Quantitatively determine the dominant driving factors of the spatial-temporal changes of vegetation-impacts of global change and human activity

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1 **Quantitatively determine the dominant driving factors of the**
2 **spatial-temporal changes of vegetation-impacts of global change**
3 **and human activity**

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13 **Abstract:** The differences of spatial-temporal distribution patterns and dominant
14 driving factors of vegetation evolution in different regions and different historical
15 periods were not clearly. Therefore, this study introduced the gravity center model and
16 geodetector to analyze the spatial-temporal change characteristics and dominant
17 driving factors of vegetation NDVI in China during 1981-2019 from the perspective
18 of geographic divisions. Results showed that: (1) During 1981-2019, the average
19 vegetation coverage in China, as a whole, showed an increasing trend and zones with
20 obviously increasing vegetation NDVI were mainly distributed in the middle reaches
21 of the Yellow River basin and the upper reaches of the Yangtze River. (2) During
22 1981-2019, the gravity centers of vegetation NDVI, nationally, were mainly
23 concentrated in Yan'an City and Tongchuan City, showing a southward migration
24 trend as a whole, which indicates that the increment and growth rates of the southern
25 were greater than those of the northern part. (3) The growth of vegetation in southern
26 China was primarily affected by temperature, while that of northern China was largely
27 influenced by precipitation. (4) Specific factors, including land use, precipitation and

soil types exerted significant influences on the vegetation NDVI, and their interaction could enhance the influence of single factor.

Key words: Vegetation NDVI; Climate change; Gravity center; Spatial-temporal evolution; Geodetector

Introduction

As an important part of terrestrial ecosystem, vegetation plays an important role in the material cycle, energy flow and information transmission for the terrestrial ecosystem (Josep et al. 2009; Guo et al., 2020a; Gomes et al. 2021;Wu et al.,2021). Vegetation is not only the natural link between soils, the atmosphere and water, but also the component most sensitive to climate change (Hu and Guo 2012; Guo et al.,2020b;Lu et al.,2020). Under the stress of global climate change, the spatial-temporal evolution pattern of vegetation is the result of climate change, land use, soil and water conservation and other natural activities, as well as human activities (Li and Shi 2000; Wu et al. 2015; Shi et al. 2018;Guo et al., 2020c). Previous studies have shown that climate change led to a significant increase in vegetation biomass in the northern hemisphere, and the same trend of vegetation change has also been detected in China (Fang et al. 2003; Liu et al. 2015; Guo et al., 2020d). Vegetation changes will trigger the fluctuation of the whole terrestrial ecosystem to a certain extent. Quantitative analysis of spatial-temporal change patterns of vegetation change and exploring its driving factors are of great significance for the improvement of ecological environment.

Vegetation index that monitored by satellite remote sensing and other quantitative indicators have been adopted to analyze the hydrological response of vegetation at different scales, which has provided a convenient approach to reveal the characteristics of regional terrestrial ecological environment. As an important indicator of vegetation growth, the normalized difference vegetation index (NDVI) can accurately reflect the growth rate and state of surface vegetation, which has been widely applied in the investigation of spatial-temporal changes of vegetation (Liu et

al. 2012; Ya et al. 2015; Zheng et al. 2016; Jin 2019;Guo and Wen, 2020). Zhong et al. (2010) analyzed the spatial-temporal pattern of vegetation NDVI on the Qinghai-Tibet Plateau based on SPOT-VGT NDVI from 1998 to 2006, and found that the spatial distribution of vegetation NDVI was consistent with the climatic pattern of the Qinghai-Tibet Plateau. Wu et al. (2014) investigated the changes of global vegetation coverage over the past 30 years, and found that the annual variation of global average vegetation coverage fluctuated between an index of 0.2 and 0.6, and most of the global continental vegetation showed an increasing trend (except for Oceania). Piao et al. (2011) analyzed the changes in vegetation coverage in the cool temperate zone of Eurasia from 1982 to 2006 based on GIMMS NDVI data, and found that the change of vegetation NDVI in Eurasia had obvious stages. Chen et al. (2021) analyzed the influencing factors of vegetation in different climatic regions of the Yellow River Basin from 1982 to 2015, indicating that precipitation exerted the greatest impacts on vegetation NDVI in semi-arid areas, whereas temperature had the greatest impacts on vegetation NDVI in semi-humid areas. By exploring the response of global vegetation NDVI to extreme weather events, Liu et al. (2013) found that vegetation in semi-humid and semi-arid areas, especially temperate grasslands and hardwood forests, were very sensitive to extreme precipitation events. Lu et al. (2020) utilized the datasets of GIMMS NDVI of the vegetation growing season from 1982 to 2012 to investigate the spatial-temporal response characteristics of NDVI, temperature and precipitation of the 8 typical vegetation coverage types in China. Zhang et al. (2020) analyzed the characteristics of vegetation change in Inner Mongolia based on SPOT NDVI data from 2000 to 2015, and found that annual precipitation, soil type, vegetation type and annual average temperature played a dominant role in the spatial-temporal change process of vegetation NDVI. The above previous studies showed the average NDVI of growing season was significantly correlated with the average temperature and precipitation with obviously great differences. In addition, the human activities had played more important role in the evolution process of surface

vegetation rather than natural factors. However, the differences of dominant factors in different sub-region in China during different periods were urgent to clarify, which was urgent and critical for regional protection of vegetation ecosystem (Liu et al.,2013; Jin et al.,2020). Moreover, how to distinguish the effects of natural factors and human activities was still a difficult problem and a hot issue in the field of ecology (Gao et al.,2019;Lu et al.,2020;Chen et al.,2021) .

