Spatiotemporal Variation Characteristics of Drought in Xinjiang Region Based on TVDI: Postprint

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Abstract

Drought is a critical factor affecting the ecological environment and agricultural production in the Xinjiang region, and conducting timely drought monitoring holds guiding significance for ensuring food security in Xinjiang. This study constructs the Temperature Vegetation Drought Index (TVDI) based on Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) from MODIS data during 2001–2020 to investigate the drought distribution characteristics and future evolution trends in Xinjiang. The results indicate: (1) An average of 78.7% of the Xinjiang region experiences drought of varying severity annually, with a mean TVDI value of 0.58 over the past 20 years, indicating an overall mild drought level; (2) Future drought conditions in Xinjiang are expected to alleviate, with TVDI decreasing at a rate of 0.0017 per year, and 81% of the region exhibits a trend of gradual wetting; (3) TVDI shows a weak correlation with meteorological factors and a strong correlation with altitude. When drought severity is high, unused land contributes more significantly to TVDI; when drought severity is low, grassland contributes more significantly to TVDI. Unused land area shows a positive correlation with drought, while forest land and grassland areas show a negative correlation with drought; reducing unused land area and increasing forest and grassland coverage holds positive significance for drought mitigation.

Full Text

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Spatiotemporal Variations in Drought Conditions in Xinjiang Based on TVDI

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Abstract: Drought is a critical factor affecting the ecological environment and agricultural production in Xinjiang. Timely drought monitoring is essential for guiding food security efforts in the region. This study constructed the Temperature Vegetation Drought Index (TVDI) based on Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) from MODIS data to investigate the spatial distribution characteristics and future evolution trends of drought in Xinjiang. The results show that: (1) On average, 78.7% of the region experiences varying degrees of drought annually, with a mean TVDI of 0.58 over the past 20 years, indicating an overall mild drought condition. (2) Future drought conditions in Xinjiang are expected to alleviate, with TVDI decreasing at a rate of 0.0017 per year, and 81% of the region showing a trend toward increasing moisture. (3) TVDI exhibits weak correlation with meteorological factors but strong correlation with elevation. When drought severity is relatively high, unused land contributes significantly to TVDI, whereas when drought severity is relatively low, grassland contributes significantly to TVDI. Unused land area shows a positive correlation with drought, while forest and grassland areas show negative correlations. Reducing unused land area and increasing forest and grassland coverage are beneficial for drought mitigation.

Keywords: TVDI; drought; trend analysis; Xinjiang

Introduction

Drought, as a widespread natural disaster in global climate change, significantly impacts ecosystem balance and sustainable agricultural development[1-3]. Xinjiang is one of China' s most ecologically diverse regions[4]. Characterized by a typical temperate continental climate, Xinjiang receives low precipitation overall with uneven spatiotemporal distribution, leading to frequent drought occurrences[5-7]. Water resource shortages directly affect agricultural production, ecosystem stability, and regional socio-economic development. Therefore, timely and accurate regional-scale drought monitoring in Xinjiang is crucial for safeguarding agricultural production and food security[8-9]. Currently, drought monitoring is divided into two main categories: station-based monitoring and remote sensing monitoring[10]. Station-based monitoring relies on key meteorological elements such as precipitation, evapotranspiration, temperature, and humidity from weather stations to construct indices like the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index

(SPEI), and Palmer Drought Severity Index (PDSI). These indices, through standardized processing of long-term meteorological data, can reflect drought onset, development, and intensity. In contrast, remote sensing monitoring constructs drought indices such as the Soil Moisture Index (SMI), Crop Water Index (CMI), and Vegetation Condition Index (VCI) to enable long-term drought monitoring over large areas, effectively overcoming the spatial and temporal limitations of station data.

