Impacts of climate change and human activities on NDVI changes in the Central and West Asia Economic Corridor during 2013 - 2022

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***Abstract*: *The implementation of the "The Belt and Road" initiatives have brought great economic benefits to the countries along the route, and Central and West Asia, as a key link of the " The Belt and Road", demands attention to the changes of the regional environmental health during the construction process due to its fragile ecological environment. Based on MOD13A3 NDVI data and ERA5 meteorological reanalysis data, this study analyzed the spatial and temporal evolution of NDVI in Central and West Asia during the ten years of the implementation of the Belt and Road policy by using the trend analysis method, and explored the impacts of climate change and human activities on the changes of NDVI and their relative contributions by using the multivariate regression residual analysis method. The results indicated that NDVI in Central and West Asia has shown a decreasing trend over the past decade, with an average rate of $-0.26\times10^{-2}a^{-1}$, and 50.74% of the region exhibited insignificant degradation, with significant degradation in the hilly areas of Kazakhstan in the north, in the low-altitude areas bordering the Tian Shan and Hindu Kush mountains, and in the central part of the region, and significant restoration in the hinterland of Kazakhstan and the coastal areas of the Caspian Sea. With 65.24% of the region's NDVI changes inhibited by climate change and 49.64% facilitated by human activities, the combined impacts of human activities and climate change are the main causes of NDVI changes in the region, with human activities contributing 60.65% of the increase in NDVI and climate change contributing 39.35% on average. This study clarified the driving factors of vegetation change in Central and West Asia since the implementation of the "The Belt and Road" initiative, which can provide scientific support for the sustainable development of the Green Belt and Road Initiatives.*

Keywords: The Belt and Road Initiatives, Central and West Asia, multivariate regression residual analysis, driving force

1. Introduction

“The Belt and Road” construction is China’s initiative to promote win-win international cooperation in the new era, proposed by President Xi Jinping in 2013, with one of the goals aimed at practicing the new concept of green development, advocating a green, low-carbon, recycling, and sustainable way of production and lifestyle, strengthening eco-environmental cooperation, building an ecological civilization and jointly achieving the 2030 Sustainable Development Goals(Xi, 2017). The construction of the Belt and Road has brought great economic benefits to the countries along the route (Huang, 2016), however, due to its huge spatial span, the conditions of resources and environment also vary greatly between regions, and the ecological conditions in some areas are fragile. Therefore, in the process of the Belt and Road construction, it is necessary to maintain attention to the regional environment.

The central and west Asia economic corridor is the core hub of the belt and road, and it is the region with the most fragile ecological environment, as well as the most outstanding desertification problem in the entire route. Its spatial scope roughly matches the ancient Silk Road, with temperate continental and subtropical desert climates, the central Asia region with extensive Gobi, strong evapotranspiration, and arid climate, and the west Asia region with high plateaus, widespread deserts, and low precipitation, all facing environmental problems such as drought and desertification (Shaohong et al., 2018). Some studies indicated that water resources in central and west Asia would become more shortage in the future (Botao et al., 2020; Masson-Delmotte et al., 2021). Quantitatively modelling and revealing the trend of ecosystem change in the region is of great significance to the sustainable development of the Belt and Road Initiative and the construction of the Green Belt and Road (Weidong, 2015).

Normalized difference vegetation index (NDVI) is linearly related to vegetation productivity, biomass and leaf area index, and is an effective indicator for monitoring vegetation cover and growth at large scales. Based on the AVHRR GIMMS NDVI dataset, the temporal and spatial evolution of NDVI in the Belt and Road region from 1982 to 2015 was analyzed, and it was found that the central and west Asia region was an area of low vegetation cover with NDVI lower than 0.27 (Fan et al., 2020; Yujie et al., 2020). In the context of global warming, the response of vegetation evolution trends to extreme events such as increased temperature and decreased precipitation has become increasingly important to understand the impacts of climate change on ecosystem structure and function (Xu et al., 2020). The dual impacts of climate change and human activities have also brought unprecedented disturbances and threats to terrestrial ecosystems, with some studies suggesting that warmer temperatures and drought are the causes of vegetation change in central and west Asia, and that human activities, such as land-use changes due to increased foreign trade, are also drivers of vegetation change (Kai et al., 2022; Xu et al., 2021; Zemeng et al., 2019). However, most of the existing studies have focused on the period before and at the beginning of the implementation of the Belt and Road policy, and fewer studies have been conducted in the decade or so since its implementation.

This study takes the seven countries along the economic corridor in central and west Asia as the study area, analyses the spatial and temporal evolution of NDVI in the region during the 10 years of the implementation of the Belt and Road policy based on MOD13A3 NDVI data and ERA5 meteorological reanalysis data by using trend analysis methods, and explores the impacts and relative contributions of climate change and human activities to the changes in NDVI by using multivariate regression residual analysis methods. This study can clarify the driving factors of vegetation changes in central and west Asia since the implementation of the Belt and Road Initiative, and provide scientific basis and data support for the construction of the green Belt and Road Initiative.

2. Materials and methods

2.1. Study area

Kazakhstan (KAZ), Kyrgyzstan (KGZ), Tajikistan (TJK), Uzbekistan (UZB), Turkmenistan (TKM), Iran (IRN), and Turkey (TUR) along the Central Asia-West Asia Economic Corridor (CWAEC) were selected as the study area, with a total area of about 6.53 million km^2, and a geographic range of 25.06°N-55.43°N, 25.66°E-87.21°E (Figure 1). The altitude ranges from -140 m to 7217 m, with an average altitude of 755 m. The western and southern Iranian Plateau and the eastern Tian Shan regions have higher altitudes, while the rest of the area has less topographic relief. The climate type of the study area is dominated by temperate continental arid and semi-arid climate with perennial drought and low rainfall, and water is the most important climatic factor limiting vegetation growth in central and west Asia (Wang et al., 2017). The annual average temperature is about 15°C and the annual average cumulative precipitation is about 170 mm, with spatial heterogeneity in its distribution. Temperature shows a zonal difference with latitude from high in the south to low in the north, while precipitation is mainly concentrated in mountainous and hilly areas. The desert and Gobi zones in the Central Asia region have higher temperatures, and the temperatures around the Tian Shan are lower, with the average annual temperature below 0℃. The climate of the Kavel desert distributed in the eastern part of the West Asia region is extremely arid with an average annual rainfall of 30-250 mm, while the central part of the region has better hydrothermal conditions and the western part has a typical Mediterranean climate (Chen et al., 2020). Grassland and desert and sparse vegetation dominate the land cover type of the region, accompanied by a few forests, and the vegetation is less green. The region's population totals about 252 million by the end of 2022, with a total GDP of about $1705.1 billion, and the total import and export trade with China has risen from $111.9 billion to $123.9 billion in the 10 years since the implementation of the Belt and Road policy.