Therefore, based on the datasets of GIMMS NDVI, MODIS NDVI and meteorological data, this paper introduced the gravity center model and geodetector to analyze the spatial-temporal evolution patterns of vegetation NDVI in China from 1981 to 2019 and then quantitatively determined the dominant factors in different sub-regions during different periods.

Materials and methods

Study area

China is located in eastern Asia, the west coast of the Pacific Ocean, bordering North Korea on the east, and facing South Korea and Japan across the sea, Kyrgyzstan, Tajikistan, Pakistan and India in the west, Vietnam, Laos and Myanmar to the south, and Russia and Mongolia in the north (Figure 1). China covers a vast territory, spanning nearly 50 degrees latitude from north to south and more than 60 degrees longitude from east to west, with the area of about 9.6 million km². The eastern part of China has a monsoon climate, while the northwest region and Qinghai-are dominated by temperate continental climate and alpine climate, respectively. The topography of China is complex and diverse, including plateaus (19%), mountains (26%), hills (10%), plains (12%) and basins (19%). The distribution characteristics of vegetation types in China are greatly affected by climatic factors, which can be categorized into eight types: cold temperate coniferous forest, temperate coniferous and deciduous broad-leaved mixed forest, warm temperate deciduous broad-leaved forest, subtropical evergreen broad-leaved forest, tropical monsoon rain forest, temperate steppe, temperate desert and alpine vegetation on the Qinghai-Xizang

Plateau.

Figure 1. Geographical location of China

Data sources and pre-processing

The meteorological data was obtained from the China Meteorological Data Network (<http://data.cma.cn/>), including daily precipitation (0.1mm), daily average temperature (0.1°C) , sunshine hour (0.1h) and other factors from 824 ground meteorological stations in China. Then the grid datasets, including temperature, precipitation, sunshine and accumulated temperature, with a spatial resolution of 8km were obtained by the interpolation with the method of Kriging method of ArcGIS 10.2 and C#. The Normalized Difference Vegetation Index (NDVI) data include GIMMS NDVI (1981-2006a, at a 15d temporal resolution and 8km spatial resolution) and MODIS NDVI data (2000-2019a, at a 16d temporal resolution and 1 km spatial resolution) were downloaded from the Resource and Environment Data Cloud Platform (<https://www.resdc.cn/>) and Geospatial Data Cloud (<http://www.gscloud.cn/>). In order to confirm the consistency of the spatial resolution, the MODIS NDVI datasets were resampled into images with 8km and the annual NDVI were

obtained utilizing the maximum value calculation method. Considering the different sources of the two datasets, this study constructed the correction model by regression analysis based on the overlapping year's data from 2000 to 2006: $Y_{\text{MODISNDVI}} = 1.0777X_{\text{GIMMSNDVI}} + 0.0046$ ($R^2 = 0.925$, $P < 0.001$). Then, the above model was utilized to correct the MODIS NDVI from 2007 to 2019. The land use data of 1980 and 2020 with the spatial resolution of 1km was obtained from the Resource and Environment Data Cloud Platform (<https://www.resdc.cn/>), which is used to analyze the influences of anthropogenic interference on vegetation. Digital Elevation Model (DEM) data that derived from STRM3 was collected from Geospatial Data Cloud with a spatial resolution of 90m. All these above datasets with different spatial resolution were interpolated to grids with the spatial resolution of 8km utilizing the tool of Resample of ArcGIS 10.2.

Methods

The workflow of this study was showed in Figure 2.

Figure 2. The workflow of the study

Linear trend and change rate

Linear trend is to utilize a univariate linear regression to analyze the change intensity and trend of regional vegetation. The calculation formula is as follows (Zhang et al. 2015; Li et al. 2018; Sun et al. 2019):

$$\text{slope} = \frac{n \times \sum_{i=1}^n (i \times M_{\text{NDVI},i}) - \sum_{i=1}^n i \sum_{i=1}^n M_{\text{NDVI},i}}{n \times \sum_{i=1}^n i^2 - \left(\sum_{i=1}^n i \right)^2} \quad (1)$$

Where Slope refers to the gradient of the trend line, i represents the year i , n refers to the serial number of year ($n = 39$), $M_{\text{NDVI},i}$ denotes the maximum value of the year (i). If slope > 0 , it indicates that the vegetation condition has been improved; otherwise, it means that the vegetation condition has degraded.

The change rate of vegetation was used to indicate the change degree of vegetation NDVI in study periods, and its equation is as follows:

$$\text{NDVI}_{\text{cr}} = \frac{\text{Slope}}{\text{NDVI}_{\text{mean}}} \times n \times 100\% \quad (2)$$

Where NDVI_{cr} refers to the change rate of NDVI during the study period; $\text{NDVI}_{\text{mean}}$ refers to the average value of NDVI during the study period; n refers to the length of the study period.

