Variation Characteristics of Meteorological Drought and Its Impact on Grain Yield: A Case Study of Wuwei City, Gansu Province (Postprint)

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Abstract

Drought is the most severe meteorological disaster in Wuwei City, Gansu Province. Based on precipitation data from 1960–2019 and grain yield data from 1970–2019 for Wuwei City, Gansu Province, this study employs statistical methods to analyze the variation characteristics of meteorological drought and grain yield, as well as the relationship between drought and grain yield. The results indicate: (1) The spatial variation patterns of frequency for spring drought, late spring and early summer drought, and midsummer drought are relatively consistent, all demonstrating that the northern desert region experiences higher frequencies than the oasis plain region, which in turn experiences higher frequencies than the southern mountainous region. (2) The inter-decadal frequency variations of spring drought, early summer drought, and midsummer drought are inconsistent. Spring drought exhibits an increasing trend in Liangzhou and Minqin, but a decreasing trend in Gulang, Tianzhu, and the entire municipality; early summer drought shows no change in Liangzhou and Gulang, but a decreasing trend in Minqin, Tianzhu, and the entire municipality; midsummer drought shows no change in Liangzhou, a decreasing trend in Minqin and Gulang, and an increasing trend in Tianzhu and the entire municipality; as drought severity intensifies, the frequency of all drought types generally shows an increasing trend. (3) Grain yield (wheat, corn, and total grain) demonstrates a significant increasing trend both annually and decadally; the annual variation of meteorological yield lacks obvious regularity with substantial fluctuation; the inter-decadal variation of meteorological yield follows a pattern of initial increase, subsequent decrease, and final increase. Meteorological yield is essentially negatively correlated with the inter-decadal frequency of all drought types, with the correlation between meteorological yield and early summer drought frequency being statistically significant, while correlations with other drought types are not significant.

Full Text

Characteristics of Meteorological Drought Variation and Its Impact on Grain Yield: A Case Study of Wuwei City, Gansu Province

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Abstract

Drought represents the most severe meteorological disaster in Wuwei City, Gansu Province. Using precipitation data from 1960-2019 and grain yield data from 1970-2019, this study employs statistical methods to analyze the spatiotemporal variation characteristics of meteorological drought and grain yield, as well as their interrelationships. The results demonstrate that: (1) The spatial patterns of spring drought, early summer drought, and midsummer drought frequencies are consistent, showing a gradient of highest frequency in the northern desert region, moderate in the oasis plain, and lowest in the southern mountainous area. (2) Interdecadal trends in drought frequency vary by drought type and location. Spring drought frequency increased in Liangzhou and Minqin but decreased in Gulang, Tianzhu, and the city overall. Early summer drought showed no change in Liangzhou and Gulang but decreased in Minqin, Tianzhu, and the city overall. Midsummer drought exhibited no change in Liangzhou, decreased in Minqin and Gulang, but increased in Tianzhu and the city overall. (3) Grain yield (wheat, maize, and total grain) increased significantly over years and decades. As drought severity intensified, the frequency of all drought categories generally increased. Annual meteorological yield fluctuations showed no clear pattern and were highly variable, while decadal meteorological yield followed a pattern of initial increase, subsequent decrease, then increase again. Meteorological yield was negatively correlated with decadal drought frequency for most drought types, with the correlation against early summer drought frequency being statistically significant, while correlations with other drought types were not significant. Decades with higher drought frequency corresponded to lower meteorological yields, and vice versa, indicating that drought constitutes a critical factor limiting grain production.

Keywords: drought disaster; variation characteristics; grain yield; Wuwei City

1.1 Study Area Overview

Severe drought represents a primary constraint on agricultural production in China. Wuwei City lies in the eastern Hexi Corridor of Gansu Province, bordered by the Qilian Mountains to the south, Inner Mongolia to the north, Lanzhou and Baiyin cities to the southeast, and Zhangye and Yongchang counties to the northwest. The jurisdiction encompasses Liangzhou District, Minqin County, Gulang County, and Tianzhu Tibetan Autonomous County. Situated at the convergence of the Loess, Mongolian-Xinjiang, and Qinghai-Tibet plateaus, the terrain slopes from southwest to northeast, forming three distinct geomorphological zones: the southern Qilian Mountain water collection area (Gulang, Tianzhu), the central oasis piedmont alluvial plain (Liangzhou), and the northern desert region (Minqin). Wuwei' s inland location in northwest China produces a typical temperate continental arid climate with inherently insufficient precipitation and intense evaporation. Annual precipitation ranges from 110–410 mm, while annual evaporation reaches 1500–2700 mm, yielding evaporation-to-precipitation ratios of 3.7–24.5. Drought occurrence is inevitable and profoundly impacts agricultural production and socio-economic stability.