Drought formation is not caused by a single factor but results from multiple interacting factors; thus, using a single type of remote sensing data to describe drought phenomena has lower accuracy[11]. The Temperature Vegetation Drought Index (TVDI) integrates the responses of Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) to drought and has been widely applied in regional drought dynamic monitoring. For instance, Chen et al.[12] studied drought variations in Xilingol League, demonstrating that TVDI effectively monitors drought conditions in the study area; Kang et al.[13] constructed TVDI to investigate drought changes in Inner Mongolia, revealing that drought on the Mongolian Plateau increased at a rate of 0.0017/a; Sandholt et al.[14] compared multiple drought indices, showing that TVDI exhibits higher applicability than other indices; Wang et al.[15] revealed spatial distribution characteristics of drought on the Loess Plateau based on TVDI, identifying the combination of elevation and NDVI as the strongest influence on drought in the region; Qin et al.[16] studied drought changes during the growing season in Inner Mongolia, noting high drought frequency in the Ordos Plateau and Hulunbuir Grassland; Younes et al.[17] explored monthly-scale drought conditions on the Iranian Plateau using TVDI, finding negative correlations between TVDI and precipitation/evapotranspiration and positive correlations with temperature in most areas. In summary, TVDI, as a product integrating vegetation growth status and surface temperature, has achieved considerable success in large-scale drought monitoring[18].

Xinjiang possesses vast land and abundant natural resources, yet faces significant drought risks due to its unique climate conditions and geographical location[12-14]. Previous studies indicate that Xinjiang’ s average annual precipitation is below the national average, with extremely uneven spatiotemporal distribution, resulting in frequent drought occurrences[15-16]. Current drought monitoring in Xinjiang primarily focuses on small-area monitoring or analysis of past drought trends, emphasizing the revelation of spatial distribution patterns. Dilihumaer · Ahanmujiang et al.[17] demonstrated that TVDI can effectively reflect soil moisture in the Xinjiang section of the Tianshan Mountains, but its applicability for drought monitoring across the entire Xinjiang region remains to be verified. This study utilizes MODIS NDVI and LST data to construct the TVDI feature space, obtaining a 20-year TVDI time series for Xinjiang. Based on clarifying the spatiotemporal distribution characteristics of drought in Xinjiang, trend analysis and Hurst index methods are employed to study drought evolution trends, while Pearson correlation coefficients are used to explore drought impact factors, aiming to provide scientific guidance for agricultural production and drought disaster prevention in Xinjiang.

1. Materials and Methods

1.1 Study Area Overview

Xinjiang is located in the northwestern hinterland of China, extending from Gansu Province in the east to the national border in the west, bounded by the Kunlun and Altun Mountains in the south and the Altai Mountains in the north, with geographical coordinates ranging from 73°~97°E and 34°~50°N. The region covers a total area exceeding 1.60$×10^{6}$ km^2, making it China' s largest provincial-level administrative region. The Tianshan Mountains divide the region into southern and northern parts, with the Tarim Basin in the south and the Junggar Basin in the north. The climate is characterized as a typical temperate continental climate, with average annual precipitation less than 200 mm and average annual potential evapotranspiration exceeding 1200 mm. Vegetation coverage is low, with deserts and gobi occupying most of the area. The region is rich in resources, with enormous reserves of oil, natural gas, and other minerals, but has a fragile ecological environment and suffers from water resource shortages.

[Figure 1: see original paper]

1.2 Data Sources and Processing

The remote sensing data used in this study include the MODIS MOD13A2 NDVI product with a spatial resolution of 1 km and a temporal resolution of 16 days, and the MODIS MOD11A2 LST product with a spatial resolution of 1 km and a temporal resolution of 8 days. Both datasets were obtained from Google Earth Engine and batch-processed to generate annual TVDI data for Xinjiang. Annual precipitation and temperature data were sourced from the Xinjiang Uygur Autonomous Region Bureau of Statistics. Land use/cover data were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences, with a spatial resolution of 30 m. Detailed data source information is provided in Table 1.