Correlation analysis

Correlation analysis mainly reflects the degree of correlation between vegetation NDVI and natural factors, which is measured by Pearson correlation coefficient of pixel-by-pixel is utilized in this study. Based on this, partial correlation analysis is unitized and applied to investigate the relationship between the two elements (excluding the influence of other elements), and multiple correlation analysis reflects the comprehensive influence of each factor. The corresponding calculations formulas are as follows (Yang et al. 2019; Chen et al. 2020; Peng et al. 2020):

$$r_{x,y} = \frac{\sum_{k=1}^n (x_k - \bar{x})(y_k - \bar{y})}{\sqrt{\sum_{k=1}^n (x_k - \bar{x})^2 \sum_{k=1}^n (y_k - \bar{y})^2}} \quad (3)$$

$$r_{xy_1, y_2} = \frac{r_{xy_1} - r_{xy_2} r_{y_1 y_2}}{\sqrt{1 - r_{xy_2}^2} \sqrt{1 - r_{y_1 y_2}^2}} \quad (4)$$

$$R_{x, y_1 y_2} = \sqrt{1 - (1 - r_{xy_1}^2)(1 - r_{xy_2, y_1}^2)} \quad (5)$$

Where $r_{x,y}$ represents the correlation coefficient between the independent variable and the dependent variable (in this article, the relationship between NDVI and climate elements), $\bar{x}$, $\bar{y}$ refer to the average value of the two variables and x_k , y_k denote the value of the year (k) of the two variables. r_{xy_1, y_2} means the partial correlation value between x and y_1 after fixed y_2 , and r_{xy_2, y_1} represents the similar meaning of r_{xy_1, y_2} . r_{xy_1} refers to the correlation coefficient between x and y_1 and r_{xy_2} , $r_{y_1 y_2}$ represents similar meaning as r_{xy_1} . $R_{x, y_1 y_2}$ refers to the multiple correlation coefficient between x and y_1 , y_2 . Considering the confidence levels of $p < 0.05$ and $p < 0.01$, the significant relationships between NDVI and temperature, precipitation have been discussed. T test (Eqs.(5)) is adopted to analyze the significance of the partial correlation coefficient, and the F-test (Formula (6)) is utilized to analyze the significance of the multiple correlation coefficient.

$$T = \frac{r_{xy_1, y_2}}{\sqrt{1 - r_{xy_1, y_2}^2}} \sqrt{n - m - 1} \quad (6)$$

$$F = \frac{R_{x, y_1 y_2}^2}{1 - R_{x, y_1 y_2}^2} \times \frac{n - k - 1}{k} \quad (7)$$

Gravity centre model and standard deviation ellipse

Gravity center can better reflect the unbalance of spatial-temporal distribution of geographical elements, which has been widely utilized in economy, population studies, ecology and other fields. In addition, the migration trajectory of the gravity centre of vegetation NDVI can also directly indicate the imbalance of grown rate and increments in different parts through the map form. The gravity center of a region is defined as: if a region is composed of n sub-regions, where the coordinate of gravity center of the sub-region i is (x_i, y_i) , M_i stands for the attribute value of the sub-region, then the geographical coordinate of gravity center of the region is expressed as (Rong and Fang 2017; Guo et al. 2019):

$$\bar{x} = \frac{\sum_{i=1}^n M_i x_i}{\sum_{i=1}^n M_i} \quad (8)$$

$$\bar{y} = \frac{\sum_{i=1}^n M_i y_i}{\sum_{i=1}^n M_i} \quad (9)$$

The standard deviation ellipse is mainly composed of the rotation angle, the standard deviation along the principal axis (major axis) and the auxiliary axis (minor axis). The long axis represents the direction of the largest spatial distribution of gravity centre, while the short axis denotes the direction of the least spatial distribution of gravity centers (Zhu et al. 2019). The standard deviation ellipse can be applied to identify the change and migration trend of vegetation NDVI gravity centers in the region, because it can more directly reflect the spatial evolution trend of vegetation coverage.

Geodetector

The geodetector model is utilized to detect the spatial differentiation of vegetation NDVI in order to reveal the explanatory power of a factor to NDVI (Li et al. 2016; Peng et al. 2019). The correlation degree is measured by the q value, which is ranged [0,1]. The higher the value, the more obvious the explanatory power of the influencing factor (X) to vegetation NDVI(Y), and vice versa, which can be expressed as follows:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} = 1 - \frac{SSW}{SST} \quad (10)$$

$$SSW = \sum_{h=1}^L N_h \sigma_h^2 \quad (11)$$

$$SST = N \sigma^2 \quad (12)$$

where $h = 1, \dots, L$ stands for the classifications of variable Y or X; N_h denotes the number of units of class h , and N represents the number of units of the whole

region. σ_h^2 refers to the variance of Y value of class h and σ^2 means the variance of Y value of the whole region. SSW refers to the sum of the variance in layer, and SST represents the total variance of the whole region.

