015, with moderately vulnerable areas decreasing from 27 to 20 and low-vulnerability areas increasing from 19 to 31. However, regional equilibrium weakened, showing a "polarization" phenomenon where 36 regions maintained vulnerability levels, 24 upgraded, and 24 downgraded. From 2015–2020, vulnerability continued declining, with the mean index dropping from 0.52 to 0.48, but the reduction rate slowed. The vulnerability core gradually shifted from western Xinjiang, southern Gansu, and southern Qinghai toward southern regions. High-vulnerability areas near Qinghai and southern Gansu experienced cascading upgrades in surrounding regions, creating a "radiation effect." This resulted from: (1) unreasonable farming-pastoral structures in irrigation-based agriculture creating excessive water demand that intensified vulnerability under water constraints; and (2) lagging agricultural development where climate variability increased drought probability, challenging stable agricultural supply and farmer income. Key vulnerability-driving factors included drought frequency, multiple cropping index, fertilizer application per sown area, primary industry value share, rural disposable income, total agricultural machinery power, and grain yield per unit area. Exposure showed initial increase then decrease, reflecting weakening drought trends under "warming-wetting" climate patterns, though drought frequency remained the primary exposure factor. Sensitivity consistently increased with accelerating growth rates, as farmers expanded crop sown areas and material inputs to ensure stable supply, intensifying land pressure. Adaptive capacity improved as macroeconomic conditions enhanced regional GDP and water infrastructure, though low rural disposable income limited production factor and machinery investments, leaving substantial room for grain yield improvement.

2.3 Cold and Hot Spot Spatial Evolution of Agricultural Drought Vulnerability

From 2010 to 2015, few hot or cold spots existed. Sub-hot spots were distributed in southwestern Xinjiang (Kizilsu Kirghiz Autonomous Prefecture, Kashgar, and Hotan) due to low farmer economic levels forcing production scale expansion for income, while severe, prolonged droughts heightened crop vulnerability. Sub-cold spots included six regions in northern Xinjiang and two in Ningxia (Yinchuan, Zhongwei), where better economic development, higher rural incomes, smaller agricultural population shares, and high agricultural modernization levels improved production and water use efficiency, reducing vulnerability.

[Figure 1: see original paper]

From 2015 to 2020, hot spots remained concentrated in southwestern Xinjiang (Kashgar and Hotan), but cold spots became fragmented. In Xinjiang, three subhot spots upgraded to hot spots, and Gannan Tibetan Autonomous Prefecture was added as a sub-hot spot due to lagging economic development, insufficient agricultural machinery investment, severe drought impacts, and the lowest grain yields in Gansu. Sub-cold spots decreased significantly and became the most dispersed, primarily because western development initiatives during the 12th Five-Year Plan improved agricultural infrastructure and addressed engineering water shortages, reducing water resource dependency. However, regional disparities in resource allocation and agricultural production matching caused fragmented low-vulnerability distribution.

[Figure 2: see original paper]

From 2010 to 2020, hot spots shifted to southern Gansu and Qinghai, radiating outward from core areas (Tianshui, Dingxi, Longnan, Gannan Tibetan Autonomous Prefecture, and Huangnan Tibetan Autonomous Prefecture) to Baoji, Xianyang, Hanzhong, Lanzhou, Baiyin, Pingliang, Linxia Hui Autonomous Prefecture, Xining, and Golog Tibetan Autonomous Prefecture. These regions suffer severe resource-based water shortages, increasing population density, lagging economic development, and high land loading—key factors driving high-vulnerability clustering. Cold spots were concentrated in northern regions, including eight areas in northern Xinjiang and Jiuquan (Gansu), which optimized planting structures, leveraged natural resource advantages, and achieved mechanized, intensive production that improved resource use efficiency, thereby reducing sensitivity and enhancing adaptive capacity.

3 Discussion

Northwest China is a typical arid and semi-arid region where topographic heterogeneity and uneven water distribution have created diverse farming systems (rain-fed, semi-irrigated) that are extremely sensitive to drought disturbance. This study focuses on agricultural drought vulnerability, examining exposure, sensitivity, and adaptive capacity under ecological fragility, farmer poverty risk, and meteorological drought. Multi-scale Standardized Precipitation Evapotranspiration Index (SPEI) and Palmer Drought Severity Index (PDSI) were incorporated to characterize drought features, distinguishing it from previous research. Key findings include: (1) Vulnerability declined from 2010–2020, with exposure fluctuating and shifting southeastward, sensitivity decreasing and forming an “east-west high, central low” pattern, and adaptive capacity strengthening but with intensifying regional imbalance; (2) The 2010–2015 period saw the largest vulnerability reduction but weakened regional equilibrium (“polarization”), while 2015–2020 showed a southward vulnerability core shift with “radiation effects”; (3) Cold/hot spot patterns changed significantly, with 2010 hot spots in southwestern Xinjiang and cold spots in northern Xinjiang and Ningxia, 2015 hot spots stabilizing but cold spots fragmenting, and 2020 hot spots migrating to southern Gansu and Qinghai with outward radiation while cold spots concentrated in northern Xinjiang.

These findings differ from previous studies. For instance, research on northern China agricultural drought vulnerability ranked vulnerability as Shaanxi > Gansu > Ningxia > Qinghai > Xinjiang, whereas this study finds Shaanxi > Ningxia > Xinjiang > Qinghai > Gansu. The discrepancy may arise from using provincial-level data that overlooks significant intra-provincial differences in Xinjiang and Qinghai, and from only including annual precipitation while ignoring meteorological drought and evapotranspiration effects. Key vulnerability drivers identified—drought frequency, multiple cropping index, and grain yield—differ from studies identifying terrain, precipitation, vegetation, agricultural disasters, water resources, and desertification as primary obstacles, because this research focuses specifically on agricultural drought vulnerability from perspectives of natural drought characteristics, agricultural inputs, and farmer risk resilience.

Based on these conclusions, recommendations include: (1) Enhance meteorological station data analysis to provide farmers with short-term (weekly, monthly) forecasts for agricultural planning; (2) Adjust farming-pastoral structures and promote drought-resistant crop varieties to mitigate meteorological drought constraints; (3) Increase agricultural machinery investment to reduce labor inputs and improve production efficiency; (4) Improve disaster prevention and reduction systems to minimize drought impacts on agricultural output, safeguarding regional food security and preventing large-scale poverty relapse; (5) Adopt tailored water resource development and management approaches—Gansu should prioritize "supply-side" infrastructure investment despite high upfront costs for long-term drought risk reduction, while Xinjiang should shift to "demand-side" management by promoting farmer water-saving awareness and technology adoption to increase water productivity.

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