Impacts of climate change and human activities on vegetation dynamics on the Mongolian Plateau, East Asia from 2000 to 2023 (Postprint)

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Abstract

The Mongolian Plateau in East Asia is one of the largest contiguous arid and semi-arid areas in the world. Under the impacts of climate change and human activities, desertification is becoming increasingly severe on the Mongolian Plateau. Understanding the vegetation dynamics in this region can better characterize its ecological changes. In this study, based on Moderate Resolution Imaging Spectroradiometer (MODIS) images, we calculated the kernel normalized difference vegetation index (kNDVI) on the Mongolian Plateau from 2000 to 2023, and analyzed the changes in kNDVI using the Theil-Sen median trend analysis and Mann-Kendall significance test. We further investigated the impact of climate change on kNDVI change using partial correlation analysis and composite correlation analysis, and quantified the effects of climate change and human activities on kNDVI change by residual analysis. The results showed that kNDVI on the Mongolian Plateau was increasing overall, and the vegetation recovery area in the southern region was significantly larger than that in the northern region. About 50.99% of the plateau showed dominant climate-driven effects of temperature, precipitation, and wind speed on kNDVI change. Residual analysis showed that climate change and human activities together contributed to 94.79% of the areas with vegetation improvement. Appropriate human activities promoted the recovery of local vegetation, and climate change inhibited vegetation growth in the northern part of the Mongolian Plateau. This study provides scientific data for understanding the regional ecological environment status and future changes and developing effective ecological protection measures on the Mongolian Plateau.

Full Text

Preamble

Impacts of Climate Change and Human Activities on Vegetation Dynamics on the Mongolian Plateau, East Asia from 2000 to 2023

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Abstract: The Mongolian Plateau in East Asia is one of the world's largest contiguous arid and semi-arid regions. Under the combined pressures of climate change and human activities, desertification is becoming increasingly severe. Understanding vegetation dynamics in this region is essential for characterizing its ecological changes. Based on Moderate Resolution Imaging Spectroradiometer (MODIS) images, we calculated the kernel normalized difference vegetation index (kNDVI) for the Mongolian Plateau from 2000 to 2023 and analyzed kNDVI trends using Theil-Sen median trend analysis and the Mann-Kendall significance test. We further investigated climate change impacts on kNDVI through partial and composite correlation analyses, and quantified the relative effects of climate change and human activities using residual analysis. Results showed that kNDVI increased overall, with vegetation recovery in the southern region substantially greater than in the north. Temperature, precipitation, and wind speed were the dominant climate drivers in 50.99% of the plateau. Residual analysis revealed that climate change and human activities jointly contributed to vegetation improvement in 94.79% of the region. Appropriate human activities promoted local vegetation recovery, while climate change inhibited vegetation growth in the northern Mongolian Plateau.

This study provides scientific data for understanding regional ecological status and future changes, supporting the development of effective ecological protection measures on the Mongolian Plateau.

Keywords: kernel normalized difference vegetation index (kNDVI); human activities; climate change; partial correlation analysis; composite correlation analysis; residual analysis; Mongolian Plateau

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1 Introduction

The Mongolian Plateau in East Asia is highly susceptible to frequent sandstorms and severe desertification, representing one of the world's most ecologically fragile regions [?, ?]. Under global climate change, desertification poses significant challenges to the plateau's ecological environment [?]. In 2023, numerous large dust storms originated on the plateau, spreading from Ulaanbaatar, Mongolia to Beijing, China, and extending to South Korea and Japan [?]. These events cause profound ecological damage, including exacerbated soil erosion [?, ?], loss of shallow soil water [?], decreased vegetation coverage [?, ?], and reduced water body area [?]. Vegetation plays a crucial role in water cycling, energy flow, and particle transmission, making it a vital component of terrestrial ecosystems [?, ?, ?]. As one of the world's largest plateaus, vegetation coverage on the Mongolian Plateau significantly influences surface water circulation, soil conservation, and biodiversity in northern China [?, ?]. Studying vegetation coverage is essential for evaluating ecological protection and restoration effectiveness in this region [?, ?].