Results

Change rate of vegetation NDVI in China during 1981-2019

Based on the analysis of the change rate of vegetation NDVI in China from 1981 to 2019 (Figure 3), the study indicated that in the past 40 years, zones of change rate between -10% and 10% that belonged to stable areas had largest area with accounting for 35.57%. Zones of change rate between 10% and 30% that belonged to slightly increased areas accounted for 23.42%. Zones of change rate less than -30% that belonged to significantly reduced areas had the smallest area, accounting for 6.93%. The above analysis results showed that the average vegetation coverage in China has shown an overall increasing trend in the past 40 years with the stable areas (-10%~10%) and increased areas (>10%) amounting to 78.22% of the total study area.

Figure 3. Area percentage of different grades of NDVI change rate in China in recent 40 years

As is shown in Figure 4, zones of the change rate between -10% and 10% were

the most widely distributed, mainly concentrated in southern Xinjiang, western Inner Mongolia and the northern Qinghai-Tibet Plateau. Zones of NDVI change rate more than 30% were mainly distributed in the middle and upper reaches of the Yellow River, the middle and upper reaches of the Yangtze River and the Liaohe River basin. The slightly reduction zones of NDVI ($-30\% < \text{change rate} < -10\%$) were mainly distributed in northern China, including northern Heilongjiang, northeastern Inner Mongolia and so on.

Figure 4. Spatial distribution of different grades of NDVI change rate in China in recent 40 years

Inter-annual variation of vegetation coverage in China

From the inter-annual variations of vegetation NDVI (Figure 5), the overall fluctuation range of vegetation NDVI in China was relatively large in the past 40 years. Among them, the annual average vegetation NDVI in northeast China was the largest, which amounted to 0.830, followed by that of the central-south part (0.752). The northwest part, a desert and grassland-dominated area whose vegetation growth was restricted by precipitation, had the minimum annual NDVI, which only reached 0.294. During the study period, the minimum of NDVIs in most areas appeared around 2000, which may be a consequence of meteorological disasters. Since 1999,

243 the projects of “returning farmland to forest and grassland” and afforestation have
 244 been implemented in various regions of China with remarkable result, the average
 245 NDVI of national scale and different sub-regions showed a fluctuating increasing
 246 trend. The results were consistent with results of Zhao et al (2018) and Jin et al
 247 (2020). Before 2000, the NDVIs in most areas of China decreased in varying degrees,
 248 among which the northeast region was the most serious, and its NDVI value
 249 decreased from 0.834 in 1981 to 0.757 in 2000, with a decrease rate of 0.077/20a.
 250 After 2000, the NDVI in China has increased in varying degrees, basically consistent
 251 with the previous research results.

Figure 5. Change trend of annual mean values of NDVIs at the national scale and in different geographical regions (a) northeast ; (b) north ; (c) northwest ; (d) east ; (e) central south ; (f) southwest ; (g) national

Migration trajectory of gravity centers

Distributions of gravity center of vegetation coverage at national and regional scale

In order to explore the imbalance and bias of the spatial distribution of vegetation NDVI in the study area, the gravity center model was utilized to analyze the dynamic changes of national and regional NDVI in recent 40 years. As was shown in Figure 6, the standard deviation ellipse was adopted to identify the change and migration trend of gravity centers. Utilizing a polar coordinate system and taking the

average gravity center of the NDVI from 1981 to 2019 as the origin, the distance (polar radius) and offset angle (polar angle) to the origin were calculated to directly reflect the migration direction and distance of the gravity center.

The gravity centers of vegetation NDVI in northeast China were mainly concentrated in Harbin, Heilongjiang Province. The area of the standard deviation ellipse was 92.62km² (Table 1), which was the smallest among the six sub-regions, indicating that the distribution of NDVI gravity centers was relatively concentrated. In the polar coordinate system, the proportion of the gravity centers in the north half (northeast quadrant and northwest quadrant) was 84.62%, whereas the proportion of the gravity centers in the south half (southwest quadrant and southeast quadrant) was merely 15.38%, which was much smaller than that in the north half, demonstrating that the grown rate and increment of the vegetation NDVI in the south half was smaller than that in the north half. The gravity centers of NDVI in north China were mainly distributed in Xilingol League and Chifeng City, Inner Mongolia. The area of standard deviation ellipse in north China was significantly larger than that of northeast China, which showed that the change of vegetation NDVI in north China was more salient than that in northeast China. The gravity centers of vegetation NDVI in northwest China were mainly concentrated in the vicinity of the polar angle of the line from 150° to 330°, which showed a northwest-southeast distribution pattern as a whole. The shape of the standard deviation ellipse was flatter, which had the largest area of 1549.87km² in the six sub-regions, showing that the spatial distribution of the gravity centers was obviously uneven.