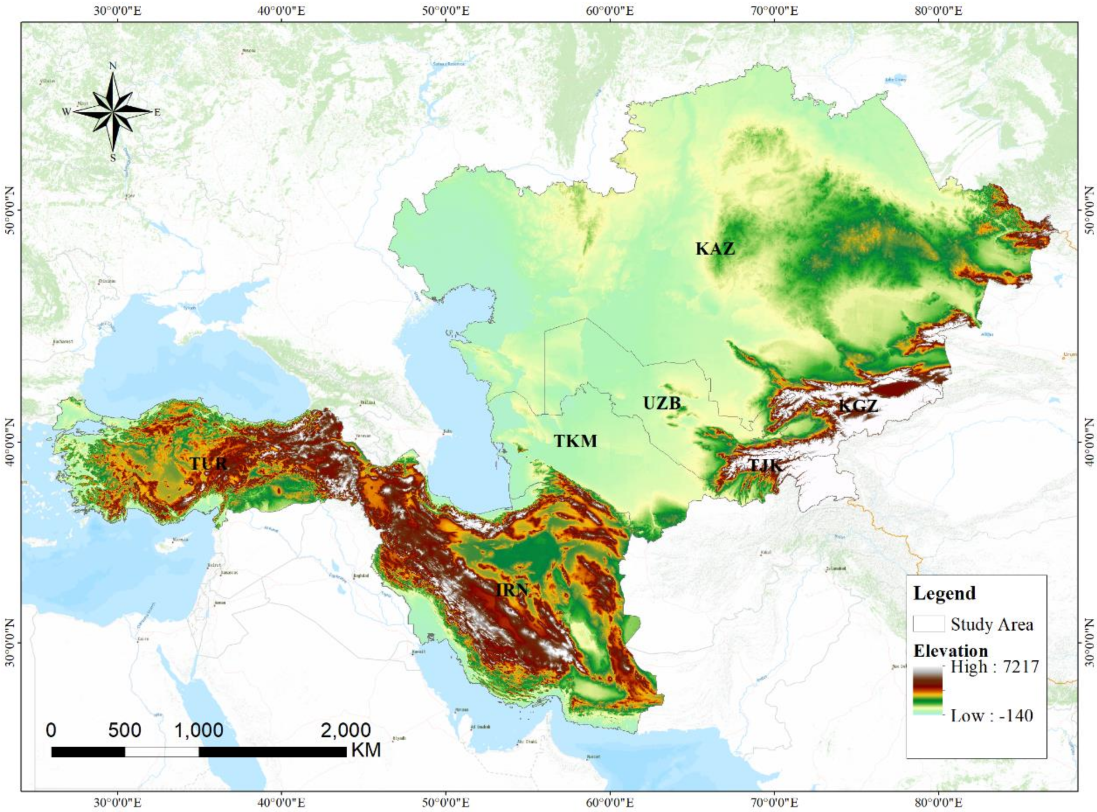

Figure 1 Distribution of the 7 countries along the CWAEC.

2.2. Data sources

The data involved in this study include MODIS NDVI data, ERA5 reanalysis data, and related statistics covering seven countries along the CWAEC for the period 2013-2022.

The NDVI data were obtained using the MODIS MOD13A3 NDVI 16d synthetic product provided by NASA (https://ladsweb.modaps.eosdis.nasa.gov), with spatial resolution of 1000m, temporal resolution of 16d, and data acquisition track numbers h19v04, h19v05, h20v03, h20v04, h20v05, h21v03, h21v04, h21v05, h21v06, h22v03, h22v04, h22v05, h22v06, h23v03, h23v04, h23v05, h23v06, h24v04, h24v05, and the data collection time was selected from 2013 to 2022 per 16 days of data. Using the study area boundaries obtained from the Resource and Environmental Science and Data Platform (https://www.resdc.cn), the NDVI data were preprocessed on the Google Earth Engine platform by batch projection, splicing, cropping, and quality control of the NDVI data using the MOD13A3 quality control field. The yearly NDVI data products were obtained based on the maximum value synthesis method. The meteorological data were obtained from the ERA5-Land Monthly Aggregated - ECMWF Climate Reanalysis of Copernicus Climate Change Service Centre (https: //climate.copernicus.eu), with a horizontal resolution of 0.1°× 0.1° and an original resolution of 9 km, and monthly temperature and precipitation data were extracted from 2013 to 2022 on the Google Earth Engine platform (Guo et al., 2018). Bilinear interpolation was used to resample them to a spatial resolution consistent with NDVI (Chen et al., 2019; Xu et al., 2019), and the temperature and precipitation were processed by ArcGIS to obtain the annual mean temperature and cumulative precipitation data. Since NDVI in central and west Asia is low, a spatial mask with NDVI greater than zero was applied to the above data to obtain the dataset for analysis, and the above data were projected using the GCS_WGS_1984 uniform projection.

2.3. Methods

2.3.1. Theil-Sen Median trend analysis and Mann-Kendall significance test

Theil-Sen Median trend analysis and Mann-Kendall (MK) test were used to investigate the spatial trend of NDVI and its significance in study area. Theil-Sen Median trend analysis is a robust non-parametric statistic for trend calculation (Hoaglin et al., 2000; Sen, 1968), which can reduce the influence of data outliers and is suitable for trend analysis of long time series data (Cai et al., 2009; Lunetta et al., 2022). The calculation formula is as follows:

$$\beta = Median(\frac{NDVI_j - NDVI_i}{j - i})$$

In the formula, Median means taking the median value, i and j are time series, $2013 \leq i \leq j \leq 2022$. When $\beta > 0$, NDVI has an increasing trend, and when $\beta < 0$, NDVI has a decreasing trend.

MK test does not require the sample to follow a normal distribution, is less disturbed by outliers and missing values, and is suitable for testing the significance of trends in long time series data (Kendall, 1948). Significance test is performed using the test statistic Z. The Z value is calculated as follows:

$$Z = \begin{cases} \frac{S}{\sqrt{Var(S)}} & (S > 0) \\ 0 & (S = 0) \\ \frac{S+1}{\sqrt{Var(S)}} & (S < 0) \end{cases}$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(NDVI_j - NDVI_i)$$

$$sgn(NDVI_j - NDVI_i) = \begin{cases} 1 & (NDVI_j > NDVI_i) \\ 0 & (NDVI_j = NDVI_i) \\ -1 & (NDVI_j < NDVI_i) \end{cases}$$

$$Var(S) = \frac{n(n-1)(2n+5)}{18}$$

where n is the length of the time series and sgn is the sign function. In this study, the significance of the NDVI trend was judged at the significance level α = 0.05, and when the absolute value of Z is greater than 1.96, it indicates that the trend has passed the significance test with a confidence level of 95%, respectively.