1.2 Data Sources and Statistical Standards

Wuwei City is a major grain-producing region dominated by spring wheat and maize, with beans and other crops as secondary products. This study examines wheat, maize, and total grain yields. Grain yield data (actual yield per unit area, $\text{kg} \cdot \text{hm}^{-2}$) were obtained from the Wuwei Municipal Bureau of Statistics for the period 1970–2019. The data exhibit excellent continuity, completeness, and reliability, fully meeting research requirements.

Meteorological drought refers to water shortages caused by evaporation-precipitation imbalance during specific periods, where water expenditure exceeds income. Based on drought standards from the China Meteorological Administration and Gansu Provincial Meteorological Bureau, adapted to local conditions, meteorological drought is classified into spring drought, early summer drought (hereinafter "early summer drought"), and midsummer drought. Drought criteria are determined using ten-day precipitation anomaly percentage (ΔR) and drought duration. Spring drought is defined as [specific criteria]. Early summer drought is defined as [specific criteria]. Midsummer drought is defined as [specific criteria] with intervals between effective rainfall events \$ 35*days.Ayearisclassifiedasaspring*, *earlysummer*, *ormidsummerdroughtyearwhenthecorrespondingdroug*
lightdrought(\$R% ≤ -10%), moderate drought (ΔR% ≤ -30%), severe drought (ΔR% ≤ -50%), and extreme drought (ΔR% ≤ -80%).

1.3 Research Methods

Based on these drought standards, the occurrence years of spring drought, early summer drought, and midsummer drought were statistically analyzed (expressed as frequency).

1.3.1 Separation of Meteorological Yield

In statistical studies of long-term crop yield-meteorological factor relationships, crop yield is typically decomposed into trend yield, meteorological yield, and noise term [15]:

$$y_i = y_{ti} + y_{wi} + \Delta y_i, \quad i = 1, 2, 3, \cdots, n$$

where y_i is total yield, y_{ti} is trend yield, y_{wi} is meteorological yield, and Δy_i is the noise term. Trend yield represents the basic yield characteristics under normal weather conditions, reflecting continuous improvement in agricultural technology over time and representing stable growth factors affecting yield from all natural and non-natural factors except meteorological changes. Meteorological yield represents meteorological impacts on yield, including certain meteorological disasters—particularly drought—that play crucial roles in interannual yield fluctuations. The moving average method simulates trend yield [16]:

$$y_{ti} = \frac{y_{i-2} + y_{i-1} + y_i + y_{i+1} + y_{i+2}}{5}, \quad i = 1, 2, 3, \cdots, n$$

Thus, meteorological yield is calculated as:

$$y_{wi} = y_i - y_{ti}, \quad i = 1, 2, 3, \cdots, n$$

1.3.2 Linear Trend Coefficient

The linear trend coefficient method [17] analyzes temporal variation trends in drought frequency, grain yield, and meteorological yield, calculating climate tendency rates:

$$x_i = a + bt_i, \quad i = 1, 2, 3, \cdots, n$$

where x_i is the element, t_i is the corresponding time, and b is the linear tendency rate. Trend significance is tested using the correlation coefficient R between time and sequence variables (the climate trend coefficient). Based on Monte Carlo simulation [18], critical values for climate trend coefficients at significance level α are: [values]. When the absolute climate trend coefficient exceeds these critical values, trends are considered relatively significant, significant, and highly significant, respectively. The Pearson correlation coefficient method [19] and climate trend method [20] assess drought impacts on meteorological yield.

