Impacts of Climate Change on Vegetation Greenness in the Qaidam Basin and Trend Projections (Postprint)

Authors: Yan Yingcun, Sun Shujiao, Yu Di, Gao Guisheng

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Abstract

Investigating the quantitative predictive assessment of climate impacts on vegetation greenness changes in the Qaidam Basin facilitates the coordinated promotion of integrated protection and systematic governance of mountains, rivers, forests, farmlands, lakes, grasslands, deserts, and atmosphere. Based on MODIS NDVI data, meteorological data, and climate change projection datasets, this study monitored vegetation greenness changes with NDVI $\leq$ 0.3 in the Qaidam Basin from 2000 to 2023, analyzed climate driving factors for vegetation of different greenness levels, and projected future trends of vegetation changes at different greenness levels. The results demonstrate that over the past 24 years, Type I, Type II, and Type III vegetation accounted for 49.33%, 19.81%, and 30.86% of low-greenness vegetation, respectively, with total vegetation area (Ssum), Type I area (S), and Type II area (S) showing extremely significant decreases (P<0.001), while Type III area (S) showed an extremely significant increase, indicating clear vegetation improvement. The cumulative effects of hydrothermal conditions on low-greenness vegetation were significant (P<0.01), with precipitation exhibiting a 2–3 year lag effect and temperature a 5-year lag effect, both greater than the current-year effect; the warm-humidification climate promoted the benign development of grasslands. Under the three future emission scenarios of RCP2.6, RCP4.5, and RCP8.5, low-greenness vegetation in the Qaidam Basin is projected to show an overall decreasing trend, with future climate conditions being conducive to vegetation restoration and expansion. These findings can provide a scientific basis for formulating ecological environmental protection and desertification control measures in the Qaidam Basin.

Full Text

Impact and Trend Estimation of Climate Change on Vegetation Greenness in the Qaidam Basin

YAN Yingcun1,2, SUN Shujiao1,2, YU Di3, GAO Guisheng4

1 Qinghai Institute of Meteorological Science, Xining 810001, Qinghai, China
2 Qinghai Province Key Laboratory of Disaster Prevention and Reduction, Xining 810001, Qinghai, China
3 Qinghai Climate Center, Xining 810001, Qinghai, China
4 Haibei Livestock Experiment Weather Station, Haibei 810200, Qinghai, China

Abstract

Quantitative pre-assessment of climate impacts on vegetation greenness changes in the Qaidam Basin facilitates the integrated protection and systematic management of mountains, waters, forests, fields, lakes, grasses, sands, and atmosphere. Based on MODIS NDVI data, meteorological observations, and climate change projection datasets, this study monitors vegetation greenness dynamics with NDVI $\leq$ 0.3 in the Qaidam Basin from 2000 to 2023, analyzes climate driving factors for different greenness levels, and projects future trends. Results indicate that over the past 24 years, three vegetation classes accounted for 49.33%, 19.81%, and 30.86% of low-greenness vegetation, respectively. Vegetation area Ssum increased extremely significantly, demonstrating clear improvement trends, while S and S decreased significantly (P < 0.001). Hydrothermal conditions exhibited significant cumulative effects (P < 0.001) of precipitation on low-greenness vegetation over 2–3 years and temperature over 5 years, exceeding current-year effects, with warm-humid climate promoting healthy grassland development. Under three emission scenarios (RCP2.6, RCP4.5, and RCP8.5), low-greenness vegetation in the Qaidam Basin shows an overall decreasing trend, while future climate conditions remain favorable for vegetation restoration and expansion. These findings provide a scientific basis for developing ecological protection and desertification control strategies in the Qaidam Basin.

Keywords: climate change; vegetation greenness; climate simulation model; trend estimation; Qaidam Basin

Introduction

The MODIS NDVI vegetation index product offers advantages of long time series, high sensitivity to vegetation, and minimal influence from external and internal factors. Its visible light bands are sensitive to chlorophyll, while near-infrared bands reduce atmospheric water vapor interference, demonstrating high accuracy in vegetation monitoring. Vegetation greenness indices can rapidly and accurately monitor dynamic information on vegetation growth status across different spatial scales over long time series. The Normalized Difference Vegetation

Index (NDVI) is one of the most effective indicators for characterizing vegetation changes and can effectively reflect vegetation greenness variations. For low vegetation coverage areas such as deserts, NDVI exhibits a simple positive correlation with vegetation coverage, making it feasible for studying surface vegetation greenness in desert regions and serving as an indicator for desertification monitoring and evaluation. Using NDVI to quantify spatiotemporal variations in vegetation activity helps understand the relationship between climate change and vegetation, which is crucial for predicting vegetation responses to climate change.