Table 1 Data sources

Data Type	Product/Source	Spatial Resolution	Temporal Resolution	Data Source
NDVI	MODIS/MOD13A2	1 km	16 days	Google Earth Engine
LST	MODIS/MOD11A2	1 km	8 days	Google Earth Engine

Data Type	Product/Source	Spatial Resolution	Temporal Resolution	Data Source
Annual precipitation and temperature	Statistical data	-	1 year	Xinjiang Uygur Autonomous Region Bureau of Statistics
Land use/cover	Resource and Environment Science and Data Center	30 m	-	Chinese Academy of Sciences (http://www.resdc.cn)

1.3 Temperature Vegetation Drought Index (TVDI)

1.3.1 TVDI Calculation TVDI comprehensively considers factors representing vegetation growth status. By constructing the NDVI-LST feature space, it inverts and assesses soil moisture, enabling drought monitoring under variable climate and complex terrain conditions. The formula is as follows:

$$TVDI = \frac{LST - LST_{min}}{LST_{max} - LST_{min}}$$

where LST represents the land surface temperature of any pixel, and LST_{min} and LST_{max} represent the minimum and maximum land surface temperatures corresponding to the same NDVI value, respectively. The wet and dry edges of the NDVI-LST feature space are determined through linear fitting. The TVDI value ranges from [0, 1]; lower values indicate higher soil moisture and less severe drought, while higher values indicate lower soil moisture and more severe drought. Referencing relevant literature and considering the study area' s conditions, this study classifies drought levels as shown in Table 2.

Table 2 Classification of drought levels

TVDI Range	Drought Level
$0 < \text{TVDI} \leq 0.2$	Wet
$0.2 < \text{TVDI} \leq 0.4$	Normal
$0.4 < \text{TVDI} \leq 0.6$	Mild drought
$0.6 < \text{TVDI} \leq 0.8$	Moderate drought
$0.8 < \text{TVDI} \leq 1$	Severe drought

1.3.2 Trend Analysis Methods This study employs the Sen's Median trend analysis method and the Mann-Kendall test to analyze TVDI variation trends in Xinjiang from 2001 to 2020, combined with significance testing.

Sen' s Median trend analysis is a robust non-parametric statistical method for trend calculation, suitable for time series trend analysis. The formula is:

$$\beta = \text{Median}\left(\frac{X_m - X_n}{m - n}\right), \quad \forall n < m$$

where β is the slope of the trend; m and n are time indices; X_m and X_n represent TVDI values in year m and year n, respectively. Based on β values, trends are classified into three categories: $\beta > 0.001$ indicates an increasing trend (worsening drought); $-0.001 < \beta < 0.001$ indicates essentially no change; and $\beta < -0.001$ indicates a decreasing trend (drought alleviation).

The Mann-Kendall test is a non-parametric statistical method whose advantage lies in not requiring assumptions of normal distribution and effectively handling missing values and outliers. The test statistic Z_c is calculated to determine trend significance. The significance levels are categorized as shown in Table 3.

Table 3 Sen+M-K trend change levels

Test Statistic	Significance Level
$\|Z_c\| \geq 1.96$	Significant change
$1.65 \leq \|Z_c\| < 1.96$	Moderately significant change
$\|Z_c\| < 1.65$	Non-significant change

1.3.3 Hurst Index The Hurst exponent (H) is a measure of long-term persistence or anti-persistence in time series data. The calculation steps are:

1) Collect time series data $X(t)$, $t = 1, 2, 3, ..., N$
2) Calculate the mean $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} X(i)$ and cumulative deviation series $Y(t) = \sum_{i=1}^{t}(X(i) - \bar{x})$
3) Calculate the range $R(t) = \max(Y(t)) - \min(Y(t))$ and standard deviation $S(t) = \sqrt{\frac{1}{t}\sum_{i=1}^{t}(X(i) - \bar{x})^2}$
4) Calculate the R/S ratio: $(R/S)_t = R(t)/S(t)$
5) Establish the logarithmic relationship: $\log(R/S)_t = H\log(t) + C$

The Hurst exponent typically ranges between 0 and 1. Values closer to 0 indicate anti-persistence (future trends opposite to past), values closer to 1 indicate long-term persistence (future trends continue past), and values near 0.5 indicate random changes with no long-term memory.