The distribution of gravity centers of vegetation NDVI in east China was concentrated mainly in Huangshan City, Anhui Province. The rotation angle of standard deviation ellipse was 90.75°, and the gravity centers were distributed in north-south direction. During 1981-2019, the gravity centers of vegetation NDVI were distributed in the northern half, accounting for 64.10%, while the gravity centers of vegetation NDVI in the southern half accounted for 35.90%, indicating that the

increment and growth rate of vegetation NDVI in the northern parts was higher than that in the southern parts. The gravity centers of NDVI in the central south were mainly distributed in Zhaoyang City, Hunan Province, and the angle of standard deviation ellipse was 71.50° , suggesting that the gravity centers were distributed from northeast to southwest as a whole. The NDVI gravity centers in southwest China were distributed in the northwest-southeast direction, the standard deviation ellipse major axis was in the northwest-southeast direction, with a length of 20.21 km, and the minor axis was in the northeast-southwest direction, with a length of 5.35 km, demonstrating that the discreteness of the NDVI gravity center in the northwest-southeast direction was greater than that in the northeast-southwest direction. From the polar coordinate images, it could be found that there were two years when the deviation distance of NDVI gravity centers was larger, which were 1981 and 1988, respectively, indicating that the increment of NDVI gravity center in the northwest was more significant in these two years.

The national NDVI gravity centers were mainly distributed in Yan'an City and Tongchuan City, Shaanxi Province, the standard deviation ellipse area was 1450.26 km^2 , and spatial distribution of the gravity centers was relatively discrete. The distribution of the gravity centers in the four quadrants under the polar coordinate system was relatively uniform, in which the gravity centers in the northeast quadrant were the largest, reaching 28.20%, followed by the northwest quadrant (25.64%), whilst the southwest quadrant and the southeast quadrant had the same proportion, both standing at 23.08%. The proportion of the gravity centers in the north half (53.84%) was greater than that in the south half (46.16%), indicating that the increment of the NDVI gravity center in the northern half was higher than that in the southern half. Prior to 2000, the gravity center of NDVI was mostly concentrated in the northern part, and after 2000, the gravity center was mostly concentrated in the southern part, indicating that the gravity center had a trend of southward movement. Among them, there were four years with a deviation distance within 10 km, namely

2002, 2005, 2011 and 2012, and only in one year (1999) an offset distance ranged between 40~50km occurred, indicating that the increment of vegetation NDVI in the north was larger in that year.

Table 1. Standard deviation ellipse parameters of NDVIs in China and different sub-regions from 1981 to 2019

Standard deviation ellipse parameters	Northeast	North	Northwest	East	Central South	Southwest	National
Rotation angle(°)	104.86	74.80	151.03	90.75	71.50	157.62	92.61
Major axis(km)	7.30	23.89	54.79	10.91	10.36	20.21	28.93
Minor axis(km)	4.04	10.94	9.01	3.55	4.53	5.35	15.96
Area(km ²)	92.62	820.92	1549.87	121.73	147.59	339.37	1450.26

Figure 6. Distribution of gravity centers of NDVI at the national scale and in different sub-regions
(a1) northeast (in space) ; (a2) northeast (in polar coordinates) ; (b1) north (in space) ; (b2) north
(in polar coordinates) ; (c1) northwest (in space) ; (c2) northwest (in polar coordinates) ; (d1)
east (in space) ; (d2) east (in polar coordinates) ; (e1) central south (in space) ; (e2) central south
(in polar coordinates) ; (f1) southwest (in space) ; (f2) southwest (in polar coordinates) ; (g1)
national (in space); (g2) national (in polar coordinates)

Migration of gravity centers of vegetation NDVI at national and regional scales

In order to further analyze the spatial variation of vegetation NDVI in the study area, the gravity center migration of vegetation NDVI on the basis of a 5-year scale from 1981 to 2019. As was shown in Figure 7, during 1981-2000, the gravity centers of vegetation NDVI in northeast China showed a migration trend of southwest-

northeast-southwest. The gravity center of 2006-2010 migrated to the southwest, compared with that of 2001-2005, indicating that the growth rate and increments of vegetation NDVI in the southwest was larger than that in the northeast during this period. However, compared with gravity centers of 2011-2015 and 2016-2019, those of 2006-2010 showed a northward swinging trend. On the whole, in the past 40 years, the gravity center of vegetation NDVI in northeast China showed a moving trend of south-north, and the distance to the south was greater than that to the north. The gravity center of vegetation NDVI in north China exhibited obvious regularity. The gravity center of 2006-2015 shifted northward, and in other periods, the gravity centers gradually shifted to the south, suggesting that the increment of the gravity center in the south was larger than that in the north. Among them, the migration distance of the gravity center of 1996-2000 to 2001-2005 was the largest, which amounted to 15.07 km, while that of 1991-1995 to 1996-2000 was the smallest with 2.04 km. The gravity centers of NDVI in northwest China migrated northwestward in the first three periods, namely 1981-1985 to 1986-1990, 1986-1990 to 1991-1995, and 1991-1995 to 1996-2000, respectively. In the last four periods, they all moved to the southeast, namely, 1996-2000 to 2001-2005, 2001-2005 to 2006-2010, 2006-2010 to 2011-2015, and 2011-2015 to 2016-2019. Among them, the migration distance from 1996-2000 to 2001-2005 was the maximum with 50.53 km. From 2001-2005 to 2006-2010, the migration distance was the minimum with 4.73km.