Vegetation coverage indices are crucial indicators of vegetation growth status that can indirectly characterize desertification impacts on dryland ecosystems, facilitating rapid ecological restoration to reduce drought disasters including sandstorms [?, ?, ?]. Various indices integrating multiple spectral bands have been designed for specific applications to more accurately reflect vegetation status and environmental characteristics [?, ?, ?, ?]. Research increasingly considers vegetation dynamics across different temporal and spatial scales, including long-term monitoring and comparative analyses across seasons and regions [?, ?, ?, ?, ?]. Current vegetation indices include the enhanced vegetation index (EVI), vegetation condition index (VCI), soil-adjusted vegetation index (SAVI), and normalized difference vegetation index (NDVI) [?, ?]. Camps-Valls et al. [?] proposed the kernel normalized difference vegetation index (kNDVI), which outperforms NDVI and near-infrared vegetation index (NIRv) across various applications, biomes, and climate zones [?]. Compared to NDVI and NIRv, kNDVI demonstrates stronger correlations with gross primary productivity and sun-induced fluorescence [?], and is superior for vegetation surveys and assessing climate change impacts [?]. kNDVI exhibits smaller errors regarding vegetation saturation, bias, and complex phenological cycles, showing greater resistance to noise and stability across temporal and spatial scales [?]. Specifically, it optimizes biases and periodicities caused by satellite and environmental factors, making it more suitable for phenology studies in arid and semi-arid regions. Additionally, its solid theoretical basis addresses vegetation unsaturation limitations in low-coverage areas like the Mongolian Plateau, holding high value for natural and agricultural system research [?].

Understanding vegetation dynamics drivers can improve our assessment of ecological health on the Mongolian Plateau, providing a scientific basis for protection and restoration [?]. Previous studies observed predominantly positive climate change impacts on vegetation coverage [?], with rising temperatures promoting forest growth while precipitation patterns determine grassland fluctuations. Human activities have emerged as a crucial factor, with growing population density on the plateau causing marked vegetation dynamics [?]. In recent years, China's Inner Mongolia Autonomous Region has implemented major ecological policies including returning farmland to forest and grazing land to grassland, resulting in vegetation recovery. Consequently, the plateau's eastern region has experienced relatively rapid recovery. In arid and semi-arid regions, climate change impacts on vegetation are very significant, and human activity impacts are increasing [?]. Current research on climate drivers of vegetation dynamics on the Mongolian Plateau is limited, lacking comprehensive multi-factor correlation analyses. Therefore, further studies are warranted to assess climate change and human activity impacts on vegetation dynamics.

Accordingly, this study utilized the Google Earth Engine (GEE) platform to investigate spatiotemporal kNDVI variation characteristics on the Mongolian Plateau from 2000 to 2023. We employed Theil-Sen median and Mann-Kendall methods for trend and significance analysis, conducted partial and composite correlation analyses to explore multilayered impacts of precipitation, temperature, and wind speed on kNDVI, and used residual analysis to quantify climate change and human activity effects. This study addresses two questions: (1) Which climate variables are the main factors affecting vegetation dynamics under global climate change? and (2) How do human activities affect vegetation dynamics? The findings can support regional responses to land desertification and sandstorms, as well as ecological barrier establishment on the Mongolian Plateau.

2.1 Study Area

The Mongolian Plateau (37°22 –53°20 N, 87°43 –126°04 E; Fig. 1 [Figure 1: see original paper]) in East Asia is one of the world's largest contiguous arid and semi-arid regions, comprising Inner Mongolia in the south and east, and Mongolia in the north. The plateau is generally higher in the west and lower in the east, characterized by a temperate continental climate with average annual precipitation of approximately 200.0 mm [?]. The region experiences dry conditions year-round, with cold, prolonged winters and hot summers featuring significant temperature variations. According to ecological zone data (https://geospatial.tnc.org), the Sayan Alpine Meadows and Tundra occupies the largest area, primarily in the central and western plateau, while the Alashan Plateau Semi-Desert occupies the second largest area, mainly in the southwestern plateau.