2.3.2. Multiple regression residual analysis

Multiple regression residual analysis was used to investigate the effects and relative contributions of human activities and climate change on NDVI changes (Evans et al., 2004; Wessels et al., 2007). Firstly, a binary linear regression model was established based on the time series data of NDVI, temperature and precipitation, with NDVI as the independent variable and temperature and precipitation as the dependent variables, and the parameters in the model were calculated; then, the predicted value of NDVI($NDVI_{CC}$) was obtained based on the regression model, which was used to represent the effect of climatic factors on the NDVI; and finally, the difference between the observed value of NDVI ($NDVI_{obs}$) and $NDVI_{CC}$ was calculated, which was the residual of NDVI($NDVI_{HA}$), representing the effect of human activities on vegetation NDVI, and the specific formula was as follows:

$$NDVI_{CC} = a \times T + b \times P + c$$

$$NDVI_{HA} = NDVI_{obs} - NDVI_{CC}$$

where T and P referred to the annual mean temperature and cumulative precipitation in °C and mm, respectively, and a, b, and c were the model parameters.

2.3.3. Determination of NDVI driving factors

$Slope(NDVI_{obs})$, $Slope(NDVI_{CC})$, $Slope(NDVI_{HA})$are the interannual trends of $NDVI_{obs}$, $NDVI_{CC}$, $NDVI_{HA}$, respectively, which were calculated using simple linear regression to serve as the basis for the subsequent determination of the NDVI drivers (Chun-sen et al., 2016). The calculation is as follows:

$$Slope = \frac{n \times \sum_{i=1}^{n} i \times NDVI_{i,xy} - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} NDVI_{i,xy}}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

Where $Slope$ was the slope of the simple linear regression equation fitted to NDVI and the time variable, characterizing the trend of NDVI from 2013 to 2022, $Slope$ >0 and $Slope$

<0 represented the increasing and decreasing of NDVI with the time series, respectively, and the absolute value of them was much faster; n represented the length of the time series, which was 10 in this case, and i was the time variable, which was equal to an integer of 1-10; $NDVI_{i,xy}$represented the pixel value of the x-row and y-column of the NDVI data of the ith year. $Slope(NDVI_{CC})$ and $Slope(NDVI_{HA})$ represent the trends of NDVI change under the influence of climate change and human activities, respectively. A positive trend indicates that climate change or human activities can promote the increase of NDVI and the recovery of vegetation, while a negative trend indicates that it will lead to the decrease of NDVI and the inhibition of the vegetation restoration. In order to threshold the effects of climate change and human activities on NDVI changes in central and west Asia, $Slope(NDVI_{CC})$ and $Slope(NDVI_{HA})$ were classified into seven categories of obvious inhibition, moderate inhibition, slight inhibition, no effect, slight enhancement, moderate enhancement and obvious enhancement in equal intervals with reference to the previous study (Kai et al., 2020) , and the classification criteria is shown in the table 1.

Table 1 Classification of impacts of climate change and human activities on NDVI change.

$\boldsymbol{Slope(NDVI_{CC}/NDVI_{HA})}$**($10^{-3}a^{-1}$)**	**Impact level**
< -2.0	obvious inhibition
-2.0 ~ -1.0	moderate inhibition
-1.0 ~ -0.2	slight inhibition
-0.2 ~ 0.2	no effect
0.2 ~ 1.0	slight enhancement
1.0 ~ 2.0	moderate enhancement
≥ 2.0	obvious enhancement

The division criteria for distinguishing the dominant drivers of NDVI changes is shown in Table 2 (Sun et al., 2015). When the interannual trends $Slope(NDVI_{obs})$, $Slope(NDVI_{CC})$, $Slope(NDVI_{HA})$ had the same sign, it was considered to be the combined effect of climate change and human activities (CC & HA), and when only $Slope(NDVI_{obs})$, $Slope(NDVI_{CC})$ signs were consistent, it was regarded as climate change alone (CC), and when only $Slope(NDVI_{obs})$, $Slope(NDVI_{HA})$ signs were consistent, it was regarded as human activity alone (HA).

Table 2 Determination of drivers of NDVI changes.

$\boldsymbol{Slope}$	**Driver**	**Classification of drivers**	
$\boldsymbol{(NDVI_{obs})}$		$Slope(NDVI_{CC})$	$Slope(NDVI_{HA})$
> 0	CC & HA	>0	> 0
	CC	> 0	< 0
	HA	< 0	> 0
< 0	CC & HA	< 0	< 0
	CC	< 0	> 0

HA	> 0	< 0

3. Results

3.1. Spatial and temporal distribution characteristics of NDVI in Central and West Asia

The spatial distribution of the average NDVI in central and west Asia from 2013 to 2022 showed a pattern of gradual decrease from north to south, with the NDVI ranging from 0 to 0.93, and the multi-year average for the whole region is 0.34(Figure 2). High values of NDVI were concentrated in the northern Kazakh hills, the eastern Tian Shan and Altai Mountains at low altitude, the Elburz Mountains in northern Iran, and the coastal areas of Turkey, with good thermal and hydrological conditions, and grassland as the dominant vegetation type, with the NDVI above 0.50. Low values of NDVI were concentrated in the central Turan lowland and southern Iranian plateau, where desertification was serious, with the Kyzylkum Desert, Karakum Desert, and Kavir Salt Desert, etc., and the NDVI was below 0.30. In terms of countries, Turkey had the highest average NDVI value of 0.55, followed by Kyrgyzstan with an average NDVI value of 0.46, and the lowest average NDVI value of 0.19 in Iran.