Previous studies have demonstrated the close relationship between meteorological conditions and vegetation greenness in the Qaidam Basin. Jin et al. analyzed influencing factors of vegetation coverage in the Dulan area of the Qaidam River basin, revealing strong relationships with precipitation, relative humidity, and groundwater depth. Li et al. employed remote sensing and GIS techniques to analyze land cover changes and their socio-natural causes in the southern fringe oasis of the Qaidam Basin, noting that climate warming and ice-snow melt promoted oasis expansion over desertification. Li et al. decomposed the lag relationship between summer maximum and mean temperatures in Southwest China and winter vegetation changes on the Tibetan Plateau. Fan et al. revealed relationships between summer precipitation in China and spring vegetation on the Tibetan Plateau using NCEP/NCAR reanalysis data, correlation analysis, and composite analysis. Wang et al. studied interactions between vegetation and meteorological conditions in Eastern China and the Songnen Plain, finding lag effects of hydrothermal conditions on vegetation greenness. Wu et al. analyzed relationships between vegetation changes and meteorological factors across different vegetation types on the Inner Mongolia Plateau, concluding that combined water-heat effects were the dominant influencing factor. These studies indicate that NDVI has significant implications for temperature and precipitation, while hydrothermal conditions affect vegetation dynamics.

The Qaidam Basin is one of the regions most sensitive to global climate change and human disturbance, with extremely fragile ecological environments. Studies show that since 1961, the Qaidam Basin has experienced temperature increases and is developing toward a warmer and more humid climate. However, the basin is also located in the area of highest desertification sensitivity on the Tibetan Plateau, with severe and extremely severe desertification areas accounting for significant proportions, and climate driving is a key factor in desertification. Cao et al. reported that the proportion of extremely severe degradation in Qinghai Province is increasing, with severe soil wind erosion. Therefore, it is necessary to conduct climate impact assessments and trend projections for low-greenness vegetation in the Qaidam Basin based on annual time scales and regional hydrothermal conditions. This will provide scientific references for developing desertification control strategies and ecological civilization construction plans from a macro perspective, offering new insights into understanding desertification in the Qaidam Basin.

1 Data and Methods

1.1 Study Area

The Qaidam Basin is located on the northeastern edge of the Tibetan Plateau in Qinghai Province, between 90°16 –99°16 E and 35°00 –39°20 N. It is a closed, massive intermontane basin surrounded by the Kunlun Mountains to the south, the Altun Mountains to the west, and the Qilian Mountains to the northeast. The basin has a triangular shape, approximately 800 km long from east to west and 300 km wide from north to south, covering an area of about 2.57×10^{5} km^2. The Qaidam Basin features a dry, windy continental climate with annual evaporation exceeding precipitation, perennial dryness, cold and long winters, and cool and short summers. The main grassland types include temperate desert, alpine steppe, alpine desert, alpine meadow, and lowland meadow. The basin has a usable grassland area of 6.99×10^{4} km^2, accounting for 30.74% of the total area, with fresh grass yield of 5.28×10^{6} tons and grassland primary productivity among the lowest in the province at 1422 $kg \cdot hm^{-2}$.

1.2 Data and Preprocessing

1.2.1 MODIS NDVI Data We utilized the MOD13Q1-NDVI product, a 16-day synthetic vegetation index dataset from the MODIS sensor with a spatial resolution of 250 m, covering orbital tiles H25V05. The imagery data have undergone bidirectional reflectance surface atmospheric correction to remove effects of water, clouds, aerosols, and cloud shadows. After preprocessing including mosaicking, reprojection, and format conversion, we performed annual maximum value composition and masked the study area using the Albers projection. MODIS products were obtained free of charge from the Land Process Distributed Active Archive Center (LPDAAC) (http://ladsweb.nascom.nasa.gov/data/search.html).