2.2 Data Sources

NDVI data with 250 m spatial resolution from 2000 to 2023 were obtained from the 'MODIS/061/MOD13Q1' dataset on the GEE platform (https://earthengine.google.com). Annual average temperature and precipitation data (2000–2023) were obtained from the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis ERA5 Land dataset (https://cds.climate.copernicus.eu), both with 0.25° spatial resolution. Annual average wind speed data (2000–2023) were sourced from the National Centers for Environmental Information (NCEI) (https://www.ncei.noaa.gov) with 1 km spatial resolution. Human footprint data (2000–2020) were obtained from the global Human Footprint dataset developed by Mu et al. [?], which includes wilderness (human footprint value < 1), intact area ($1 \leq$ human footprint value < 4), and highly modified area (human footprint value ≥ 4) at 1 km spatial resolution.

2.3.1 Calculation of kNDVI

The original kNDVI formula is as follows:

kNDVI NIR Red

where NIR represents the near-infrared band value; Red represents the red-light band value; tanh is the hyperbolic tangent function; and σ is the length scale parameter in vegetation coverage studies, representing the index's sensitivity to different vegetation covers [?]. In this study, σ was calculated as the average value of NIR and Red, allowing kNDVI to be calculated as:

kNDVI tanh NDVI (NIR Red) (NIR Red)

2.3.2 Theil-Sen Median Trend Analysis and Mann-Kendall Significance Test

The Theil-Sen median trend analysis is a robust non-parametric statistical method that characterizes kNDVI change trends by calculating the median slope between any two time points in the data [?]. It effectively avoids outliers and measurement errors, making it suitable for long time series analysis. The calculation formula is:

median

where β is the Theil-Sen median; xj and xi are kNDVI values in years j and i, respectively. When $\beta > 0$, vegetation coverage shows an increasing trend; when $\beta < 0$, it shows a decreasing trend. Trend significance is determined using the Mann-Kendall test, with the test statistic calculated as:

= = + sgn x sgn x

where S is the test statistic; n is data length; xk and xl are kNDVI values in years k and l, respectively. The variance of S (var(S)) and standardized test statistic (Z) were calculated as:

var S var S var S

Introducing significance level α, when $|Z| \geq Z_1{-}\alpha/_2$, a significant trend exists. Based on β and $|Z|$, trends are classified into four levels at the 0.05 confidence level: significant increase ($\beta \geq 0$ and $|Z| \geq 1.96$), significant decrease ($\beta < 0$ and $|Z| \geq 1.96$), non-significant increase ($\beta \geq 0$ and $|Z| < 1.96$), and non-significant decrease ($\beta < 0$ and $|Z| < 1.96$).

2.3.3 Correlation Analysis

The Pearson correlation coefficient reflects the relationship between two variables and explores their degree of association [?]. This study calculated Pearson correlations between kNDVI and human footprint index, kNDVI and individual climate factors, and kNDVI and pairs of climate factors. The calculation formula is:

where Rxy is the Pearson correlation coefficient between kNDVI and variable y; yi is variable y's value in year i; and $\bar{x}$ and $\bar{y}$ are mean values of kNDVI and variable y, respectively. For correlations between two climate factors, corresponding variable values were substituted into Equation 9.

Partial correlation analysis calculated correlations between kNDVI and one climate factor while eliminating other factors' influences [?]. Pixel-based partial correlation analysis separately examined effects of wind speed, temperature, and precipitation on kNDVI change. The calculation formulas are:

ab xb xa bc xc b ac b

where Rxa,b is the partial correlation coefficient between kNDVI and variable a controlling for variable b; Rxa is the Pearson correlation between kNDVI and variable a; Rab is the Pearson correlation between variables a and b; Rxb is the Pearson correlation between kNDVI and variable b; Rxa,bc is the partial correlation between kNDVI and variable a controlling for variables b and c; Rxc,b is the partial correlation between kNDVI and variable c controlling for variable b; and Rac,b is the partial correlation between variables a and c controlling for variable b. Rxa,bc > 0 indicates positive correlation, Rxa,bc < 0 indicates negative correlation, and larger absolute values indicate stronger partial correlations. Variables a, b, and c represent the three climate factors.