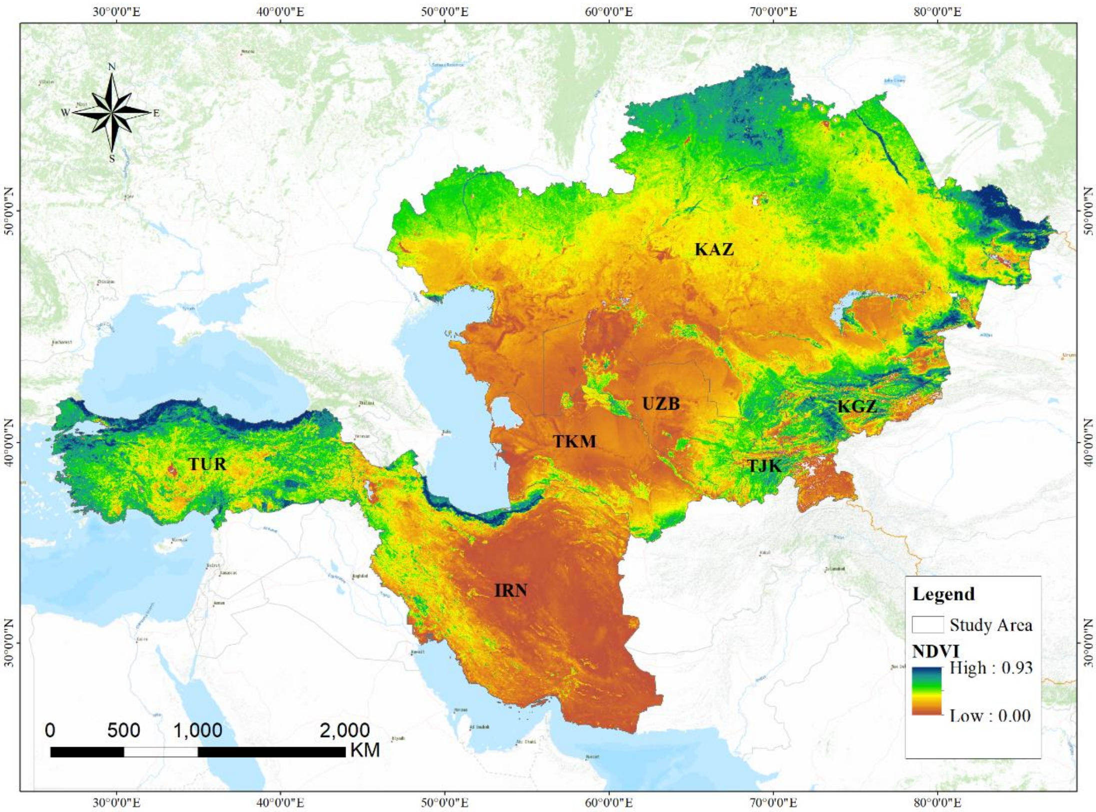

Figure 2 Spatial distribution of average NDVI in central and west Asia from 2013-2022.

As for the temporal changes, the mean NDVI fluctuated between 0.30 and 0.37 during the decade, with the highest mean NDVI value occurring in 2016 and the lowest in 2021, as shown in Figure 3. Over the past ten years, NDVI showed a declining trend, with an annual rate of -0.23×10^{-2}, of which 2013-2016 showed an increasing trend with an annual rate of 1.2×10^{-2}, and 2016-2022 showed a decreasing trend, with an average annual rate of -0.78×10^{-2}. NDVI changes varied among countries, Turkey's NDVI fluctuated at 0.54 and peaked at 0.57 in 2015, Kyrgyzstan's NDVI fluctuated at 0.46 and peaked at 0.49 in 2017, Kazakhstan's NDVI fluctuated at 0.38 and showed a decreasing trend, with an average annual rate of -0.42×10^{-2}, and peaked at 0.44 in 2016, Tajikistan, Uzbekistan and Turkmenistan had more consistent interannual changes, and all peaked in 2019 with large interannual variations and unstable changes, and Iran and Turkmenistan NDVI fluctuated up and down at 0.20, indicating that NDVI in regions with lower vegetation cover is more susceptible to perturbations.

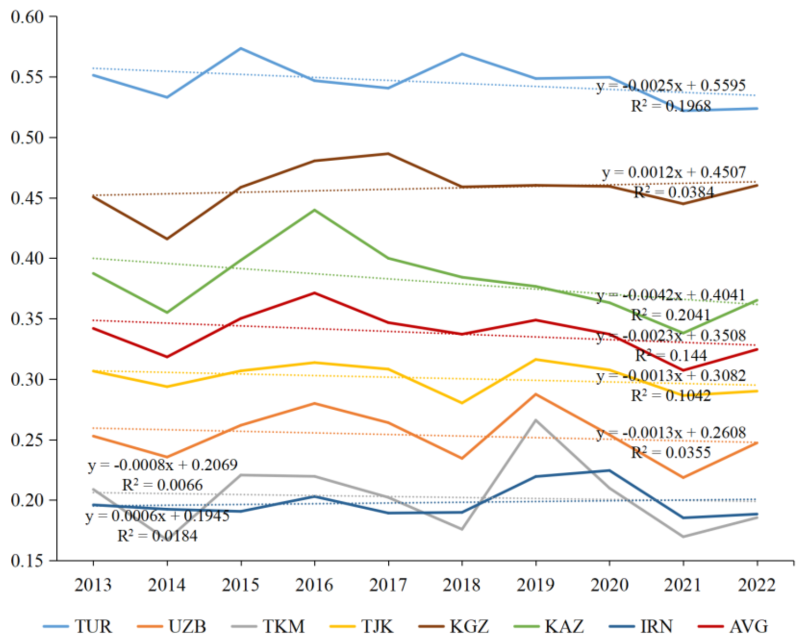

Figure 3 Temporal changes of NDVI in central and west Asian countries, 2013-2022.

3.2. Changing trends of NDVI in central and west Asia

Based on the Theil-Sen Median trend analysis method, the trends of NDVI changes in central and west Asia was shown in Figure 4, the annual trend of NDVI changes in central and west Asia varied from -0.11 to 0.12 a^{-1}, with an average rate of change of -0.0026 a^{-1}. Vegetation degradation was significant in the hilly regions of northern Kazakhstan and in the central low-altitude regions bordering the Tian Shan and Hindu Kush mountains ranges, while vegetation recovery was significant in the hinterland of Kazakhstan and the

Caspian Sea coastline. The Mann-Kendall method was used to test the significance of the change trend. On the basis that the change trend β basically conformed to normal distribution, our study, with reference to previous studies, classified $\beta \geq 0.0005$ as an improving region, $-0.0005 \leq \beta < 0.0005$ as a no-change region, and $\beta < 0.0005$ as a degrading region. Given the significance level $\alpha = 0.05$, when the absolute value of the MK test value $Z \geq 1.96$, it indicated that the trend passed the test with a confidence level of 95% with a significant change, respectively, and the change was not significant when the absolute value of the MK test value $Z < 1.96$. Five categories of significant degradation (SD), insignificant degradation (ISD), no change (NC), insignificant improvement (ISI) and significant improvement (SI) were identified. The statistical results of trend significance categories were shown in Figure 4,5. The results showed that ISD dominated the trend of NDVI change, accounting for 50.74% of the total area, followed by ISI, accounting for 28.58%, SD and SI were less, accounting for 5.69% and 2.21%, respectively, and NC of NDVI in the whole area accounted for 12.78%.

