# ASSESSING THE IMPACT OF TOPOGRAPHIC FACTORS ON THE ECOSYSTEM CLIMATE SENSITIVITY OF THE CHINESE LOESS PLATEAU

XU, Q. F.[1] – YU, R. Y.[2] – GUO, L. L.[1*]

[1]*Yellow River Engn Consulting Co Ltd, Zhengzhou 450003, P. R. China*
*(e-mail: xqflol@163.com;ORCID: 0009-0000-6087-0874)*

[2]*College of Land Science and Technology, China Agricultural University, Beijing 100193, P. R. China*

[*]*Corresponding author*
*e-mail: maboite000@163.com*

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**Abstract.** There is strong heterogeneity and gradient in various environmental variables in different terrains, resulting in a microclimate zone that deviates from the regional climate, and its impact on ecosystem function is very complex. Based on long-term moderate-resolution imaging spectroradiometer (MODIS) datasets, terrain and vegetation data of Chinese Loess Plateau, we estimate the ecosystem climate sensitivity under different terrain conditions. Our results show that, the ecosystem precipitation sensitivity is significantly higher than the temperature sensitivity in the Loess Plateau. The regional net primary productivity (NPP) shows a significant positive correlation with the precipitation more than 47.41% areas in the Loess Plateau, while with the temperature accounts for 2.06%. The precipitation sensitivity is the highest in flat territory with an average altitude around 2200 meters. Water deficit restricts the growth of plants in the temperate meadow at the middle altitude more seriously than in alpine meadow and deciduous broadleaf at high and low altitudes. With the increase of altitude and terrain position index, the precipitation sensitivity has an obvious linear trend of increasing first and then decreasing. This result can provide an important reference for us to delimit key environmental protection areas in the Loess Plateau and predict climate sensitivity.
**Keywords:** *topography, net primary productivity, climatic controls, ecosystem sensitivity, elevational gradients*

## Introduction

With the frequent occurrence of extreme climate events in the world, climate change has significantly affected the productivity and water use pattern of terrestrial ecosystems (Piao et al., 2013; IPCC, 2014; Huang et al., 2015). It is an important consideration to estimate the sensitivity of ecosystems to climate for natural environmental protection, thus providing help for climate adaptation (Keppel et al., 2015; Xu et al., 2020). The difference can be partly attributed to landscape heterogeneity between predictions of existing models and ground observations, which is driven by terrain complexity (Pappas et al., 2015; Novick et al., 2016). Environmental variables generate strong heterogeneity and gradients in different terrains, and its impact on ecosystem functions is very complex (McLaughlin et al., 2017). In order to reliably predict whether hillslope topography can produce hydrologic refugia in the earth system model, there is an urgent need to assess the impact of topography on ecosystem productivity and climate sensitivity (Hoylman et al., 2019; Tai et al., 2020).

Topographic factors are important factors that directly or indirectly control the fine-scale abiotic conditions experienced by vegetation under similar regional climate


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conditions, such as elevation and topographic fluctuation (Hoylman et al., 2018). In many semi-arid ecosystems, plant productivity is limited by underground water use efficiency, which is determined by regional hydrologic conditions, including runoff, evaporation, etc. (Hoylman et al., 2019). Topographically driven hydrological processes (e.g., the lateral flow of soil water and groundwater from ridge to Valley) alter the climatic distribution of water in complex landscapes (Fan et al., 2015). However, these processes may help improve vegetation moisture and productivity, but not all. This may depend on the location and topology of local hillside topography and soil characteristics in the area (Hoylman et al., 2018). Therefore, on the hillside scale, the water availability of vegetation may change widely, forming a microclimate area deviating from the regional climate (Goldsmith et al., 2017; Xue et al., 2019; Li et al., 2020).

Global studies have recorded stability assessments of ecosystem productivity in response to various climate changes, mainly including temperature, precipitation, solar radiation and other factors (Seddon et al., 2016; Li et al., 2019). Under the interference of different external driving factors, the state of the ecosystem can change gradually and smoothly, or it may change suddenly due to exceeding the regulation limit (Li et al., 2020). However, it was not clear how the microclimate zone caused by special terrain interacted with and wide geographic areas of the productivity and water patterns. The influence of complex terrain on ecosystem stability has become an important topic in the field of ecology and hydrology (Dobrowski et al., 2011; McLaughlin et al., 2017).