Composite correlation analysis investigated the combined impact of temperature, precipitation, and wind speed on kNDVI change [?]. The formulas are:

where Rx,ab denotes the composite correlation coefficient between kNDVI and variables a and b; Rxb,a is the partial correlation between kNDVI and variable b controlling for variable a; $\hat{x}$ is the kNDVI predicted value from the regression model; d_1, d_2, and d_3 represent standardized regression coefficients for the three climate factors; d_0 is the constant term; and R represents the composite correlation between kNDVI and variables a, b, and c.

Composite correlation analysis was conducted using two climate factors (Equation 12) and three climate factors (Equations 13 and 14) to analyze their combined impacts. Table 1 shows the criteria for determining climate drivers of kNDVI change.

2.3.4 Residual Analysis

Residual analysis investigated climate change and human activity effects on kNDVI change [?]. This involves predicting kNDVI based on three climate factors and comparing predictions with actual kNDVI to calculate residuals. The formulas are:

= − ,

Slope , (16)

Slope Slope Slope Slope

where xres represents residual kNDVI; x is actual kNDVI from remote sensing; Slope is the time series trend; r_1 denotes climate change's relative contribution to kNDVI change (%); r_2 denotes human activities' relative contribution (%); and Slope($\hat{x}$), Slope(x), and Slope(xres) indicate trends of predicted kNDVI, actual kNDVI, and residual kNDVI, respectively. Slope $>$ 0 indicates an upward trend, while Slope $<$ 0 indicates a downward trend.

Table 2 shows the criteria for determining relative contributions of climate change and human activities to kNDVI change.

3.1 Spatiotemporal Variations in kNDVI on the Mongolian Plateau

From 2000 to 2023, kNDVI on the Mongolian Plateau exhibited an overall upward trend (Fig. 2 [Figure 2: see original paper]), indicating increasing vegetation coverage under combined climate change and human activity influences. The kNDVI change rate was 0.001/a over the 24-year period. The fastest increase occurred between 2017 and 2018 (0.014), while the fastest decline occurred between 2021 and 2022 (0.011). The highest kNDVI value was 0.160 in 2021, the lowest was 0.091 in 2007, and the average was 0.110 during 2000–2023.

As shown in Figure 3 [Figure 3: see original paper], noticeable vegetation growth trends occurred across the plateau, with degradation in the north and recovery in the south. Recovery areas accounted for 65.47% of the total area, primarily concentrated in eastern and southern regions. Significant kNDVI increases covered only 1.53% of the plateau, mainly on the southern edge of Inner Mongolia and southeastern edge of Mongolia in mountainous areas. Non-significant kNDVI decreases covered 34.53% of the plateau, primarily in northeastern and northwestern regions, possibly due to global warming and aridification. Overall, Mongolia showed a larger proportion of non-significant kNDVI decreases, while

Inner Mongolia showed a larger proportion of non-significant increases. Both regions exhibited vegetation degradation in the north and recovery in the south.

3.2.1 Temporal Variations in Climate Factors

As shown in Figure 4 [Figure 4: see original paper], all three climate factors exhibited increasing trends from 2000 to 2023. Wind speed showed the fastest change rate (0.149 m/(s · a)), followed by precipitation. Wind speed peaked at 13.270 m/s in 2018 and reached its minimum at 9.690 m/s in 2003. Since 2013, wind speed has remained relatively high, averaging 12.590 m/s. Precipitation fluctuated significantly, peaking at 361.2 mm in 2003 and reaching its minimum at 244.7 mm in 2017, with a very slow overall increase. Temperature increased at 0.036°C/a, showing a relatively slow upward trend.

3.2.2 Analysis of Single-Factor Driving Mechanism of kNDVI Change

The proportions of areas showing positive correlations between kNDVI and temperature, precipitation, and wind speed were similar, ranging between 76.00% and 80.00%. However, spatial differences existed in kNDVI responses to different climate factors (Fig. 5 [Figure 5: see original paper]).