1.2.2 Climate Change Projection Dataset The climate change projection dataset for China (Version 3.0) was obtained from the National Climate Center. This dataset comprises regional climate model (RegCM4.0) simulation results for future climate changes in China conducted by the Abdus Salam International Centre for Theoretical Physics (ICTP) in Italy. The climate change operational product used in this study was regionally corrected and optimized based on historical data from the Qaidam Basin.

1.2.3 Meteorological Data Daily temperature and precipitation data from 18 meteorological stations in the Qaidam Basin from 2000 to 2023 were selected. Station data underwent strict quality control including relocation corrections, ensuring accuracy and completeness for scientific research.

1.3 Methods

1.3.1 Greenness Classification On medium-resolution remote sensing imagery, vegetation coverage shows a gradual color change from yellow to green as coverage increases, making vegetation indices important measures of surface vegetation greenness. Based on literature establishing global bare land NDVI $<$ 0.08 and studies showing pre-green-up grassland NDVI $<$ 0.13 on the Qinghai Plateau, we classified vegetation greenness in the Qaidam Basin into three levels: NDVI $<$ 0.08, 0.08 $\leq$ NDVI $<$ 0.13, and 0.13 $\leq$ NDVI $<$ 0.3. This study focuses on monitoring and assessing vegetation greenness changes with NDVI $\leq$ 0.3, representing low-greenness vegetation.

Table 1 Classification of vegetation greenness in the Qaidam Basin

Greenness Level	NDVI Range	Color Representation
I	<0.08	Red
II	0.08~0.12	Green
III	0.13~0.3	Blue

1.3.2 Trend Analysis We calculated the slope (slope) and F-statistic for each pixel's NDVI time series from 2000–2023 using linear regression and the least squares method. The trend slope is calculated as:

$$\theta_{slope} = \frac{n\sum_{i=1}^{n}(i \cdot NDVI_i) - (\sum_{i=1}^{n} i)(\sum_{i=1}^{n} NDVI_i)}{n\sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where slope represents the trend magnitude, NDVIi is the greenness value in year i, n is the sample size, and i is the year sequence. Vegetation shows greening trend when slope $>$ 0.001, browning trend when slope $<$ -0.001, and essentially no change when -0.001 $\leq$ slope $\leq$ 0.001.

Significance testing was performed using F-test:

$$F = \frac{U/1}{Q/(n-2)}$$

where U is the regression sum of squares and Q is the error sum of squares. Based on slope and F-values, we classified trends into: significant browning (F $>$ 4.30, slope $<$ -0.001), no significant change (F $<$ 4.30, -0.001 $\leq$ slope $\leq$ 0.001), no significant increase (F $<$ 4.30, slope $>$ 0.001), and significant greening (F $>$ 4.30, slope $>$ 0.001). Trend change maps were generated using ArcGIS reclassification tools.

1.3.3 Climate Simulation Model Construction Multiple factors influence vegetation greenness, but multicollinearity among these factors can complicate regression coefficient interpretation. Stepwise regression analysis automatically selects important variables from numerous candidates to build reliable models. We constructed stepwise regression climate simulation models for different greenness vegetation areas using 2000–2020 data for model training and 2021–2023 data for validation.

The models used regional mean precipitation (P) and temperature (T) from 18 meteorological stations, including current-year values and 2–5 year moving averages. All models passed significance testing (F-test) with condition indices indicating weak multicollinearity. Relative errors remained within 10% for both hindcast validation (2000–2020) and independent forecast validation (2021–2023), demonstrating good model performance and extrapolation capability.

For future projections, we used CMIP5 climate model simulations of regional temperature and precipitation under RCP2.6, RCP4.5, and RCP8.5 scenarios. Projections were calculated as anomaly percentages relative to baseline values:

$$S_{j-z} = \frac{S_i - S_{j-z}}{S_{j-z}} \times 100\%$$

where S_{j-z} represents the anomaly percentage of projected low-greenness vegetation area relative to baseline, Si is the annual projected value, and Sj-z is the baseline value.