The gravity center of vegetation NDVI in east China from 1986 to 1990 shifted to the northwest compared with that from 1981 to 1985. During the five periods from 1986 to 2015, the migration trajectory of the gravity centers of NDVI exhibited a circular trend of "southwest to northeast to northeast to southwest to south", whereas the gravity center continued to migrate southward from 2016 to 2019 compared with that from 2011 to 2015. The migration trajectory of the gravity center of NDVI in central south China showed a "Z" shape. The gravity center of 1981-1985 to 1986-1990 migrated northeastward, while that of 1986-1990 to 1991-1995, 2006-2010 to

2011-2015 and 2011-2015 to 2016-2019 moved to the southwest. Meanwhile, the gravity centers migrated to the northwest in the three periods of 1991-1995 to 1996-2000, 1996-2000 to 2001-2005 and 2001-2005 to 2006-2010. The gravity center of vegetation NDVI in the central south China showed a trend of moving to the southwest as a whole. The gravity centers of NDVI in southwest China in 1986-1990 and 1991-1995 shifted to the northwest compared with that in 1981-1985 and the migration distance of 1981-1985 to 1986-1990 was the largest. The gravity centers of 1991-1995 to 1996-2000 and 2001-2005 to 2006-2010 both shifted to the southeast, while the gravity center of 1996-2000 migrated to the southwest compared to that of 2001-2005. And gravity centers of 2011-2015 and 2016-2019 moved northwest compared with that of 2006-2010.

The gravity centers of national vegetation NDVI were mainly concentrated in Yan'an City, Shaanxi Province in the first four periods (1981-2000), and Tongchuan City in the last four periods (2001-2019). The gravity center of vegetation NDVI shifted to the northwest during 1986-1990 compared with that of 1981-1985, indicating that the increment and growth rate of vegetation NDVI in the northwest of the study area was larger than that in the southeast during this period. The gravity centers of vegetation NDVI in the two periods of 1991-1995 and 1996-2000 moved to the southwest as a whole compared with that of 1986-1990, indicating that the increment of vegetation NDVI in southwest China was larger than that in northeast China in recent decade. The gravity center of 1996-2000 migrated to the southeast compared to that of 2001-2005 and its migration distance was the maximum. The gravity center of 2006-2010 migrated westward compared with 2001-2005. From 2006 to 2019, the gravity center first moved to the northwest and then to the southwest. Base on the analysis, in the past 40 years, the gravity center of vegetation NDVI shifted to the south as a whole, and the migration distance amounted to 36.25 km.

Figure 7. Migration trajectory of gravity centers of NDVI at the national scale and in different sub-regions (a) northeast ; (b) north ; (c) northwest ; (d) east ; (e) central south ; (f) southwest ; (g)national

Influence of single climate factor on vegetation NDVI

The vegetation grown was significantly influenced by climate factors. In this study, we analyzed the correlation between vegetation NDVI and single climate factor, and the correlation coefficients between NDVI and temperature, precipitation, sunshine and accumulated temperature were calculated based on pixel scale.

As was shown in Figure 8(a), zones with significantly positive correlation ($P < 0.01$) between NDVI and temperature accounted for 53% of the total area, which were mainly distributed in the south parts that around latitude 35°N . Zones with negative correlation ($P < 0.05$) between NDVI and temperature were mainly concentrated in the northern part of China (near latitude 40°N), including central Xinjiang, the Inner Mongolia-Gansu border zone, northwest of Gansu and Qinghai, the Inner Mongolia Plateau and the central Northeast Plain. As was shown in Figure 8(b), zones with positive correlation ($P < 0.05$) between NDVI and precipitation accounted for 60% of the total area, which were mainly distributed in the Inner Mongolia Plateau and the middle and upper reaches of the Yellow River basin. Zones with negative correlation ($P < 0.05$) between NDVI and precipitation were mainly concentrated in the Tarim Basin, the Qaidam Basin in Xinjiang and the western part of

412 Inner Mongolia Plateau. In southern China, in areas such as Yunnan, Hubei, Anhui,
 413 Jiangsu, the correlation between NDVI and precipitation was also negative. Figure
 414 8(c) showed that 42% of the total area exhibited a positive correlation ($P<0.05$)
 415 between NDVI and sunshine, and zones with obvious positive correlation mainly
 416 concentrated in central Xinjiang, Gansu and northwest Qinghai, and the western
 417 Yunnan-Guizhou Plateau. Zones with negative correlation ($P<0.05$) between NDVI
 418 and sunshine were mainly concentrated in central China (between 105°E and 115°E),
 419 such as Guizhou, Shanxi and Henan. Figure 8(d) showed that zones with negative
 420 correlation ($P<0.05$) between NDVI and accumulated temperature accounted for 50%
 421 of the total area, which were mainly concentrated in northern China, including the
 422 three provinces in northeast China, Inner Mongolia and Xinjiang.

423 Figure 8. Correlation analysis of vegetation NDVI and climatic factors (a) NDVI and temperature;
 424 (b) NDVI and precipitation; (c) NDVI and sunshine; (d) NDVI and accumulated temperature
 425 ($> 10^{\circ}\text{C}$)

Influence of double climate factors on vegetation NDVI

Partial correlation analysis could eliminate the influence of other elements, while multiple correlation analysis could reflect the comprehensive influence of each factor. Because the vegetation NDVI was affected by a variety of climatic factors and the climatic factors in this study were often interactive and independent. Considering that temperature and precipitation were the main factors affecting change of vegetation NDVI, this study calculated the partial correlation coefficients and multiple correlation coefficients between vegetation and temperature, precipitations in China from 1981 to 2019 and tested its level of significance.