2. Results

2.1 Spatiotemporal Characteristics of Drought

2.1.1 Temporal Variations As shown in Figure 2, the annual average TVDI in Xinjiang exhibited an overall decreasing trend from 2001 to 2020, declining at a rate of 0.0017 per year, indicating that drought conditions in the region have alleviated to some extent over the past two decades. The TVDI values ranged between 0.55 and 0.62, with a multi-year average of 0.58, representing a mild drought level. The lowest TVDI value occurred in 2019, while the highest occurred in 2008. Analysis of area proportions for different drought levels shows that mild and moderate drought occupy the largest areas, with mild drought accounting for 25.2%–58.9% of the total area and moderate drought accounting for 21.3%–26.8%. In 2008, moderate and severe drought areas exceeded 52.8% of the total area, representing the most severe drought conditions. In 2011, moderate and severe drought areas accounted for 48.1% of the region, also indicating relatively severe drought.

[Figure 2: see original paper]

2.1.2 Spatial Patterns Figure 3 illustrates the pronounced spatial heterogeneity of drought distribution in Xinjiang. The region is dominated by moderate and mild drought, accounting for 52.8% and 21.3% of the area respectively, while wet and normal conditions comprise 15.1%, and severe drought accounts for the smallest proportion at 10.8%. Figure 4 shows that drought distribution exhibits strong locality, with significantly higher drought severity in central Xinjiang compared to other areas. The region is primarily characterized by mild and moderate drought, with severe drought mainly distributed near the Tarim Basin. Southern Xinjiang experiences higher drought area and intensity than northern Xinjiang, with the Tarim Basin and its surrounding low-lying areas being the most severely affected. These areas receive annual precipitation generally below 200 mm while experiencing extremely high evapotranspiration, leading to severe soil water deficits. According to the spatial distribution of TVDI, severe drought areas in southern Xinjiang are concentrated in Kashgar, Hotan, and other locations, where drought is extensive and frequent, severely impacting local agricultural production and ecological environments. In contrast, northern Xinjiang shows relatively lighter drought conditions, mainly concentrated in the eastern Junggar Basin and the southern foothills of the Altai Mountains.

[Figure 3: see original paper] [Figure 4: see original paper]

2.2 Analysis of Drought Evolution Trends

2.2.1 Trend Analysis This study calculated TVDI variation trends and their significance in Xinjiang using the Theil-Sen Median method. The spatial distribution of change rates (β) is shown in Figure 5. The results indicate that TVDI in Xinjiang shows an overall decreasing trend, with β values ranging from -0.025 to 0.032. Regions with decreasing interannual changes account for 81% of Xinjiang' s total area, while regions with increasing changes account for 19%. After significance testing of β values, the results are shown in Figure 6. Areas with significant and non-significant wetting trends are mainly concentrated in the Tarim Basin, Bayingolin Mongol Autonomous Prefecture, and Hami region. Regions where $\beta <$ -0.001 and pass the significance test account for 25.5% of the total area, indicating improved drought conditions in Xinjiang over the past 20 years.

[Figure 5: see original paper] [Figure 6: see original paper]

2.2.2 Future Drought Trends The Hurst index can reflect long-term trends and stability in time series data. Figure 7 shows that the Hurst index for Xinjiang from 2001 to 2020 ranges from 0.11 to 0.88. Areas with Hurst < 0.5 account for 69.2% of the study area, indicating obvious anti-persistence trends. Lower Hurst values indicate stronger randomness, meaning future changes are independent of past trends. Based on correlation characteristics, Hurst values are divided into four categories: strong persistence ($0.65 \leq$ Hurst < 1.0), weak persistence ($0.50 \leq$ Hurst < 0.65), weak anti-persistence ($0.35 \leq$ Hurst < 0.50), and strong anti-persistence ($0 <$ Hurst < 0.35).

By overlaying pixel-by-pixel Sen+Mann-Kendall trends with Hurst index values, the relationship between future drought changes and past trends is obtained, as shown in Figure 8 and Table 4. Regions that may become wetter in the future account for 55.5% of Xinjiang' s total area (strong persistent wetting and weak persistent wetting account for 23.3% and 32.2% respectively). Regions with past drying trends that will become wetter account for 25.5%. Regions with past wetting trends that will become drier account for 10.8% (anti-weak persistent wetting and anti-strong persistent wetting account for 5.5% and 5.3% respectively). Regions with persistent drying trends account for 4.6% (strong persistent drying and weak persistent drying account for 1.2% and 3.4% respectively). Regions with essentially no change account for 3.6%. Persistently wetting areas are mainly located in the Tarim Basin and north of the Altun Mountains, while persistently drying areas are mainly located on the northern side of the Tianshan Mountains and the southern side of the Altai Mountains.