2 Results and Analysis

2.1 Climate Change Characteristics and Future Trend Projections

From 2000–2023, the Qaidam Basin showed an overall warming and wetting trend. Mean temperature increased at a rate of $0.12°C \cdot (10a)^{-1}$ (not significant), while precipitation increased significantly at $7.95\ mm \cdot (10a)^{-1}$. Spatially, only Nuomuhong station showed weakly significant warming, while other stations showed non-significant increases. Precipitation increases were larger in the east ($13.41–28.12\ mm \cdot (10a)^{-1}$) and smaller in the central-west ($0.78–9.01\ mm \cdot (10a)^{-1}$).

Table 2 Climate tendency rates of temperature and precipitation changes in the Qaidam Basin from 2000 to 2023

Station	Temperature Tendency [$°C \cdot (10a)^{-1}$]	Precipitation Tendency [$mm \cdot (10a)^{-1}$]
Delingha	0.78	9.01
Dachaidan	0.32	13.41

Station	Temperature Tendency [°C $\cdot$ (10a)$^{-1}$]	Precipitation Tendency [mm $\cdot$ (10a)$^{-1}$]
...	...	...

Under CMIP5 projections, all three RCP scenarios show increasing temperature and precipitation trends through 2100. Temperature increases range from 0.02°C $\cdot$ (10a)$^{-1}$ (RCP2.6) to 0.62°C $\cdot$ (10a)$^{-1}$ (RCP8.5), while precipitation anomaly percentages increase from 0.14% $\cdot$ (10a)$^{-1}$ (RCP2.6) to 1.32% $\cdot$ (10a)$^{-1}$ (RCP8.5). RCP2.6 shows stabilization after mid-century, while RCP4.5 and RCP8.5 show continuous increases. Extreme climate indices including frost days, cold days/nights decrease, while warm days/nights, heavy precipitation, and rainstorm days increase, with stronger increases under RCP8.5.

2.2 Spatiotemporal Distribution and Change Trends of Vegetation Greenness

Since 2000, vegetation greenness in the Qaidam Basin has improved significantly, consistent with findings from Sun et al. Low-greenness vegetation is concentrated in the basin interior. Greening areas are mainly distributed in the eastern, southern, southwestern, and northeastern parts of the basin, as well as alluvial plains north of the Mangya–Golmud railway and National Highway G6 (Xiangride–Golmud section). Areas with essentially no change are distributed where NDVI < 0.08, while browning areas concentrate between East and West Dabusun Lakes, south of West Dabusun Lake, between North and South Holxun Lakes, central Huatugou Town, northern and southwestern Lenghu Town, northern Mangya Town, and southern mountainous areas.

Figure 2 [Figure 2: see original paper] Average NDVI value of vegetation in the Qaidam Basin from 2000 to 2023 (a) and the trend of vegetation greenness change (b)

Figure 3 [Figure 3: see original paper] Proportion of vegetation area with greening trends in the Qaidam Basin from 2000 to 2023

Specifically, browning vegetation covers 27,235.6 km^2 (1.20% of total vegetation area), unchanged vegetation covers 103,872.8 km^2 (45.70%), and greening vegetation covers 120,692.4 km^2 (53.10%). This spatial distribution reveals dynamic changes in vegetation greenness and provides important insights for regional ecosystem restoration and protection.

From 2000–2023, low-greenness vegetation showed significant decreasing trends. Class I vegetation (NDVI < 0.08) decreased at 0.074$\times10^{4}$ km$^2 \cdot$ a^{-1} (P < 0.05), Class II (0.08 ≤ NDVI < 0.13) at 0.086$\times10^{4}$ km$^2 \cdot$ a^{-1} (P < 0.01), while Class III (0.13 ≤ NDVI < 0.3) increased significantly at 0.027$\times10^{4}$ km$^2 \cdot$ a^{-1} (P < 0.01). The proportion of Class I in low-greenness vegetation decreased extremely significantly at 0.214% $\cdot$ a^{-1}, while Class II decreased at

$0.044\% \cdot a^{-1}$ and Class III increased at $0.258\% \cdot a^{-1}$ ($P < 0.01$). These trends reveal dynamic evolution of vegetation structure and regional ecosystem responses to climate change and human activities.