The Loess Plateau is located in the mid-north part of China, which is one of the four major plateaus in China. According to the different dominant species, the vegetation composition is divided into temperate meadow, temperate steppe, desert shrub, deciduous shrub and so on. The main geomorphic type is ditch, and the terrain fluctuates greatly, which makes the soil erosion very seriously, and the ecological environment needs to be improved urgently in this area. It is worth noting that since the 1990s, China has formulated a series of ecological protection plans for the Loess Plateau, such as the plan for returning farmland to forests (Li et al., 2017; Zhang et al., 2020). Under the trend of global climate change, the sensitivity of plateau ecosystems to climate change has also received widespread attention (Ma et al., 2017; Xue et al., 2019). It is necessary to study whether the ecosystem climate sensitivity of the Loess Plateau is highly dependent on the terrain, so as to formulate policies for large-scale plateau management and climate change adaptation.

The complex terrain of the Loess Plateau provides an ideal place to study how the terrain factors influence the ecosystem climate sensitivity. Remote sensing data such as moderate-resolution imaging spectroradiometer (MODIS) provide a great convenience for long-term ecological monitoring at the regional scale (Zheng et al., 2019). Our objectives are: (1) to quantify the ecosystem climate sensitivity on the Loess Plateau (2) to analyze the impact of different topographic factors (elevation, terrain position index (TPI) and terrain wetness index (TWI)) on the ecosystem climate sensitivity (3) to investigate the distribution of different vegetation types on the terrain and their ecosystem climate sensitivity. The research results will improve our understanding of ecosystem functions mediated by hillside hydrological processes, and further provide important references for ecosystem management and protection in complex terrain areas.


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## Materials and Methods

### *Study area*

Loess Plateau is located in the arid and semi-arid areas of northern China, covering an area of about 640000 square kilometers. The elevation range of this area is about 90 m to 4945 m. The main geomorphic type of this area is ditch, with large topographic relief (*Fig. 1a*). The main vegetation components include temperate meadow, temperate steppe, desert shrub, deciduous shrub, needle leaf, deciduous broadleaf and alpine meadow, of which temperate meadow accounts for the largest proportion (*Fig. 1b*). The annual average temperature of the Loess Plateau is 3.6-14.3°C, which is characterized by cold winter and warm summer (*Fig. 1c*). The annual average precipitation is 400-600 mm, mainly concentrated in 60 mm from June to August (*Fig. 1d*) (Tang et al., 2018). At the same time, most precipitation events are high-intensity rainstorms (Wen et al., 2020).