[Figure 7: see original paper] [Figure 8: see original paper]

Table 4 Future trends of TVDI in Xinjiang

Future Trend	Area Proportion (%)
Strong persistent wetting	23.3
Weak persistent wetting	32.2
Past drying, future wetting trend	25.5
Anti-weak persistent drying	3.4
Anti-strong persistent drying	1.2
Past wetting, future drying trend	10.8
Anti-weak persistent wetting	5.5
Anti-strong persistent wetting	5.3
Weak persistent drying	3.4
Strong persistent drying	1.2
Essentially unchanged	3.6

2.3 Impact Factors Analysis

2.3.1 Correlation with Meteorological Factors High temperatures and low precipitation are often primary factors causing drought. To investigate correlations between drought and meteorological factors, this study compiled annual precipitation and temperature data for Xinjiang from 2001 to 2020 (Figure 9). The highest annual precipitation was 229.7 mm in 2016, while the lowest was 141.8 mm in 2008. The highest annual temperature was 10.9°C in 2015, and the lowest was 8.8°C in 2003. In 2008, TVDI values were higher than the multi-year average, while in 2016 they were lower.

To explore correlations between meteorological factors and TVDI, Pearson correlation coefficients between annual precipitation, annual temperature, and TVDI were calculated. Results show that TVDI exhibits a weak negative correlation with annual precipitation ($r = -0.25$, $P < 0.05$) and a weak positive correlation with annual temperature ($r = 0.21$, $P < 0.05$), with neither correlation being statistically significant. In summary, TVDI does not show strong correlations with meteorological factors in Xinjiang. Although the correlation with precipitation is slightly higher than with temperature, it remains weak. This does not diminish their role as potential influencing factors. While direct correlations are weak, meteorological factors may influence drought through complex indirect pathways. Furthermore, meteorological factors are often primary drivers during extreme drought events.

[Figure 9: see original paper]

2.3.2 Impact of Land Use Types As shown in Figure 10, unused land is the dominant land use type in Xinjiang, mainly distributed in the southeastern part of Xinjiang and on the northern side of the Tianshan Mountains, followed by grassland, which is primarily distributed in western Xinjiang. Cultivated land, water bodies, forest land, and construction land are relatively limited, mainly distributed near grassland areas. From 2001 to 2020, TVDI values for all land use types in Xinjiang showed decreasing trends, though the decline was gradual.

By extracting five land use types and statistically analyzing their relationship with TVDI values in Xinjiang in 2020, the variation between each land use type and TVDI was obtained (Figure 11). Areas with lower drought severity are mainly characterized by grassland and forest land, while areas with higher drought severity are dominated by unused land. Unused land in Xinjiang accounts for approximately 46.7% of the total area, primarily comprising deserts, bare land, saline-alkali land, and sandy land. These areas typically lack vegetation cover, have fragile soil structure and poor water retention capacity, and are prone to drought intensification.

There is a close relationship between land use type and TVDI values. Different land use types exhibit significantly different water retention capacities and drought response characteristics, which directly influence the spatial distribution and intensity of drought. Unused land has the highest TVDI values in

Xinjiang; these areas with sparse vegetation are more vulnerable to drought impacts. Cultivated land and construction land have similar TVDI values, both higher than the regional average. Forest land and grassland have relatively low TVDI values, indicating strong water retention capacity. Water bodies have the lowest TVDI values.

The contribution rate of different land use types to TVDI varies with drought severity. At higher drought severity, unused land contributes significantly to TVDI, while at lower drought severity, grassland contributes significantly. The contribution rates of grassland in wet, normal, and mild drought conditions are 45.2%, 38.6%, and 28.4% respectively (Figure 12). Grassland and forest land typically have high vegetation coverage, enabling effective absorption and storage of precipitation and reducing surface evaporation.