As was shown in Figure 9(a), the partial correlation between NDVI and temperature ranged from -0.82 to 0.87. Zones with positive correlation were mainly concentrated in east China, south-central and southwest China, accounting for 53.65% of the total area, while zones with negative correlation were mainly distributed in the central area of Xinjiang, Inner Mongolia, Qinghai and Gansu, and the eastern area of the Northeast Plain, amounting to 46.35% of the total area. As was shown in Figure 8(c), zones with positive correlation between NDVI and precipitation were mainly distributed in north China and the border area of Shaanxi-Ningxia-Gansu, accounting for 60.34% of the total area. Meanwhile, the areas with negative correlation were mainly distributed in central Xinjiang, western Inner Mongolia and most areas in the south, amounting to 39.66% of the total area. As was shown in Figure 9(b) and Figure 9(d), the zones with extremely significant positive correlation between NDVI and temperature accounted for 18.32% ($P<0.01$, $R>0$), which were mainly concentrated in the Qinghai-Tibet Plateau, Loess Plateau and southeastern coastal areas. Zones with significant positive correlation ($P<0.05$, $R>0$) accounted for 8.43%, while the area proportion of extremely significant negative correlation ($P<0.01$, $R<0$) was 15.33%, mainly concentrated in northern arid and semi-arid areas, such as central Xinjiang and western Inner Mongolia. Zones with significant negative correlation ($P<0.05$, $R<0$) accounted for only 5.92%. The partial correlation between vegetation NDVI and

precipitation did not pass the significance test in most areas, and only 17.72% of the areas passed the significance level test. Zones with extremely significant positive correlation accounted for 8.19%, which were mainly distributed in the Inner Mongolia Plateau and the border area of Shaanxi-Ningxia-Gansu. Zones with significant positive correlation ($P < 0.05$) accounted for only 6.25%, while zones with extremely significant negative correlation ($P < 0.01$) covered the smallest area, accounted for only 0.81%. Meanwhile, zones with significant negative correlation area accounted for 2.48%.

As was shown in Figure 9(e), the multiple correlation coefficient between NDVI temperature and precipitation ranged from 0 to 0.88, and the areas with larger multiple correlation coefficients mainly concentrated in central and southern Xinjiang, northern Inner Mongolia, Gansu-Ningxia-Shaanxi border zone, southern Tibet, northern Qinghai and the middle part of the middle and lower reaches of the Yangtze River, whilst the areas with smaller multiple correlation coefficients mainly distributed in the Northeast Plain and southeast coastal areas. Figure 9(f) was the result of F significance test, in which 14.98% of the pixels in the multiple correlation test represented significant regions ($P < 0.05$) and 35.55% referred to extremely significant regions ($P < 0.01$), which mainly distributed in the northern arid and semi-arid regions, the Qinghai-Tibet Plateau, the northern Loess Plateau and the middle and lower reaches of the Yangtze River.

Figure 9. Partial correlation coefficient, multiple correlation coefficient and significance tests on vegetation NDVI and temperature, precipitation (a) temperature partial correlation coefficient; (b) T significance test (temperature); (c) precipitation partial correlation coefficient; (d) T significance test (precipitation); (e) NDVI and temperature, precipitation multiple correlation coefficient; (f) F significance test

Interactive influence of multiple factors on vegetation NDVI

Interactive detection was utilized to evaluate the impacts of the interaction of different driving factors on vegetation NDVI, which was helpful to further investigate the driving mechanism of vegetation coverage change in various regions of China. The results showed that the q values of the interaction among factors in most areas were larger than that of single factor, indicating that the influences of driving factors on vegetation NDVI were not independent, but a process of interaction and mutual enhancement. In this paper, the vegetation NDVI of 1981(average status of 1981, 1982 and 1983) and 2019 (average status of 2017, 2018, and 2019) were selected to

explore the driving mechanisms of vegetation NDVI.

As was shown in Figure 10(a1), in northeast China in 1981, the interactive factors with higher explanation power on vegetation NDVI change were sequenced as follows: land use $\cap$ sunshine (0.657) > elevation $\cap$ sunshine (0.585) > soil type $\cap$ sunshine (0.568) > sunshine $\cap$ temperature (0.566) > aspect $\cap$ sunshine (0.528) > accumulated temperature $\cap$ sunshine (0.525), indicating that sunshine $\cap$ other factors acted as dominant factors. As was shown in Figure 10(a2), in 2019, the interactive factors with high explanation power were sequenced as follows: land use $\cap$ aspect (0.473) > land use $\cap$ temperature (0.446) > land use $\cap$ precipitation (0.356) > soil type $\cap$ land use (0.347) > soil type $\cap$ aspect (0.312) > land use $\cap$ sunshine (0.305). The explanatory power of the interaction between land use and other factors was dominant, whilst the interaction between climatic factors was relatively weak, suggesting that climate was not the main factor affecting the change of vegetation in this period. As was shown in Figure 10(b1), the maximum explanation power of interactive factors in north China in 1981 was sunshine $\cap$ temperature (0.752), while that of the aspect $\cap$ slope (0.111) was minimum. In addition, it could be found that the explanation power of the interaction between soil type and other factors was larger in this period. As was shown in Figure 10(b2), the land use $\cap$ precipitation had the largest explanation power of 0.770 in 2019, whereas the aspect $\cap$ slope had the smallest explanation power of 0.149. The interaction of precipitation, land use, soil type $\cap$ other factors had greater explanatory power in 2019. As was shown in Figure 10(c1), the soil type $\cap$ precipitation (0.669) and land use $\cap$ precipitation (0.642) in northwest China in 1981 exhibited a larger explanation power for vegetation NDVI change,. During this period, the explanatory power of the interaction between precipitation and other factors was the largest. In 2019, the explanation powers of land use $\cap$ precipitation (0.699) and land use $\cap$ sunshine (0.681) were larger, while that of the aspect $\cap$ slope was the smallest.