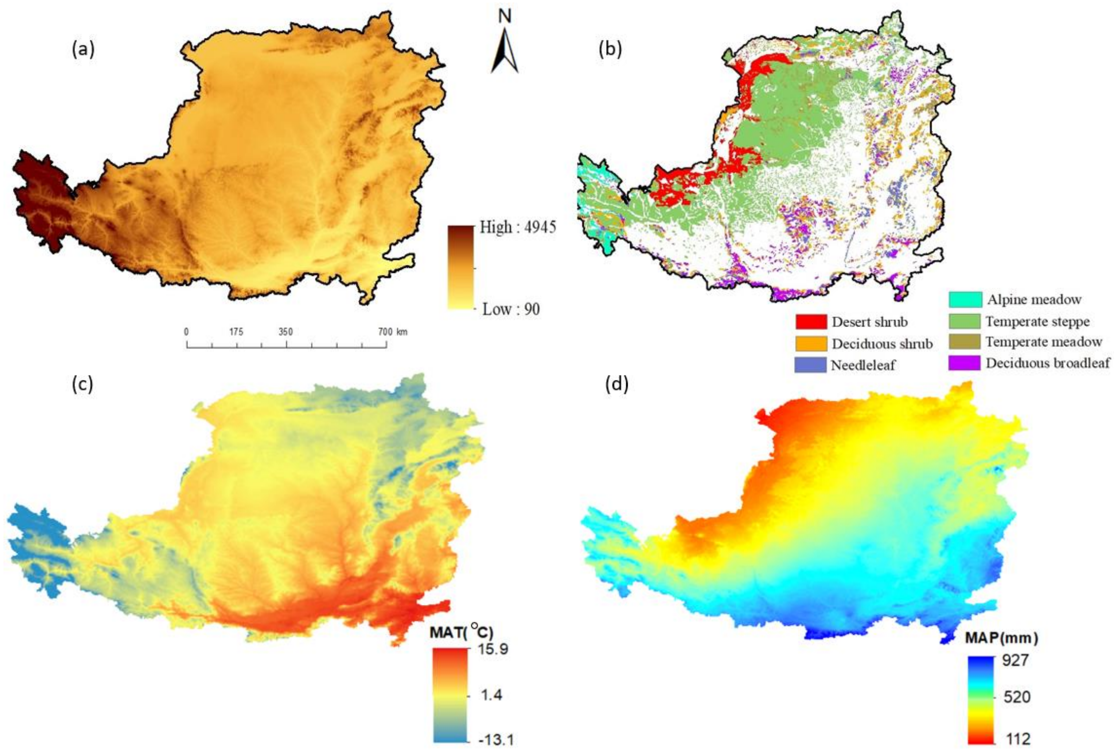


***Figure 1.*** *The elevation, vegetation types, and climate of Loess Plateau: (a)elevation; (b) vegetation types; (c) mean annual temperature (MAT); (d) mean annual precipitation (MAP)*

### *Data source and pre-processing*

Long-term remote sensing data of Loess Plateau are from MODIS data products of net primary productivity (NPP) (MOD17A3) (http://www.ntsg.umt.edu) with a spatial resolution of 1 km and a time period from January 1, 2001, to December 31, 2020 monthly. MODIS NPP algorithm is based on the logic of radiation utilization efficiency. It calculates the difference between annual NPP as annual Gross primary productivity (GPP) and annual autotrophic respiration (including annual growth respiration and annual maintenance respiration of leaves, fine roots and living cells in woody tissue) (Zheng et al., 2019).


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Meteorological data are from the Chinese Tibetan Plateau data center, including precipitation and temperature (data.tpdc.ac.cn/) (Peng et al., 2017a,b, 2019). The data were generated from the global 0.5° climate data set and the global high-resolution climate data set released by WorldClim through the Delta spatial downscaling scheme in China, which were verified by data from 496 independent meteorological observation points (Peng et al., 2017b; Ding et al., 2020).

The vegetation type data of the Loess Plateau is from the website of the resources and environment science and data center of the Chinese Academy of Sciences (https://www.resdc.cn/data.aspx?DATAID=122). The spatial distribution data is from the 1:1 million Chinese Vegetation Atlas.

The digital elevation model (DEM) data used is from the resources and environment science and data center of the Chinese Academy of Science (https://www.resdc.cn/data.aspx?DATAID=123), and the spatial distribution data is from the Radar Topography Mission (SRTM) data of the US space shuttle Endeavour, with a resolution of 1km. SRTM data has the advantages of strong reality and free access. Many researches use SRTM data to carry out environmental analysis. This data set is generated by resampling based on the latest SRTM v4.1 data, including the data of one map of the country with the accuracy of 1km, 500m and 250m. WGS84 ellipsoid projection was used for data.

### *Methods*

Then, terrain position index (TPI) and terrain wetness index (TWI) are calculated according to DEM. TPI has been applied by researchers to the classification of hydrological landform and slope position categories, representing the difference between the elevation value of each unit and the average elevation of the surrounding units. A positive value means that the unit is higher than the surrounding units, while a negative value means that it is lower than the surrounding units. When the TPI value is close to zero, the unit may be located on the flat land or on the hillside (Tai et al., 2020). TWI is an important quantitative indicator of convection path length, runoff area and soil runoff generation capacity based on digital elevation model (DEM) and has been widely used as a substitute indicator of water availability induced by lateral drainage (Weiss, 2001; De Reu et al., 2013).

The TPI calculation method is the minus operation between the elevation of the center point ($Z_0$) within the predetermined radius and the average value of the elevation within the predetermined radius.

$$TPI = z_0 - \sum_{i=1}^{n} z_i \qquad \text{(Eq.1)}$$

where *n* represents the number of DEM grids within radius; $Z_i$ represents the elevation at the corresponding grid (Weiss, 2001).

TWI is obtained by the interaction of the contribution of the fine-scale topography and the upper gradient to the surface area according to the following relationship (Beven et al., 1979):

$$TWI = ln \frac{\mathrm{CA}}{\tan\beta} \qquad \text{(Eq.2)}$$


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where CA is the local uphill catchment area drained through the grid cell, and tanβ is the steepest outward slope of each grid cell, that is, the tan value of the slope angle (Tarboton, 1997).