For kNDVI and temperature, 79.96% of the plateau showed positive correlation, with 3.61% showing significant positive correlation concentrated in the north and northwest (Fig. 5a1 and b1). Non-significant negative correlation areas covered 20.04% of the plateau, mainly in the Hulun Buir Plateau of Inner Mongolia.

For kNDVI and precipitation, 76.89% of the plateau showed positive correlation (Fig. 5a2 and b2). Except for the northern Da Hinggan Mountains, Horqin Sandy Land, and Alxa Plateau in Inner Mongolia, all areas showed positive correlation. Significant positive correlation areas reached 12.32% of the plateau, mainly in Mongolia's Khangai Mountains.

For kNDVI and wind speed, 77.35% of the plateau showed positive correlation, primarily in the east (Fig. 5a3 and b3). Significant positive correlation areas accounted for only 2.50% of the plateau, located in Inner Mongolia's Horqin Sandy Land. Non-significant negative correlation areas were distributed in the Kent and Khangai Mountains of Mongolia and the Alxa Plateau, Hobq Desert, and Mu Us Sandy Land in Inner Mongolia.

The kNDVI showed non-significant negative correlation with temperature, precipitation, and wind speed in the Ulan Buh Desert and Mu Us Sandy Land of Inner Mongolia, while exhibiting non-significant positive correlation in the central plateau, indicating some human activity influence. Areas with significant positive correlation between kNDVI and temperature, precipitation, and wind speed were mainly located in the southeast, central north, and southwest of the plateau, respectively.

3.2.3 Analysis of Two-Factor Driving Mechanism of kNDVI Change

Using single driving factors alone has limitations for analyzing kNDVI response to climate change. Therefore, we examined combined effects of temperature-precipitation, temperature-wind speed, and precipitation-wind speed on kNDVI change (Fig. 6 [Figure 6: see original paper]).

For kNDVI correlation with temperature and precipitation, composite correlation coefficients of 0.00–0.10 showed the highest area proportion (38.83%) (Fig. 6a1). Only the southwestern plateau showed higher coefficients (0.40–0.71) covering 4.84% of the area. Significant positive correlation areas accounted for only 4.46% of the plateau, with remaining areas showing non-significant positive correlation (Fig. 6b1). Overall, correlation gradually strengthened from north to south, particularly stronger in Inner Mongolia than Mongolia. Stronger correlation areas were located in the Hobq Desert, Mu Us Sandy Land of Inner Mongolia, and west of Mongolia's Kent Mountains, indicating vegetation recovery with temperature and precipitation changes.

For kNDVI correlation with temperature and wind speed, coefficients of 0.10–0.20 showed the highest area proportion (32.94%) (Fig. 6a2). This correlation was stronger than temperature-precipitation. Areas with higher coefficients (0.40–0.95) were located on the southwestern and southeastern edges of the plateau within Inner Mongolia. Significant positive correlation areas accounted for only 3.16% of the plateau, positioned in the west of Mu Us Sand Land and east of Badain Jaran Desert in Inner Mongolia with sufficient water sources (Fig. 6b2).

For kNDVI correlation with wind speed and precipitation, coefficients of 0.80–0.90 showed the highest area proportion (37.03%) (Fig. 6a3). Areas most affected by precipitation and wind speed were the Alxa Plateau, Badain Jaran Desert, and Tengger Desert in Inner Mongolia, with coefficients reaching 0.90–1.00. Significant positive correlation areas reached 85.11% of the plateau (Fig. 6b3), indicating that arid climate and windy conditions have the greatest vegetation impact. Correlation coefficients were smaller in Mongolia than Inner Mongolia, suggesting vegetation in Inner Mongolia is more affected by climate change.

3.2.4 Analysis of Three-Factor Driving Mechanism of kNDVI Change

We further investigated the comprehensive impact of temperature, precipitation, and wind speed on kNDVI change, identifying dominant climate drivers across regions through single-factor, two-factor, and three-factor analyses.