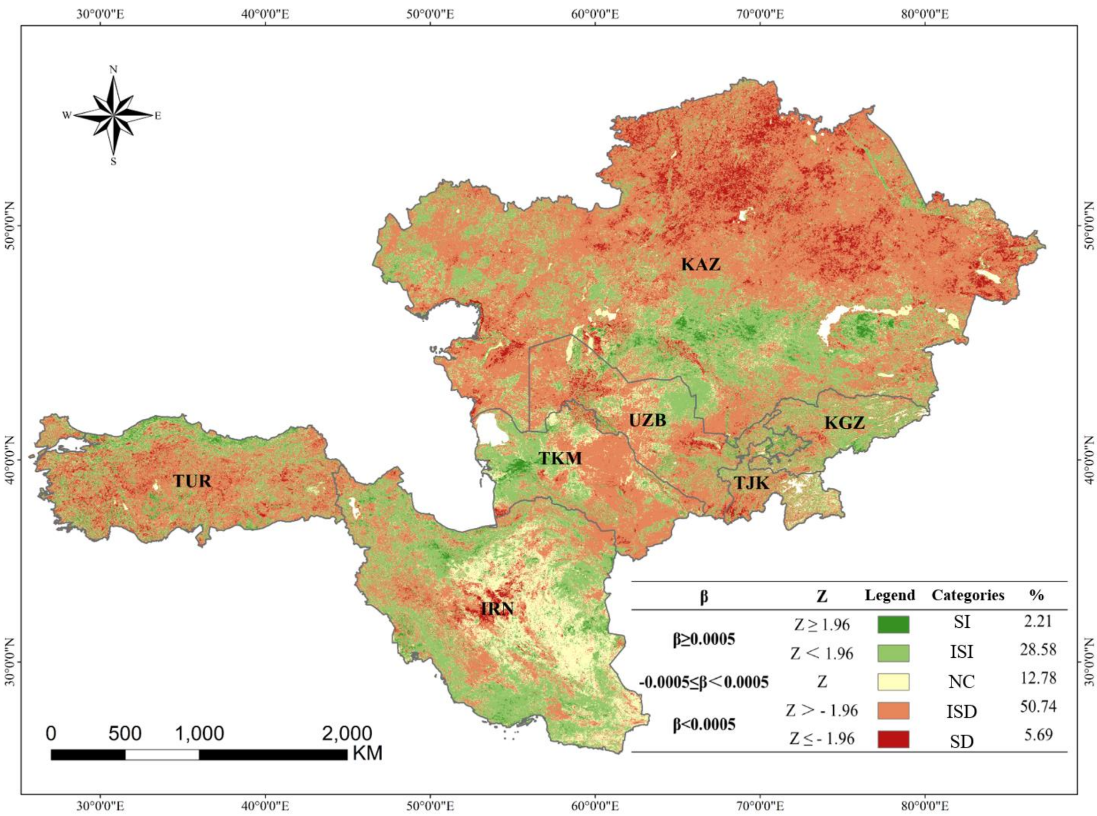

Figure 4 Changing trends of NDVI in Central and West Asia.

Except the Kyrgyzstan, which had the highest percentage of ISI at 46.51%, all the other countries along the route showed ISD at the highest percentage, with Kazakhstan having the highest percentage at 60.85%. The percentage of SI and SD areas was less in each country, with Turkey having the highest percentage of SI areas at 3.38 %, concentrated in the northern Caspian Sea coast region, and Kazakhstan having the highest percentage of SD areas at 8.11%, widely distributed in the northern and eastern regions. NC was observed in Iran with the highest percentage of 28.19%, distributed in the hinterland of the Iranian plateau.

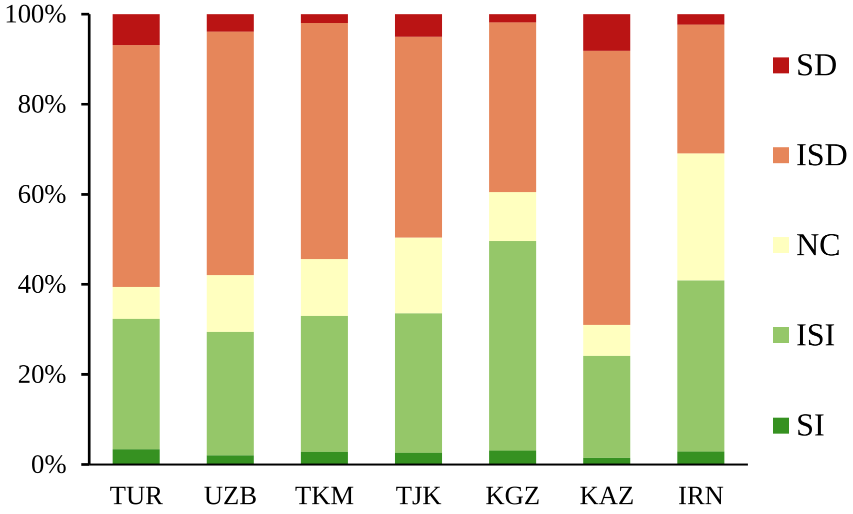

Figure 5 Statistical results for trend significance categories.