2.1.1 Spatial Distribution

Regional distribution patterns of various drought types across Wuwei City are broadly consistent. Spring drought frequency (Fig. 1b) [Figure 1: see original paper] is highest in Minqin, followed by Liangzhou, and lowest in Gulang. Early summer drought frequency (Fig. 1c) [Figure 1: see original paper] shows [values] ···with Liangzhou ranking second and Tianzhu lowest. Midsummer drought frequency (Fig. 1d) [Figure 1: see original paper] is highest in Minqin, followed by [region], with Tianzhu lowest.

Spatial variation is consistent across drought types, following the pattern: northern desert region > oasis plain region > southern mountainous region. As shown in Fig. 1a [Figure 1: see original paper], drought distribution is closely related to altitude, with frequency decreasing as elevation increases. Correlation coefficients reach [value] for spring drought and [value] for early summer drought, both significant at α=0.001. Drought distribution also relates to topography. The southern mountainous area, on the Qilian Mountains' northeastern windward slope, experiences orographic lifting that enhances precipitation, reducing drought frequency. Central and northern plains lack such lifting mechanisms, limiting precipitation and increasing drought frequency. Additionally, synoptic systems influence drought patterns. The southern mountains, affected by the southwest monsoon and plateau thermal/dynamic effects, experience frequent low-vortex and shear-line activities with abundant moisture, yielding more precipitation and less drought. Plains and desert regions under westerly circulation carry less moisture, producing less precipitation and more drought. Consequently, Wuwei exhibits a clear spatial gradient in drought frequency driven by altitude, topography, and atmospheric circulation.

2.1.2 Temporal Variation

Interannual drought frequency variability is substantial, with some years experiencing no drought events. Therefore, interdecadal analysis is employed. Table 1 shows inconsistent decadal frequency changes among spring, early summer, and midsummer droughts. Spring drought frequency peaked in the 1970s, decreased in the 1980s, and reached its minimum in the 1990s, with citywide averages of [values]. Early summer drought frequency was highest in the 1970s, moderate in the 1980s, and lowest in the 1990s, with citywide averages of [values]. Midsummer drought frequency was highest in the 1970s, moderate in the 1980s, and lowest in the 1990s, with citywide averages of [values].

Linear trend analysis (Table 2) reveals varying trends. Spring drought frequency shows positive trends (increasing) in Liangzhou and Minqin, but negative trends (decreasing) in Gulang, Tianzhu, and citywide. Early summer drought shows no change in Liangzhou and Gulang, but negative trends in Minqin, Tianzhu, and citywide. Midsummer drought shows no change in Liangzhou, negative trends in Minqin and Gulang, but positive trends in Tianzhu and citywide. Trend coefficients indicate that Minqin' s spring drought increase is highly significant (α=0.01), while Gulang' s and Tianzhu' s decreases are highly significant. For early summer drought, Minqin' s decrease is significant and Tianzhu' s highly significant. For midsummer drought, Tianzhu' s increase is highly significant. These inconsistent trends likely reflect Wuwei' s position in a climatic transition zone, where monsoon, circulation systems, topography, and altitude create complex local climate variations requiring further investigation.

2.1.3 Variation by Drought Grade

Table 3 shows substantial variation in frequency across drought grades, with inconsistent patterns. Citywide, drought frequency generally increases with severity. For spring drought, extreme drought occurs most frequently, followed by light drought. For early summer drought, extreme drought is most frequent, followed by severe drought. For midsummer drought, moderate drought is most frequent, followed by extreme drought. The increasing frequency of extreme and severe drought poses serious threats to agriculture and livelihoods [21].

2.2 Grain Yield Variation Characteristics

Wuwei' s annual grain yield shows fluctuating but increasing trends (Fig. 2a) [Figure 2: see original paper], while annual meteorological yield shows high variability without clear patterns (Fig. 2b) [Figure 2: see original paper]. Linear trend analysis (Table 4) reveals grain yield tendency rates of maize > total grain > wheat, indicating maize has the strongest increasing trend. Meteorological yield tendency rates show wheat > maize > total grain, with wheat increasing most noticeably while total grain shows a weak decreasing trend. Monte Carlo tests indicate grain yield trends for wheat, maize, and total grain are highly significant (α=0.01), while meteorological yield trends are not significant.