Composite correlation coefficients of kNDVI with three climate factors mostly ranged from 0.50 to 0.60, representing 12.67% of the plateau area (Fig. 7a [Figure 7: see original paper]). Areas with smaller coefficients were mainly distributed in northern Mongolia, while Inner Mongolia had much greater area proportions with coefficients > 0.50. Significant positive correlation areas were concentrated in the central and southern plateau, accounting for 53.86% of the region (Fig. 7b). The non-significant positive correlation area in northern Mongolia has relatively stable coniferous forest landscapes with strong environmental tolerance, making them less influenced by current climate change according to field surveys.

Through partial and composite correlation analyses, we identified climate drivers of kNDVI change (Fig. 7c). In the central and southern plateau, kNDVI change was weakly driven by all three climate factors, covering the largest area proportion (50.99%). Weakly-driven areas in Inner Mongolia were much larger than in Mongolia. Precipitation-driven areas accounted for 4.08% of the plateau, concentrated in western Kent Mountains (Mongolia) and southern Hulun Buir Plateau (Inner Mongolia). Temperature-driven areas accounted for 2.65% of the plateau, mainly in the Ulan Buh Desert, Hobq Desert, Alxa Plateau (Inner Mongolia), and Gobi Desert near the Altay Mountains (Mongolia). Wind speed-driven areas accounted for 1.88% of the plateau, located in the Horqin Sandy Land (Inner Mongolia). Strong winds increase surface erosion, directly impacting and reducing vegetation, while sustained wind action can disrupt surface vegetation systems, decreasing coverage and exacerbating desertification.

3.3 Impact of Human Footprint on kNDVI Change

We characterized human activity influences on kNDVI change using human footprint data. As shown in Figure 8a [Figure 8: see original paper], correlation coefficients between kNDVI and human footprint ranging from −0.40 to −0.20 showed the largest area proportion (24.68%). Negative correlation areas accounted for 63.62% of the plateau, with significantly negative areas (13.55%) mainly in Mongolia's Kent and Khangai Mountains (Fig. 8b). Significantly positive correlation areas were located in the Hobq Desert and Mu Us Sand Land of Inner Mongolia. Mongolia showed mostly non-significant negative correlation, while Inner Mongolia showed mostly non-significant positive correlation. Highly modified human footprint areas were evident in the desert grassland–forest transition zone and agricultural-pastoral areas in central and eastern Inner Mongolia (Fig. 8c). Almost all intact areas showed significant negative correlation between kNDVI and human footprint, indicating that vegetation in less-disturbed areas (mainly engaged in nomadic husbandry, mining, or logging) was more significantly affected by human activities. Highly modified areas mostly showed non-significant correlation, suggesting human activity impacts were less significant than climate change.

3.4 Relative Contributions of Climate Change and Human Activities on kNDVI Change

As depicted in Figure 9 [Figure 9: see original paper], climate change and human activity impacts on kNDVI change exhibited significant spatial differences. Areas where both factors affected kNDVI change accounted for 95.09% of the plateau, with 94.79% showing vegetation improvement and 0.30% showing degradation. This indicates current vegetation restoration benefits from dual positive effects. In improvement areas, climate change contributions of 20.00%–40.00% and 40.00%–60.00% accounted for 34.14% and 33.66% of the plateau, respectively (Fig. 9a). Climate change contributions of 20.00%–40.00% were mainly located east of the Badain Jaran Desert, Tengger Desert, Horqin Sandy Land, north of the Da Hinggan Mountains (Inner Mongolia), and eastern Mongolia. Human activities contributed 80.00%–100.00% to kNDVI increase in the Kent Mountains (Fig. 9b), despite significant negative correlation between kNDVI and human footprint. This may reflect reduced destructive effects from recent human activities and continued ecological protection measures improving vegetation. In degradation areas, climate-only impacts accounted for 0.32% of the plateau (northeast Altay Mountains in Mongolia and northern Inner Mongolia), while human-only impacts accounted for 0.25% (north of Khangai Mountains in Mongolia and eastern Horqin Sandy Land in Inner Mongolia) (Fig. 9c and d).