[Figure 10: see original paper] [Figure 11: see original paper] [Figure 12: see original paper]

2.3.3 Impact of Elevation Elevation is one of the most fundamental geographical elements, influencing climate, vegetation, soil, and other aspects. To investigate the impact of elevation on drought, annual average TVDI distribution data for Xinjiang were overlaid with elevation data (Figure 13). TVDI values decrease with increasing elevation; areas above 3000 m experience almost no moderate or severe drought. Areas below 2000 m show a significant negative correlation between elevation and TVDI, with $R^2 = 0.73$ and $P \leq 0.01$, passing the significance test. In summary, elevation exhibits a strong negative correlation with TVDI values; higher elevation areas have relatively lighter drought severity.

[Figure 13: see original paper]

3 Discussion

TVDI serves as an effective drought monitoring tool that can accurately reflect soil moisture and vegetation water status, enhancing drought monitoring precision. This study conducted long-term remote sensing drought monitoring in Xinjiang based on TVDI. The findings indicate that overall drought conditions in Xinjiang are at a moderate level, consistent with results from Fan et al.[29]. Drought conditions were particularly severe in 2008, aligning with findings from Tang et al.[30]. The future evolution trend is primarily toward wetting, with wetting areas concentrated in the Tarim Basin and north of the Altun Mountains, consistent with research by Wang[19].

Correlation analysis between meteorological factors and TVDI reveals weak relationships, consistent with findings from Yin et al.[20]. By extracting TVDI values for different land use types, results show that unused land, cultivated land, and construction land have higher TVDI values, while forest land, grassland, and water bodies have lower values, indicating strong correlations between land use type and TVDI, consistent with Li et al.[21]. Analysis of annual average drought spatial distribution shows severe drought in central Xinjiang, consistent with Qin et al.[22]. Correlation analysis between elevation and TVDI demonstrates a strong negative correlation, consistent with Chen et al.[23]. Results indicate that unused land is prone to drought, while increasing forest and grassland coverage helps alleviate drought, consistent with Jiang et al.[24]. Although future drought conditions in Xinjiang are expected to ease, potential drought risks still require attention. With ongoing global warming, Xinjiang continues to face severe drought challenges[25].

When analyzing correlations between meteorological factors and TVDI, this study used annual average temperature, annual precipitation, and TVDI. However, Xinjiang' s complex terrain and vast territory result in significant spatial heterogeneity of meteorological factors. Under these conditions, single annual averages may not fully capture subtle characteristics and local differences in drought variation, especially across different terrain conditions and climate zones, where complex interactions may exist between meteorological factors and TVDI. Future research could consider introducing more detailed temporal data, analyzing seasonal and monthly data to reveal dynamic relationships between meteorological factors and TVDI.

TVDI is a reliable method for monitoring drought conditions, though its accuracy decreases in low vegetation cover or bare soil areas. Future work will consider using enhanced vegetation indices or auxiliary data to improve drought monitoring precision.

4 Conclusion

This study constructed the TVDI feature space to calculate TVDI as an effective drought monitoring indicator for analyzing spatial distribution and evolution trends of drought in Xinjiang. By examining relationships between drought and meteorological factors, land use types, and elevation, the main conclusions are:

1) From 2001 to 2020, Xinjiang experienced mild drought conditions overall, with a mean TVDI of 0.58. TVDI decreased at a rate of 0.0017 per year, indicating alleviating drought conditions. Drought-affected areas are concentrated in the Tarim Basin, Kunlun Mountains, and Junggar Basin, with southern Xinjiang experiencing larger drought areas and higher intensity than northern Xinjiang.

2) Based on Theil-Sen Median trend analysis and Mann-Kendall test, regions with $\beta <$ -0.001 that passed significance testing account for 25.5% of Xinjiang' s total area, indicating improved drought conditions. Hurst index analysis shows that persistently wetting regions account for 55.5% of Xinjiang' s total area, regions with past drying trends that will become wetter account for 25.5%, regions with past wetting trends that will become drier account for 10.8%, persistently drying regions account for 4.6%, and essentially unchanged regions account for 3.6%.

3) TVDI shows weak correlation with meteorological factors but strong correlation with elevation. The Pearson correlation coefficient between TVDI and annual precipitation is -0.25, and with annual temperature is 0.21. Unused land is prone to drought, while increasing forest and grassland coverage is beneficial for drought mitigation.

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