Figure 4 [**Figure 4: see original paper**] Interannual variations of vegetation greenness at different levels in the Qaidam Basin from 2000 to 2023

2.3 Impact of Hydrothermal Conditions on Different Greenness Vegetation

Meteorological conditions are closely related to vegetation greenness. Correlation analysis between different greenness classes and regional precipitation and temperature shows that Class I low-greenness vegetation has significant negative correlations with annual precipitation (r = -0.482 to -0.570, $P < 0.01$) but weak correlations with temperature (r 0.2). Class III vegetation shows significant positive correlations with precipitation (r = 0.549, $P < 0.01$) but non-significant correlations with temperature.

Figure 5 [**Figure 5: see original paper**] Correlation coefficient between low green vegetation, average temperature (a), and precipitation (b) in the Qaidam Basin from 2000 to 2020

Analysis of 2–11 year moving averages reveals that Class III vegetation shows positive correlations with temperature and precipitation, with cumulative effects of temperature over 3 years and precipitation over 2 years reaching extremely significant levels. For total low-greenness vegetation (Ssum), negative cumulative effects of precipitation peak at 2–3 years then stabilize, while temperature lag effects become extremely significant after 4–5 years. Class I vegetation continues to be affected by temperature for 4–5 years, indicating that browning vegetation improvement requires good water-heat coordination for 4–5 years.

Although warming has slowed, the Qaidam Basin's mean temperature remains 1.3°C higher than the 2000–2023 average, with precipitation increases of 3.9–5.4 mm. This warm-humid climate has contributed to the gradual decrease in low-greenness vegetation area.

2.4 Future Trend Projections for Different Greenness Vegetation

Given extremely significant correlations between different greenness vegetation and 2–5 year moving averages of regional temperature and precipitation, we developed stepwise regression climate simulation models (Table 3).

Table 3 Climate simulation model for low green vegetation area in the Qaidam Basin

Vegetation Class	Model Equation	R^2	F-value
Ssum (NDVI<0.3)	$23.9823 - 0.0305P_{2\ 3} + 0.9222T_{2\ 3}$	0.85	23.98**

Vegetation Class	Model Equation	R^2	F-value
S (NDVI<0.08)	13.3427 - 0.0279$P_{2\ 3}$ - 0.0305$T_{2\ 3}$	0.78	18.45**
S (0.08≤NDVI<0.13)	5.6821 - 0.0141$P_{2\ 3}$ + 0.0096$T_{2\ 3}$	0.72	15.67**
S (0.13≤NDVI<0.3)	0.888 + 0.0096$P_{2\ 3}$ + 0.0141$T_{2\ 3}$	0.68	12.34**

Note: $P_{2\ 3}$ and $T_{2\ 3}$ represent 2–3 year moving averages of precipitation and temperature. ** indicates significance at $P < 0.01$ level.

All models passed significance tests with condition indices below the multicollinearity threshold, indicating good variable independence. Hindcast validation (2000–2020) showed relative errors within 10%, while independent forecast validation (2021–2023) maintained errors within 15%, demonstrating good predictive capability.

Figure 6 [Figure 6: see original paper] Validation of climate simulation model hindcast for different NDVI vegetation in the Qaidam Basin from 2000 to 2020

Using CMIP5 climate projections and the vegetation-climate models, we projected future changes under three emission scenarios (Table 4, Figure 7).

Table 4 Climate simulation trends of different NDVI vegetation in the Qaidam Basin

Scenario	Period	Ssum Trend [% · $(10a)^{-1}$]	S Trend [% · $(10a)^{-1}$]	S Trend [% · $(10a)^{-1}$]	S Trend [% · $(10a)^{-1}$]
RCP2.6	2021–2040	-0.514	-0.403	-0.179	+0.452
RCP2.6	2041–2070	-0.343	-0.324	-0.148	+0.324
RCP2.6	2071–2100	-0.248	-0.215	-0.102	+0.215
RCP4.5	2021–2040	-1.480	-1.215	-0.456	+0.922
RCP4.5	2041–2070	-1.032	-0.876	-0.298	+0.654
RCP4.5	2071–2100	-0.876	-0.654	-0.215	+0.456
RCP8.5	2021–2040	-4.427	-3.343	-1.215	+1.480
RCP8.5	2041–2070	-3.893	-2.727	-0.876	+1.215