3.3. Analysis of driving factors of NDVI change

The impacts of climate change and human activities on NDVI changes in central and west Asia exhibited great spatial heterogeneity, and for the same region there were large differences in the effects of the two driving forces on NDVI changes. Climate change inhibited the increase of NDVI by 65.24% of the region, with the obvious inhibition accounting for 38.57% of the region, mainly distributed in the Kazakhstan hilly in the northern area, the Ustyurt Plateau across the western KAZ and the northwestern UZB, the hinterland of the Karakum Desert in the central part of TKM, and the Zagros Mountains region located in eastern TUR and the south-western part of IRN. However, climate change also enhanced the increase of NDVI, accounting for 23.11 % of the total area, of which slight enhancement accounted for the highest area of 10.28 %, and obvious enhancement accounted for only 6.84 % of the total area, which was concentrated in the high-elevation areas of the Tian Shan mountains range around KGZ and the southeastern region of TKM. The proportion of areas where climate change has no effect on the increase of NDVI in the whole region was 11.65%. The area of human activities promoting the increase of NDVI in the whole region was 49.64%, and the spatial distribution of the area showed a clear strip from the north-east of KAZ to the south-west of IRN. Compared with the effect of climate change, the area of human activities contributing to the increase of NDVI was larger. Among them, the obvious enhancement area accounted for the highest proportion of 27.21%, which was distributed in south-central KAZ, the Caspian Sea coastal region, southwestern IRN, and the Black Sea coastal region in northern TUR, all of which were coastal or riverine areas. The area where human activities inhibited the increase in NDVI accounted for 42.66% of the total area, with the obvious inhibition accounting for the highest proportion of 25.82%, and it was mainly distributed in the south-eastern region of the Tian Shan Mountains and the Pamir Plateau in the lower altitude, in the north-central and eastern part of KAZ, and in the Anatolian Plateau region in central TUR. The region where human activities had no effect on the increase of NDVI accounted for about 7.70%. Further calculation revealed that the impacts of climate change and human activities on the average NDVI changes in central and west Asia during 2013-2022 were-0. 23×10^{-2} a^{-1} and -0.95×10^{-4} a^{-1}, respectively. It also illustrated that while the positive impacts of human activities were qualitatively more important, the negative impacts were quantitatively more profound.

The spatial distribution of the driving factors of NDVI changes in central and west Asia was shown in Figure 6. For positive impacts: the combined effect of CC&HA was the driving factor of NDVI increase in 15.98% of the area; the area of NDVI increase driven by CC alone accounted for the least of only 3.25%, which was relatively dispersed; and the area of NDVI increase driven by HA alone accounted for 18.69%, which was mainly located in the south-central part of Kazakhstan, the western part of Turkmenistan, and the north-south offshore region of Iran. Regarding the negative impacts: 33.92% of the area showed that the combined effect of CC&HA was the driving factor for the decrease of NDVI, which was mainly concentrated in the northern and central parts of the study area, as well as in the hinterland of Iran and Turkey; the area of NDVI decrease caused by CC alone accounted for 19.00%, and its spatial location was accompanied by the former; and the area of NDVI decrease caused by HA only was 9.17%, concentrated in the south-eastern region of Turkmenistan and the hinterland of Turkey. Overall, the combined effects of CC&HA were the dominant drivers of NDVI changes in Central and West Asia during the last decade of the Belt and Road policy implemented in the region.

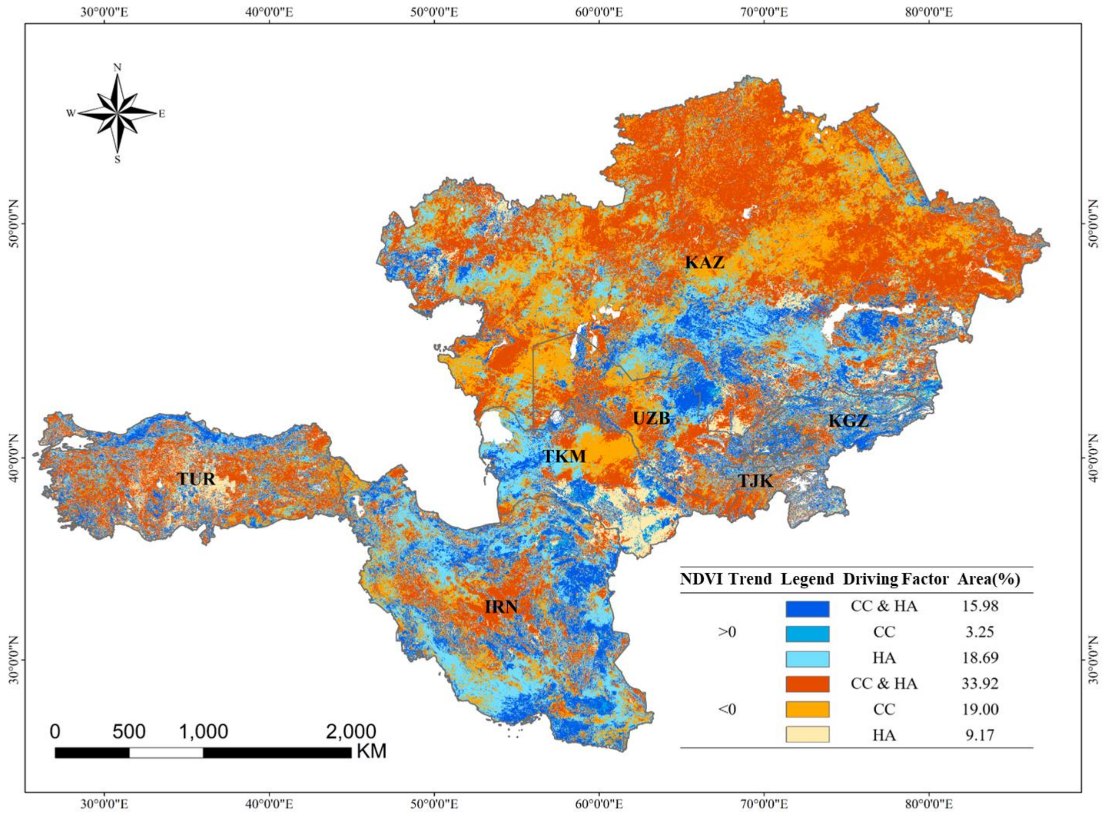

Figure 6 Spatial distribution of driving factors of NDVI change in the CWAEC, 2013-2022

Driver analysis was carried out by country, and the results were shown in Table 3, except for Iran, where the driver of NDVI change was HA alone, and the drivers of NDVI change in the other six countries were the combined effects of CC&HA. Calculation of the trend $NDVI_{CC}$ and $NDVI_{HA}$ in each country revealed that the effects of climate change and human activities on NDVI changes in each region also varied considerably. The effect of climate change on NDVI changes ranged from -0.40×10^{-2} a^{-1} (KAZ) ~0.07×10^{-2} a^{-1} (KGZ), and the effect of human activities on NDVI changes ranged from -0.17×10^{-2} a^{-1} (TUR) ~0.13×10^{-2} a^{-1} (IRN). Except for TKM and KGZ, climate change had a suppressive effect on NDVI changes in the rest of the countries, with an obvious inhibition in KAZ, a moderate inhibition in UZB, a slight inhibition in TUR, TJK and IRN, and a slight enhancement of climate change on NDVI in KGZ, and basically no effect on TKM. Human activities had a slight inhibition of NDVI changes in KAZ, TJK and TKM, a moderate inhibition in TUR, a slight enhancement in KGZ, a moderate enhancement in Iran, and virtually no effect on NDVI changes in UZB. In general, climate change and human activities were mainly inhibitory, and only in a few countries were they promotional, with Kyrgyzstan being the only country where both climate change and human activities contributed to NDVI increasing.