In order to evaluate the ecosystem climate sensitivity of the Loess Plateau, we used Person correlation analysis to analyze the relationship between ecosystem productivity and climate factors from 2001 to 2020. The specific calculation method is as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad \text{(Eq.3)}$$

where $X_i$ is the annual ecosystem NPP, $\bar{x}$ is the average value of ecosystem NPP from 2001 to 2020, $Y_i$ is the cumulative value of annual climate factors, and $\bar{y}$ is the average value of climate factors from 2001 to 2020.

In order to further evaluate the impact of topography on the climate sensitivity of ecosystems, we analyzed the ordinary least square regression method between the climate sensitivity of ecosystems and the terrain factors in the Loess Plateau and calculated the linear trend of different terrain factors and the ecosystem climate sensitivity during 2001-2020.

## Results

### *Ecosystem climate sensitivity of the Chinese Loess Plateau*

In general, the precipitation sensitivity significantly higher than temperature sensitivity in Loess Plateau (*Fig. 2*). In more than 47.41% areas of the Loess Plateau, the regional NPP shows a significant positive correlation (r>0.6) with the precipitation change, while the regional NPP shows a obvious positive correlation with the temperature variations within 2.06% areas. The proportion of regions with weak correlation (-0.2>r>0.2) is 24.72% between NPP and precipitation change, and more than 80.57% of regions with weak correlation between NPP and temperature variations. There is no significant negative correlation between both temperature and precipitation with NPP (r<-0.6).

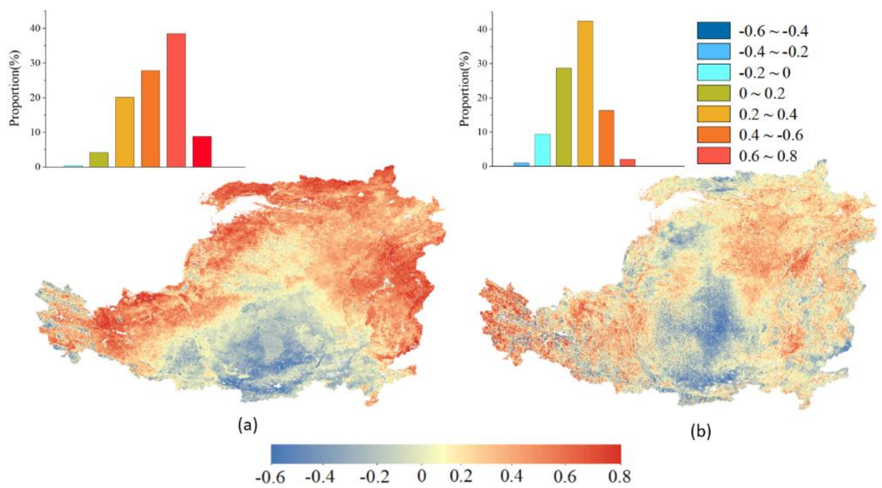


***Figure 2.*** *Ecosystem climate sensitivity of the Loess Plateau from 2001 to 2020: (a) precipitation sensitivity; (b) temperature sensitivity*


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In terms of regional distribution, the precipitation sensitivity is the highest in the northeast and northwest of the Loess Plateau, the temperature sensitivity of the western high-elevation area is relatively higher, and the NPP of the southern area is weakly sensitive to both temperature and precipitation (*Fig. 2*).

### *Impact of different topographic factors on the ecosystem climate sensitivity*

The ecosystem climate sensitivity is analyzed by three topographic factors of elevation, TPI and TWI. Due to the low temperature sensitivity in this area, we only analyze the impact of terrain factors on precipitation sensitivity (*Fig. 3*). The precipitation sensitivity increases with the elevation from 850 m to 2200 m above sea level ($R^2$ = 0.84, slope = $1.36\times10^{-4}$), and decreases with the elevation above 2200 m ($R^2$ = 0.82, slope = $-2.23\times10^{-4}$). In terms of TPI, similarly with the elevation, the precipitation sensitivity showed a trend of first increasing and then decreasing, and the precipitation sensitivity reaches the maximum value in the range of – 10 m to 5 m. The interval of linear increase is from – 120 m to 0 m ($R^2$ = 0.69, slope = $5.97\times10^{-4}$), and the interval of linear decrease is from 0 m to 120 m ($R^2$ = 0.69, slope = $-6.09\times10^{-4}$). TWI has an obvious linear increasing trend ($R^2$ = 0.63, slope=0.93) in the range of -1.97 to 1.92, and irregular fluctuation occurs beyond this range.