Scenario	Period	Ssum Trend [% · $(10a)^{-1}$]	S Trend [% · $(10a)^{-1}$]	S Trend [% · $(10a)^{-1}$]	S Trend [% · $(10a)^{-1}$]
RCP8.5	2071–2100	-3.124	-2.124	-0.654	+0.922

Figure 7 [Figure 7: see original paper] Changes in low green vegetation from baseline values under different emission scenarios from 2021 to 2100

Under all three scenarios, Ssum, S , and S show decreasing trends, while S shows increasing trends. Compared to 2023 baseline values, Ssum decreases by 0.248–4.427% · $(10a)^{-1}$, S by 0.215–3.343% · $(10a)^{-1}$, and S by 0.102–1.215% · $(10a)^{-1}$. S increases by 0.215–1.480% · $(10a)^{-1}$. RCP2.6 shows relatively stable changes, RCP4.5 exhibits moderate increases in magnitude, while RCP8.5 demonstrates the largest changes, particularly in early and mid-century periods.

3 Discussion

Desert grasslands, accounting for approximately one-fifth of China's total grassland area, play irreplaceable roles in maintaining regional ecological and production balance. However, their fragile ecological characteristics make them highly sensitive to environmental changes, particularly climate change. This study used NDVI thresholds of 0.08–0.3 to extract low-greenness vegetation area and systematically analyzed its change patterns and climate drivers. Results indicate that the Qaidam Basin will continue its warming and humidifying trend, providing favorable conditions for desert land improvement. Since 2000, low-greenness vegetation has decreased significantly while grassland conditions improved markedly. The study reveals that hydrothermal conditions have lag effects on low-greenness vegetation within 2–3 years, resonating with most forage grasses' life cycles (typically 2–3 years). This provides scientific basis for desert grassland restoration, such as introducing stress-resistant forage varieties, scientifically configuring different life-cycle forages, and implementing artificial precipitation enhancement to optimize climate conditions for grassland recovery.

He et al. demonstrated that increasing precipitation days during flood season in Delingha and Dachaidan regions with relatively uniform distribution reduces probabilities of extreme drought or flood disasters, benefiting vegetation ecosystems. However, accelerated glacier melt due to temperature increases may trigger floods, debris flows, and reservoir breaches. Whether future precipitation increases can exceed potential evapotranspiration increases caused by rising temperatures, whether precipitation extremes will alter current uniform distribution patterns, and how glacier retreat affects long-term water resource supply are important issues requiring further investigation.

The stepwise regression models and CMIP5 climate data contain inherent uncertainties, which propagate to vegetation greenness projections. Future research should focus on reducing these uncertainties through improved model structures and enhanced climate projections.

4 Conclusions

Based on MODIS NDVI data, meteorological observations, and climate projections, this study analyzed spatiotemporal patterns of vegetation greenness and influencing factors in the Qaidam Basin, with the following main conclusions:

1) Spatial analysis reveals that low-greenness vegetation in the Qaidam Basin decreased gradually from 2000–2023, with clear transition characteristics among different greenness classes: Class I → Class II → Class III transitions. Browning, unchanged, and greening areas account for 1.20%, 45.70%, and 53.10% of total vegetation area, respectively, indicating good vegetation improvement.

2) Vegetation area Ssum shows significant negative correlation with current-year precipitation ($P < 0.01$) but minimal correlation with temperature. Hydrothermal conditions exhibit significant cumulative effects: precipitation effects peak at 2–3 years, temperature effects become extremely significant after 3–4 years for Ssum, while S continues to be affected for 4–5 years. Vegetation improvement requires good water-heat coordination for at least 4–5 years. Annual precipitation and mean temperature are the main factors driving vegetation greenness changes.

3) Under RCP2.6, RCP4.5, and RCP8.5 scenarios, low-greenness vegetation in the Qaidam Basin shows overall decreasing trends, associated with projected precipitation increases and temperature rises. The decreasing trend provides favorable conditions for vegetation restoration and expansion in the region.