Table 3 Driving factors statistics by country

Country	**Slope(NDVI) (10^{-2} a^{-1})**	**Impact on NDVI increase**		**Driving Factor**
		Climate change	**Human activities**	
KAZ	-0.43	obvious inhibition	slight inhibition	CC & HA
TUR	-0.26	slight inhibition	moderate inhibition	CC & HA
TJK	-0.15	slight inhibition	slight inhibition	CC & HA
UZB	-0.14	moderate inhibition	no effect	CC & HA
TKM	-0.09	no effect	slight inhibition	CC & HA
IRN	0.06	slight inhibition	moderate enhancement	HA
KGZ	0.12	slight enhancement	slight enhancement	CC & HA

4. Discussion

The study indicated that the NDVI in Central and West Asia along the Belt and Road Economic Corridor was dominated by degradation trends from 2013 to 2022, but with large spatial heterogeneity. The combined effect of climate change and human activities was the dominant driver of NDVI degradation in the study area. The climate showed warm-drying during the decade, with the temperature increasing at the rate of 0.06°C a^{-1} and the annual precipitation decreasing at the rate of -4.74 mm a^{-1}. The area of temperature insignificantly increasing accounted for 83.16% of the total area , and the area of precipitation insignificantly decreasing accounted for 63.79% of the total area (Figure 7), which was unfavorable for the growth of vegetation in the hills, sands and deserts of arid and semi-arid regions (Jiang et al., 2023) , the vegetation in these areas was sparse, and its growth condition was greatly affected by precipitation, although the land surface evapotranspiration was increased by the rising temperature, the vegetation could not spring and grow up in time due to the lack of water, and the ecological environment of desert area represented by the Karakum Desert was even worse under the influence of climate change. Human activities brought negative impacts from grazing, agriculture, industry, population and so on. Animal feeding and trampling by grazing had changed the surface vegetation structure in low vegetation cover areas, resulting in degradation and reduction of vegetation cover, mainly in traditional pasture areas like Kazakhstan steppe and the northern foothills of the Tianshan Mountains (Shihua et al., 2022), and the continuous increase of livestock husbandry and grazing pressure in TKM and KAZ, UZB, had been one of the reasons for the decrease of NDVI of the grassland in the region (Chen et al., 2020). The land use and cover change caused by the cropland reclamation led to the reduction of vegetation cover, partial cropland in the northern Kazakhstan hilly areas, which depended mainly on rain-fed cultivation, was similarly negatively affected by the reduction of precipitation, and cropland development distributed along the Amu Darya and Syr Darya river basins in the southern KAZ, UZB, and TKM relied heavily on diverted irrigation (Hongwei et al., 2019) which led to the land salinization. Owing to warm-drying climate and strong winds, ecosystem degradation in the Central Anatolia region of Turkey has been severe, coupled with long-term anthropogenic invasions such as intensive farming and overgrazing, the naturally occurring plant cover has been partially or completely lost (Yıldız et al., 2022).The exploitation of natural resources by the numerous mining, petroleum and chemical industries established along the mineral-rich Tianshan Mountains extension zone, which runs through the hinterland of Central Asia, has severely affected the steppes in these areas, leading to a decline in productivity (Chen et al., 2020), which has also resulted in the destruction of surface vegetation and the pollution of groundwater (Liu et al., 2021), which has led to the degradation of the vegetation cover as well. In addition, the increase of population accentuated regional water scarcity, further aggravating vegetation degradation (Abuduwaili et al., 2019). Soil degradation and reduction of plant species due to inconsistent land management, deforestation and soil erosion in semi-arid regions also contribute to NDVI degradation (Mutlu, 2019; Sivakumar, 2007).

Climate change and human activities could also contribute to the increase of vegetation cover. The iceberg melting due to climate warming brought more precipitation and surface runoff to the high altitude and surrounding regions, as shown in the Figure 9b, the area of the region with non-significant increase in precipitation accounted for 27.11% , which was mainly concentrated in the high altitude areas of the Tianshan Extension Vein in the east-central part, the Pamir Plateau, and the Iranian Plateau in the southern (Dastigerdi et al., 2024), and meanwhile, the warming increased the vegetation's photosynthesis, which improved vegetation productivity and effectively promoted the growth of regional vegetation in the above regions (Gong et al., 2016). Vegetation along the Black Sea coast and Mediterranean coast in the north and south-west of Turkey has continued to recover under regional climate regulation (Aktürk et al., 2021), and vegetation recovery has occurred in parts of southern Turkey under the combined effect of non-significantly lower climate and non-significantly higher precipitation. The Central Asian region has a sparse steppe vegetation cover, with annual herbaceous plants sprouting rapidly as precipitation increases. Human activities that have increased vegetation cover are mainly manifested in ecological projects. For example, Turkey planted black pines in semi-arid artificial grasslands for ecological restoration (Ayan et al., 2021), and Turkmenistan implemented a national forest program to improve the land (Kust et al., 2022), and ecological projects can effectively increase forest cover, and reasonable planting densities can also help understory restoration of surface vegetation cover (Yıldız et al., 2022) . Cultivation in sparsely vegetated areas could increase vegetation cover in areas such as the Lake Balkhash delta and the Amu Darya delta, but increased irrigation water use from reclamation in southern Turkmenistan could exacerbate ecological water scarcity in downstream areas, leading to land degradation around the Aral Sea. Iran has effectively improved overall ecosystem functioning through the establishment of ecological reserves (Mashizi et al., 2020).