4.1 Impacts of Climate Change and Human Activities on kNDVI Change on the Mongolian Plateau

This study revealed noticeable vegetation improvement through long-term kNDVI analysis, consistent with Yao et al. [?]. Wind speed influences turbulent exchange intensity near the ground by enhancing heat, moisture, and component exchange between surface and air, increasing soil evaporation, plant transpiration, and vegetation-atmospheric CO_2 exchange, thus playing an important regulatory role [?, ?]. Zhang et al. [?] demonstrated wind speed's crucial role in vegetation degradation. Jiang et al. [?] found precipitation affected Mongolian Plateau vegetation more significantly than temperature, consistent with our results. The plateau remains under ecological stress from combined temperature, precipitation, and wind speed effects [?, ?]. Recent temperature stabilization reduces vegetation species changes and promotes growth [?]. Precipitation has more direct and significant effects than temperature [?]. Located in an arid and semi-arid climate zone, precipitation changes decisively affect vegetation growth and distribution. The plateau's stable, slightly increasing precipitation trend favors vegetation recovery [?]. Regarding human activities, the plateau is a traditional animal husbandry area [?] where overgrazing and agriculture affect grassland ecosystem stability. Both Mongolia and Inner Mongolia have enhanced vegetation protection through increased positive human activities and reduced overexploitation [?]. Vegetation improvement from positive human activities was more obvious in

Mongolia than Inner Mongolia (Fig. 9).

Climate change and human activity impacts on Mongolian Plateau vegetation are complex and far-reaching. Protecting the ecological environment requires effective measures to address climate change and reduce vegetation damage from human activities. Within natural resource carrying capacity, human activities favor vegetation growth in Mongolia, especially under the "Billion Tree Planting Program." Mongolia can accelerate restoration by increasing positive human activities. In Inner Mongolia, excessive human activities have damaged the natural environment, particularly vegetation, and should be reduced.

4.2 Limitations and Prospects

Different vegetation indices exhibit varying responses to climate change [?]. In Mongolia, NDVI-precipitation correlation was stronger than NDVI-temperature correlation for desert and steppe vegetation, while EVI correlations with temperature and precipitation were similar [?]. This study used kNDVI to characterize vegetation coverage, utilizing all higher-order spectral relationships to better reflect vegetation changes. This derived index is achieved without specific assumptions, highlighting kNDVI's ability to address linearization issues in remote sensing processing [?]. Kernel method optimization allows kNDVI to more sensitively capture climate change impacts, providing finer quantitative assessments. However, kNDVI may have vegetation spectral identification errors from aerosols and cloud cover. A research gap remains regarding kNDVI on the Mongolian Plateau. Further validation can be achieved through MODIS leaf area index fitting, correlation with related parameters, and kNDVI-based change detection [?]. Studying different vegetation index responses to climate change and human activities will contribute to understanding vegetation dynamics driving mechanisms.

Currently, ground survey data on the Mongolian Plateau are limited, especially in Mongolia. This study used GEE platform data, with only partial on-site surveys. Future research should combine ecological engineering implementation, ground surveys, and terrain analysis to determine kNDVI change driving mechanisms.

5 Conclusions

This study investigated vegetation response to climate change and human activities and their driving factors on the Mongolian Plateau. The overall ecological environment has deteriorated, but initial restoration efforts are bearing fruit. Vegetation restoration in the southern region (mainly Inner Mongolia) was significantly more obvious than in the north (mainly Mongolia). kNDVI can characterize climate change and human activity impacts on vegetation coverage. kNDVI change was primarily driven by precipitation and wind speed. Appropriate human activities are conducive to natural environment restoration. Vegetation improvement areas influenced by combined climate change and human activities accounted for 94.79% of the plateau. Positive and active human activities need strengthening to improve the plateau's ecological environment.

Conflict of Interest: The authors declare no known competing financial interests or personal relationships that could have influenced this work.

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