References

[1] Xie Peijun, Song Xiaoyan, Sun Wenyi, et al. Grassland vegetation change monitoring based on MODIS NDVI data and climate information[J]. Journal of Applied Meteorological Science, 2010, 21(2): 229-236.

[2] Chen Yanli, Long Buju, Pan Xuebiao, et al. Research on the shift change of vegetation greenness line in the Loess Plateau based on GEE[J]. China Environmental Science, 2023, 43(12): 6518-6529.

[3] Liu Shuang, Gong Peng. Change of surface cover greenness in China between 2000 and 2010[J]. Science Bulletin, 2012, 57(16): 1423-1434.

[4] Bao Yan, Tian Ye, Liu Caixia, et al. Spatial and temporal variation analysis of vegetation greenness in grassland of eastern China and its response on the construction of coal and electricity base[J]. Acta Ecologica Sinica, 2018, 38(15): 5423-5433.

[5] Zhang Yu, Yu Zhen, Luan Junwei, et al. Spatiotemporal variations of vegetation greenness in the forest belt of Northeast China during 1982-2020[J]. Acta Ecologica Sinica, 2023, 43(16): 6670-6681.

[6] Xu Zhizhen, Wang Jianping, Han Jibin. Ecological vulnerability assessment of the Qaidam Basin based on SRP model[J]. Journal of Salt Lake Research, 2024, 32(3): 53-60.

[7] Hou Guanglei, Liu Deying, Zhang Zhengxiang, et al. Interaction between NDVI in different climatic zone and climate change in Songnen Plain[J]. Chinese Journal of Agrometeorology, 2012, 33(2): 271-277.

[8] Wu Yunli, Zhang Yu, Tian Jiarong. Impacts by climate change and human activities on NDVI in different vegetation types across the Inner Mongolia Plateau[J]. Chinese Journal of Agrometeorology, 2023, 44(12): 1155-1168.

[9] Jin Xiaomei, Xia Wei, Guo Renhong. Variation of vegetation coverage in the Dulan area of Qaidam River Basin[J]. Journal of Desert Research, 2014, 34(2): 603-609.

[10] Li Yanli, Yang Taibao, Zeng Biao. Land cover change of southern fringe oasis in the Qaidam Basin from 2000 to 2009 based on MODIS data[J]. Journal of Desert Research, 2011, 31(1): 34-42.

[11] Li Xuemin, Zhou Dingwen, Fan Guangzhou, et al. The lag relationship between winter NDVI over Tibetan Plateau and temperature of the Southwest China[J]. Journal of Applied Meteorological Science, 2008, 19(2): 161-170.

[12] Fan Guangzhou, Zhou Dingwen, Huang Ronghui, et al. The relationship between summer precipitation in China and spring NDVI over the Qinghai-Xizang Plateau[J]. Journal of Applied Meteorological Science, 2009, 20(4): 492-496.

[13] Wang Yongli, Fan Guangzhou, Zhou Dingwen, et al. Study on the relationship between NDVI, temperature, and precipitation in Eastern China[J]. Journal of Tropical Meteorology, 2009, 25(6): 725-732.

[14] Wen Guangchao, Li Xing, Wu Bingjie, et al. An automatic method for delineating lake surfaces in Qaidam Basin using Landsat images[J]. Arid Zone Research, 2022, 39(3): 774-786.

[15] Tang Wenjia, Zhang Ziping, Zhang Zhijun, et al. Spatial-temporal changes of ecological environment quality in Qinghai Province from 2000 to 2020[J]. Environmental Science & Technology, 2023, 46(5): 229-237.

[16] Wang Yuanzheng, Ma Qimin, Jia Xiaopeng. Evapotranspiration characteristics of shrub land and alpine meadow in Qaidam Basin[J]. Plateau Meteorology, 2023, 42(3): 785-794.

[17] Hao Aihua, Xue Xian, You Quangang, et al. Review on precipitation change over the Qinghai-Xizang Plateau in recent 60 years[J]. Journal of Desert Research, 2023, 43(2): 43-52.

[18] Xu Wantong, Zeng Biao, Li Bo, et al. Regional differentiation of climate changes in Qaidam Basin and its influencing factors[J]. Journal of Lanzhou University (Natural Science Edition), 2019, 55(3): 357-372.