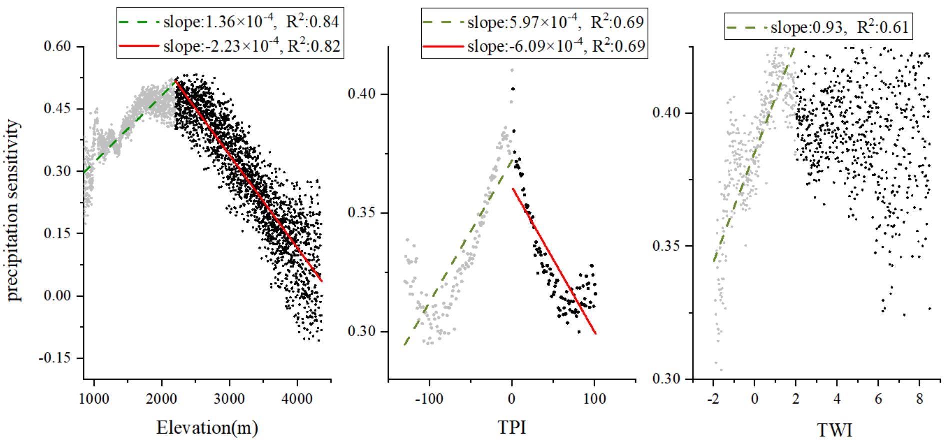


***Figure 3.*** *Variation of precipitation sensitivity along different terrain factor gradients (elevation, TPI and TWI)*

### *Distribution and ecosystem climate sensitivity of different vegetation types on the terrain*

Among all vegetation types, it can be clearly found that the vegetation is most widely distributed around 1500 m elevation and 0m TPI (*Fig. 4*). In the area with elevation of less than 3000 m, the vegetation composition includes six types: temperate meadow, temperate steppe, desert shrub, deciduous shrub, needle leaf and deciduous broadleaf. The number of temperate meadow is absolutely dominant, and the other five types are relatively less. The vegetation types above 3000 m elevation mainly include alpine meadow and deciduous shrub, while alpine meadow is the few vegetation type above 3500 m. The temperate meadow is absolutely dominant in the range of TPI from -75 to 75 m. When the TPI is lower than -75 m or higher than 75 m, the vegetation types consists largely of deciduous broadleaf and deciduous shrub. At the level of vegetation type, the


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precipitation sensitivity of desert shrub (0.55±0.07) is the highest, while that of alpine meadow (0.23±0.07) and deciduous broadleaf (0.24±0.12) is lower (*Fig. 5*). The precipitation sensitivity of the other four vegetation types is as follows: temperate meadow (0.44±0.06), temperate steppe (0.41±0.06), needle leaf (0.38±0.07), deciduous shrub (0.37±0.03).