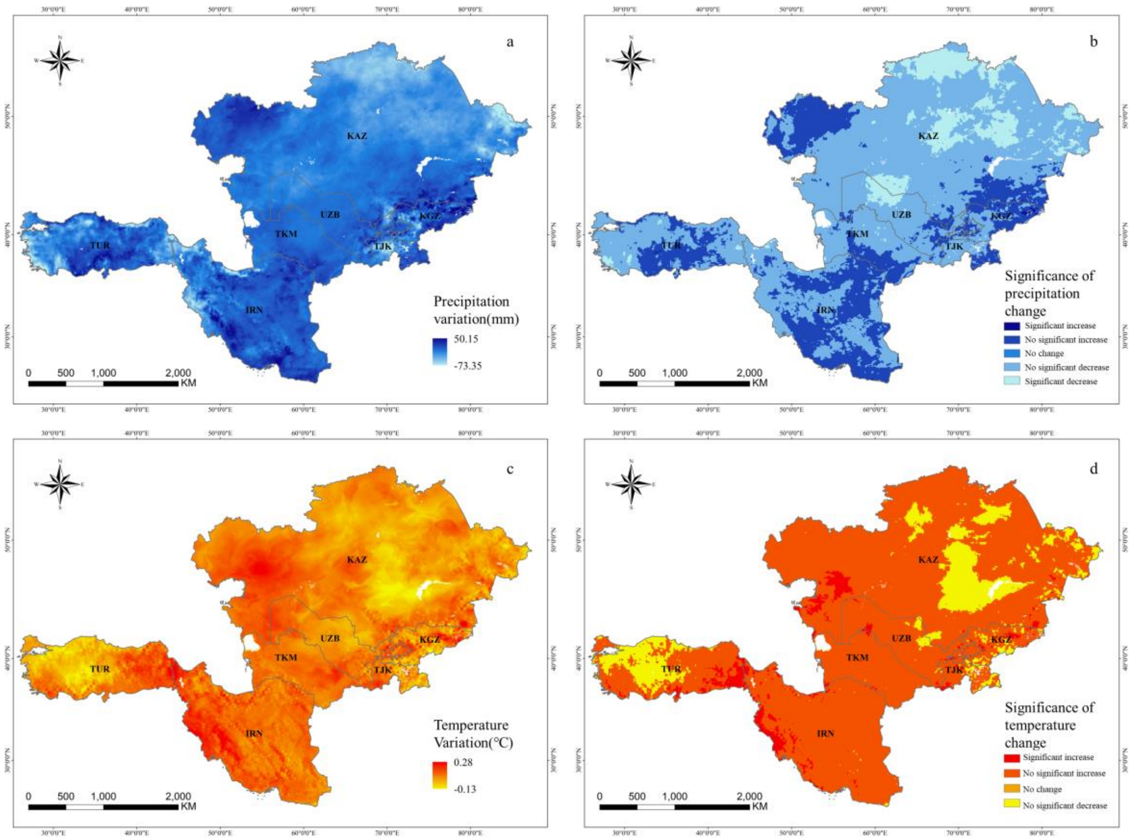

Figure 7 Changes and significance of precipitation (a, b) and temperature (c, d) in CWAEC, 2013-2022

The Belt and Road Initiative aims to harmonize environmental protection and economic development, strengthen ecological environmental protection, and jointly build a “Green Belt and Road”. At present, China and the countries along the CWAEC have developed cooperation in infrastructure, finance, energy, agriculture, electricity, communications, and many other areas, which is an important strategic pillar of the Belt and Road, and the overall trade between them is gradually recovering as the major public health incidents recede(Zhu, 2023). However, the fragile ecological environment of central and west Asia restricts the development of resources and is not conducive to long-term development, and most of the climatic and environmental types in the region are consistent with those of northwestern China, so China's successful experience in comprehensive ecological and environmental management in northwestern region can provide a reference for the ecological construction of central and west Asia, such as the Beijing-Tianjin-Hebei wind and sand source management, the Three-North Project construction, and national desertification management projects(Niu et al., 2023; Zhang et al., 2018; ZHU et al., 2019), and the specific key technologies include efficient use and protection of water resources, sand prevention and control technology, and saline and alkaline land ecological management technology(Yue et al., 2022).

However, this study also has objective shortcomings. The original resolution of the ERA5 reanalysis meteorological data selected in our study is 9 km, while the spatial resolution of NDVI is 1 km. Although the meteorological data has been resampled to 1 km, the inconsistency of the spatial resolution would bring about errors. When constructing the regression model to calculate the NDVI prediction, only the effects of temperature and precipitation on NDVI were considered because they were dominant factors of climate change in arid and semi-arid zones, but in fact, the NDVI is also affected by wind speed, hours of sunshine, relative humidity, altitude, slope, etc. Therefore, the residuals of the NDVI not only contained the effects of human activities on NDVI, but also the effects of factors not considered above. Further research could focus on the core areas of the Belt and Road, using higher resolution remote sensing data and meteorological data, combining changes in land cover and vegetation types, refining climate change and human activity elements, and using Geodetector and other methods to carry out multi-factor interaction analyses.

5. Conclusion

Based on the NDVI and climate data, we investigated the changes of NDVI in seven countries along "the Belt and Road Economic Corridor" in Central and West Asia from 2013 to 2022 by using multiple regression residual analysis, and analyzed the impacts and relative contributions of climate change and human activities to the changes of NDVI. The main conclusions are as follows:

(1) The spatial distribution of the average NDVI value in central and west Asia from 2013 to 2022 showed a pattern of gradual decrease from north to south, and the average multi-year NDVI value of the whole region was 0.34, and the overall NDVI showed a decreasing trend during the decade, with an average rate of $-0.26\times10^{-2}a^{-1}$, and the trend of change was dominated by non-significant degradation, which accounted for 50.74% of the total. Significant degradation accounted for 5.69%, concentrated in the hilly areas of northern KAZ, the agricultural areas around the Aral Sea and Syr Darya River basins, and the salty desert areas of the Iranian hinterland, while significant improvement accounted for 2.21%, concentrated in the central part of the KAZ, the western part of TKM, and the northern part of TUR.

(2) The spatial heterogeneity of the impacts of climate change and human activities on NDVI changes over central and western Asia is large, with climate change having a predominantly negative impact and human activities having a slightly larger proportion of positive impacts than negative impacts. Overall, the impacts of climate change and human activities were -0.23×10^{-2} a^{-1} and -0.95×10^{-4} a^{-1}, respectively. By country, the impacts of climate change on NDVI change ranged from -0.40×10^{-2} a^{-1} (KAZ) to 0.07×10^{-2} a^{-1} (KGZ), and the impacts of human activities on NDVI changes ranged from -0.17×10^{-2} a^{-1} (TUR) to 0.13×10^{-2} a^{-1} (IRN). The combined effects of CC&HA are the main drivers causing NDVI changes. The negative impacts of climate change were represented by climate warming and drying and the positive impacts by warming and humidifying; the negative impacts of human activities included overgrazing, intensive farming, mineral resource exploitation and deforestation, and the positive impacts included ecological engineering construction.

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