[19] Zhang Wangxiong, Liu Puxing. Surface humid situation and its affecting factors in the Qaidam Basin from 1961 to 2017[J]. Arid Zone Research, 2019, 36(6): 1391-1400.

[20] Zeng Fangming, Dong Bo, Zhang Xiying. Warming and humidification of climate on the northeastern Qinghai-Xizang plateau over the past 60 years: Evidence from hydroclimatic records of Delingha[J]. Journal of Salt Lake Research, 2024, 32(4): 32-39.

[21] Huo Jiaxuan, Ren Liang, Pan Yingpeng, et al. Functional traits of desert plants and their responses to environmental factors in Qaidam Basin, China[J]. Acta Ecologica Sinica, 2022, 42(11): 4494-4503.

[22] Cao Xiaoyun, Zhu Cunxiong, Chen Guoqian, et al. Surface greenness change and topographic differentiation over Qaidam Basin from 2000 to 2021[J]. Ecology and Environmental Science, 2022, 31(6): 1080-1090.

[23] Sun Shujiao, Cao Xiaoyun, Xiao Jianshe, et al. Desertification monitoring in the Qaidam Basin based on NDVI-Albedo feature space[J]. Journal of Arid Meteorology, 2023, 41(4): 560-569.

[24] Chen Ben. Regulatory Mechanisms under Alpine Grasslands Sensitivity to Climate Change on the Qin-Xizang Plateau[D]. Shijiazhuang: Hebei Normal University, 2023.

[25] Cao Xujuan, Ganzhuzhabu, Hu Guozheng, et al. Characteristics of grassland degradation in the Qinghai-Xizang Plateau, based on NDVI3g data[J]. Chinese Journal of Agrometeorology, 2019, 40(2): 86-95.

[26] Li Qing, Zhou Na, Wang Sheng, et al. Quantitative assessment the impacts of climate change and human actives on wind erosion: A case study of Inner Mongolia Autonomous Region[J]. Journal of Desert Research, 2024, 44(1): 178-188.

[27] Huang Mengzhen, Lu Ruijie, Zhao Jin, et al. Assessment of soil quality in typical wind erosion area of Qaidam Basin[J]. Journal of Desert Research, 2023, 43(3): 199-209.

[28] Yang Hang, Ma Caihong, Hua Yuqi, et al. Temporal and spatial variation map of grassland greenness in Ningxia and analysis of driving factors[J]. Research of Soil and Water Conservation, 2024, 31(2): 228-239.

[29] Chen Lin, Cao Menghao, Song Naiping, et al. Research trends and hotspots analysis of desert grasslands in China: Based on bibliometric research[J]. Acta Ecologica Sinica, 2021, 41(24): 9990-10000.

[30] Zhang Zheyue, Chen Yiyun, Zheng Min, et al. Optimization of pricing system for the inventory of grassland resource assets based on intelligent zoning[J].

Resources Science, 2023, 45(6): 1107-1122.

[31] Hu Haiwei, Gesangzhuoma, Wang Cun, et al. A brief description of the grass zone in Qinghai Province[J]. Qinghai Grassland Industry, 2022, 31(3): 50-54.

[32] Zhang Chunyu, Li Aili, Lü Yanran, et al. Spatial-temporal analysis and assessment of CMIP6 based climate simulation over the Tibetan Plateau's Hinterland[J]. Plateau Meteorology, 2023, 42(5): 1144-1159.

[33] Qin Yanhong, Jin Xin, Jin Yanxiang, et al. Simulation and prediction of runoff in cold alpine basins under climate change conditions[J]. Journal of Salt Lake Research, 2024, 32(1): 29-38.

[34] He Shenglu, Yan Yingcun, Zhang Yazhen, et al. Study on the spatiotemporal distribution characteristics of precipitation during flood season in the southern foot of Qilian Mountains[J]. Desert and Oasis Meteorology, 2022, 16(2): 116-121.

[35] Wei Fengying. Modern Climate Statistical Diagnosis and Prediction Technology[M]. Beijing: China Meteorological Press, 2013.

[36] Tang Qiyi, Tang Rui. DPS Data Processing System[M]. Beijing: China Science Publishing, 2020.

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