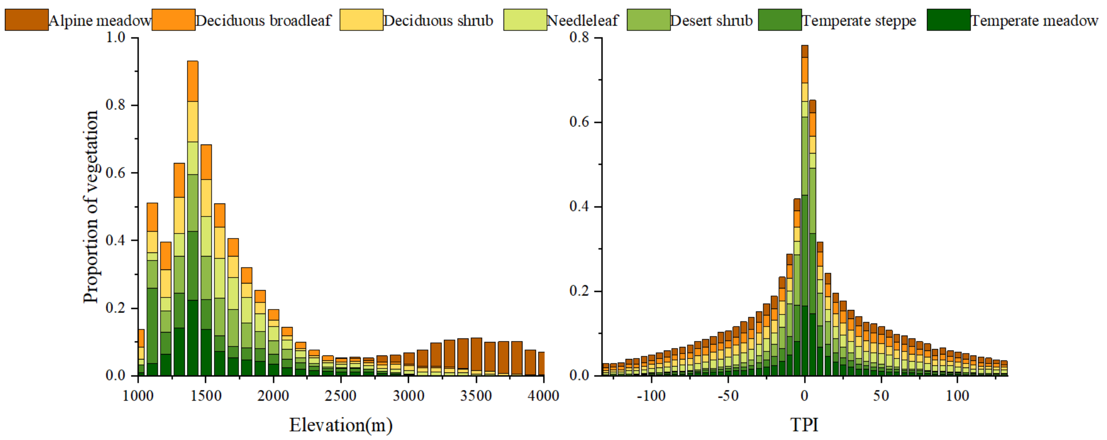


***Figure 4.*** *Distribution of various vegetation types at elevation and TPI*

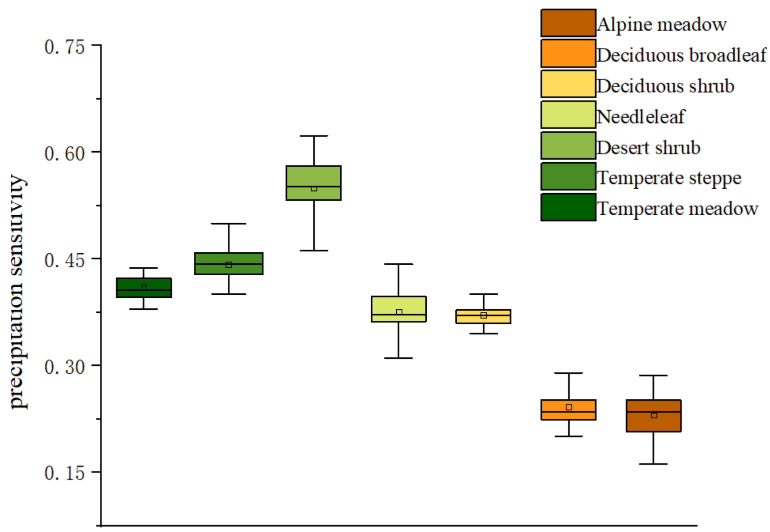


***Figure 5.*** *The variation of precipitation sensitivity for different biomes. Boxplot elements: box = values of 25th and 75th percentiles; horizontal line = median; dote = mean; whisker = ±SD*

## Discussion

### *Spatial heterogeneity of climate sensitivity in the Loess Plateau*

The Loess Plateau is located in arid and semi-arid areas. The sensitivity of mountainous environments to climate factors is consistent with research findings in western mountainous areas of the United States and the Qilian Mountains in China, indicating sensitivity to semi-arid climates caused by changes in precipitation (Hoylman et al., 2019; Xue et al., 2019). From *Figure 5*, we can find that the precipitation sensitivity of temperate meadow and temperate grassland is similar, but that of alpine meadow is


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significantly lower. This may be because water deficit has a more severe effect on the growth of plants in low elevation than that in high elevation. The temperate grassland in low elevation also increases the water demand and consumption of plants, which is under high average annual temperature. Therefore, temperate meadows in arid or semi-arid areas are highly sensitive to climate change, resulting in increased ecosystem sensitivity of grasslands (Li et al., 2020). Compared with the alpine grassland at high elevation, the temperate meadow occupies most of the area of the Loess Plateau (*Fig. 1b*), which makes the whole show obvious precipitation sensitivity (*Fig. 2*). In addition, the global warming trend may also further increase the precipitation sensitivity, because water availability strengthens the coupling between climate factors and NPP (Zhang et al., 2018).

According to the relevant research in the plateau area, the speed of the warming climate has increased at high altitudes, and the minor changes in air temperature may represent the thermal balance is affected in the cold area (Palazzi et al., 2017), which is the reason for the relatively high-temperature sensitivity in the high elevation area of the western Loess Plateau. At the same time, warming climate in high elevation areas can reduce the low-temperature limit and shorten the time of snow cover in winter, which is conducive to improving the growth rate of vegetation and directly stimulating the productivity of vegetation in alpine areas (Li et al., 2017b; Lamprecht et al., 2018). The southern plain has relatively sufficient water and heat conditions, high vegetation biodiversity and a broader climate niche. Therefore, it is less sensitive to both temperature and precipitation, with a strong ability to cope with climate change (Li et al., 2018).

### *Topographic differentiation of climate sensitivity of ecosystem*

By analyzing the impact of the gradient change of topographic factors on the climate sensitivity of the ecosystem, it can be found that the ecosystem climate sensitivity shows regular changes in elevation and TPI (*Fig. 3*). The peak of precipitation sensitivity is reached at the middle elevation around 2200 m on the Loess Plateau, while the precipitation sensitivity is relatively low at high and low altitudes. With the increase of elevation, it is an important reason that the common function variety of climate factors and vegetation type composition affect the ecosystem sensitivity (Hoylman et al., 2019; Liu et al., 2020). Comparing with the deciduous broadleaf, temperate meadow and temperate steppe in low elevation areas, the deciduous shrub at middle elevation has weak water holding capacity and lacks adaptability to extreme precipitation events (He et al., 2018). When the elevation continues to rise, the main species gradually replace deciduous shrub by alpine meadow, and the precipitation sensitivity decreases significantly. Thermal conditions become the main factors restricting the growth of vegetation (Xu et al., 2020).