Decadal analysis shows grain yields for wheat, maize, and total grain increased progressively, with yields rising by [values] $kg \cdot hm^{-2}$ from the 1970s to 2010s. Yield extrema occurred in consistent years: maximum wheat yield of [value] $kg \cdot hm^{-2}$ in [year], maize yield of [value] $kg \cdot hm^{-2}$ in [year], and total grain yield of [value] $kg \cdot hm^{-2}$ in [year]; minimum wheat yield of [value] $kg \cdot hm^{-2}$ in [year], maize yield of [value] $kg \cdot hm^{-2}$ in [year], and total grain yield of [value] $kg \cdot hm^{-2}$ in [year], all in the early 1970s. Meteorological yields for wheat, maize, and total grain increased initially, then decreased, then increased again decadally, with anomalies of [values] $kg \cdot hm^{-2}$.

2.3 Impact of Drought on Grain Yield

To further understand drought impacts, meteorological yield was isolated and correlated with moderate-or-greater drought frequency (light drought effects on agriculture are minimal). Correlation analysis (Table 6) shows negative correlations between most drought types and meteorological yields, except weak positive correlations between spring drought and maize, and between midsummer drought and wheat. Early summer drought correlations with wheat are highly significant (α=0.01), and with maize and total grain are significant (α=0.05); other correlations are not significant.

Climate trend analysis shows that each additional spring drought event reduces wheat, maize, and total grain meteorological yields by 1.47, 1.72, and 1.47 kg • hm^{-2}, respectively. Each additional early summer drought event reduces yields by 4.51, 21.52, and 23.96 kg • hm^{-2}, respectively. Each additional midsummer drought event reduces yields by 1.49, 11.35, and 0.44 kg • hm^{-2}, respectively. Early summer drought has the most pronounced impact, as June-July coincides with critical growth, development, and grain-filling stages for wheat and maize. Severe early summer drought can cause substantial yield losses or even total crop failure. Conversely, spring drought' s weak positive correlation with maize reflects that dry conditions in May facilitate planting and emergence by preventing soil crusting. Midsummer drought' s weak positive correlation with wheat reflects that hot, dry conditions in July-August aid wheat maturation, harvesting, and storage. Overall, decades with higher drought frequency correspond to lower meteorological yields, confirming drought as a key factor limiting grain production in Wuwei.

3 Discussion

The finding that extreme drought frequency increases with drought grade contrasts with Bai et al. [22], who reported decreasing frequency from light to extreme drought in Northwest China. This discrepancy likely stems from differences in meteorological variables, calculation methods, and drought classification standards, warranting further investigation. However, our results align with Ren et al. [23] on intensifying meteorological drought in Northwest China, Cao et al. [24] on extreme drought hotspots on the northern Tianshan slope, and Zhang et al. [25] on worsening summer-autumn drought in Central Asia.

Using precipitation anomaly percentage as a drought indicator offers data accessibility and computational simplicity, though drought mechanisms are complex and also influenced by temperature, evaporation, topography, and other factors [26-28]. Drought impacts on grain yield also depend on crop layout, varieties, and growth conditions [29,30]. While this study provides practical insights for agriculture, future work should further elucidate drought development patterns, establish appropriate monitoring indices, enable accurate meteorological drought monitoring, and guide rational agricultural planning and scientific defense measures to ensure grain production security.

4 Conclusions

1. Spatial patterns of spring, early summer, and midsummer drought frequencies in Wuwei City are consistent: northern desert region > oasis plain region > southern mountainous region. Temporal trends vary by drought type: spring drought frequency increased in Liangzhou and Minqin but decreased in Gulang, Tianzhu, and citywide; early summer drought frequency was unchanged in Liangzhou and Gulang but decreased in Minqin, Tianzhu, and citywide; midsummer drought frequency was unchanged in Liangzhou, decreased in Minqin and Gulang, but increased in Tianzhu

and citywide. Drought frequency generally increases with severity, with extreme drought being most frequent for spring and early summer droughts, and second most frequent for midsummer drought.

2. Grain yield in Wuwei increased significantly over years and decades, while meteorological yield showed high annual variability without clear patterns, following a decadal pattern of increase-decrease-increase.
3. Meteorological yield is negatively correlated with most drought frequencies (except weak positive correlations between spring drought and maize, and midsummer drought and wheat). The correlation with early summer drought frequency is statistically significant, while other correlations are not. Decades with higher drought frequency have lower meteorological yields, confirming drought as a critical factor limiting grain production.

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