Weathered bedrock has also been proved to be an important medium for water storage, which mainly exists in the higher position of the upper slope (Rempe et al., 2018). Vegetation can absorb water from weathered bedrock through roots, thus alleviating water shortage during drought. The presence of weathered bedrock reduces the precipitation sensitivity of plants (Fan et al., 2017). One theory that explains that the uphill and downhill positions can alleviate water deficit is that, when the terrain position with a certain uphill area has wet soil conditions, groundwater flow may be generated to supply water to the vegetation community at the downhill position (Jencso et al., 2009; Hwang et al., 2012). The atmospheric microclimate also occurs at the converging hillside, which helps to reduce the evapotranspiration level of soil and further buffer the impact of changes in soil moisture and groundwater (Hoylman et al., 2019).


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Vegetation in flat areas (TPI is about 0) is most sensitive to climate, which has also been found in other mountainous areas (Hoylman et al., 2019). The vegetation in the flat terrain of the Loess Plateau is dominated by temperate meadows and desert shrubs. It causes high demand for water in this area because of the scarcity of precipitation and the lack of water supply by the convergent hillslope positions with large upslope.

When it changes along the TWI gradient, the whole study area does not show the obvious linear relationship. The precipitation sensitivity in the low-value of TWI has an obvious linear increasing trend, and after exceeding this range, there is an irregular fluctuation. Although TWI reflects the soil water holding capacity and runoff that are critical to plant growth in the environment, the complex interaction of various abiotic and biological factors may also affect the ecosystem precipitation sensitivity (Tai et al., 2017).

### *Limitations and future work*

In this study, we found that precipitation is an important limiting factor for the Loess Plateau ecosystem, and the lack of precipitation will seriously affect the ecosystem productivity in that year. However, it shows that the response of vegetation to environmental factors such as precipitation and temperature lags, according to some research about the water use efficiency of vegetation during drought. When drought stress occurs, the drought of the previous year and this year will affect the water use efficiency of various vegetation types, including forests, shrubs and grasslands. The regionally averaged water use efficiency had a stronger correlation with drought in the previous year than with drought in the current year. Under normal water conditions, the lag effect of drought is not obvious (Heumann et al., 2007; Huang et al., 2015). This lag may produce uncertainty to our assessment of climate sensitivity.

In addition, long-term artificial vegetation restoration and natural processes such as climate change may lead to changes in vegetation species (Li et al., 2018; Peters et al., 2019). This will have a certain impact on our assessment of the ecosystem sensitivity of different vegetation types. At the same time, although artificial vegetation restoration has improved the ecological environment of the region, it may further aggravate the ecosystem sensitivity of the region to climate factors (Zhang et al., 2014; Li et al., 2019). Comparison of historical correlation between variables by combining two sets of climate models (CMIP6 multimode set and CESM multimode set) and climate sensitive data, it can further evaluate the climate sensitivity of the Loess Plateau in the future, so as to formulate corresponding ecological environment management strategies (Palazzi et al., 2017).

## Conclusions

In this study, we mainly used long-term moderate-resolution imaging spectroradiometer (MODIS) datasets to assess the impact of topographic factors on the ecosystem climate sensitivity of the Chinese Loess Plateau. Our results show that topographic factors, especially elevation and TPI, have an important impact on the climate sensitivity of the ecosystem. The Loess Plateau shows strong sensitivity to precipitation on whole, especially in the flat terrain at middle elevation. Water deficit restricts the growth of plants in the temperate meadow at the middle altitude more seriously than in alpine meadow and deciduous broadleaf at high and low altitudes. At the same time, the lack of water supply on the upper slope in the flat area is the main reason for the high level of precipitation sensitivity in this area. With the increase of


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elevation and TPI, the precipitation sensitivity has an obvious linear trend of increasing first and then decreasing. The territory is flat, with an average altitude around 2200 meters, the highest precipitation sensitivity. This result can provide an important reference for us to delimit key environmental protection areas and predict the climate sensitivity of the Loess Plateau in the future.

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