As was shown in Figure 10(d1) and Figure 10 (d2), the aspect $\cap$ precipitation

516 (0.374) had the largest explanation power in east China in 1981, while that of
 517 accumulated temperature $\cap$ temperature was the smallest with 0.074. The explanatory
 518 power of interactions between climate factors in this period was relative smaller. In
 519 2019, land use $\cap$ aspect (0.412) had the largest explanation power, while that of
 520 accumulated temperature $\cap$ temperature (0.073) was the smallest. It could be seen
 521 from the figure that the explanatory power between land use $\cap$ other factors was the
 522 largest. As was shown in Figure 10(e1), the interactive factors with larger explanation
 523 power for vegetation NDVI change in central south China in 1981 were ranked as
 524 follows: soil type $\cap$ aspect (0.303) > aspect $\cap$ precipitation (0.276) > soil type $\cap$
 525 sunshine (0.268) > accumulated temperature $\cap$ sunshine (0.255) > land use $\cap$
 526 precipitation (0.251) > sunshine $\cap$ precipitation (0.250). The explanatory power of
 527 interaction between aspect, soil type, and precipitation was larger. As was shown in
 528 Figure 10(e2), the interactive factors with larger explanation power in 2019 were
 529 ranked as follows: land use $\cap$ aspect (0.476) > land use $\cap$ precipitation (0.442) > soil
 530 type $\cap$ land use (0.407) > land use $\cap$ elevation (0.3920) > land use $\cap$ accumulated
 531 temperature (0.3919) > land use $\cap$ temperature (0.391). In this period, the explanatory
 532 power of the interaction between land use and other factors acted as dominant factors,
 533 and the explanatory power between land use and other factors was greater than that in
 534 the previous period. The interaction among climatic factors was relatively weak,
 535 revealing that climate was not the main factor influencing the change of vegetation
 536 NDVI in this period. As was shown in Figure 10(f1), the elevation $\cap$ sunshine (0.810)
 537 had the largest explanation power in southwest China in 1981, while that of aspect $\cap$
 538 slope was the smallest with 0.087. As was shown in Figure 10(f2), the elevation $\cap$
 539 sunshine had the largest explanation power of 0.807 in 2019, while aspect $\cap$ slope had
 540 the smallest value of 0.084. For the northeast parts of China in 1981, the interactions
 541 between sunshine and other factors played important roles in the change process of
 542 vegetation NDVI, while land use $\cap$ other factors became the dominant factors in
 543 2019. In the northwest parts, the dominant interactive factors shifted from

544 precipitation $\cap$ other factors from land use $\cap$ other factors.

Figure 10. Detection of the interacting of factors affecting vegetation NDVI change in different sub-regions from 1981 to 2019 (a1) northeast (1981a) ; (a2) northeast (2019a) ; (b1) north (1981a) ; (b2) north (2019a) ; (c1) northwest (1981a) ; (c2) northwest (2019a) ; (d1) east

(1981a) ; (d2) east (2019a) ; (e1) central south (1981a) ; (e2) central south (2019a) ; (f1)

southwest (1981a) ; (f2) southwest (2019a)

Discussions

Comparisons of spatial-temporal change patterns of vegetation NDVI in different sub-regions

During 1981-2019, there was an increasing trend of vegetation coverage in China, especially in the middle reaches of the Yellow River basin, the middle and upper reaches of the Yangtze River basin and the Liaohe River basin. This was due to the fact that during the past decades, national policies of “returning farmland to forest and grassland”, “Yangtze River Ecological Protection and restoration project”, “Water and soil loss control project in the Yellow River Basin”, and “Three-north Forest Protection Project” had been implemented and remarkable ecological improvement had been achieved (Gao et al., 2019; Lu et al., 2020). In addition, the vigorous implementation of afforestation project in the Liaohe River basin had greatly improved the regional vegetation condition. During the past 40 years, the change trend of vegetation NDVI in southern Xinjiang, and western Inner Mongolia was not obvious, which was consistent with the studies of Sun et al (2020). The reason was that the desert and gobi were widely distributed in these above regions with scarce precipitation, which was not conducive to the growth and restoration of vegetation (Jin et al., 2020; Ma et al., 2020). During 1981-2000, the vegetation NDVI showed a slightly decreasing trend in the sub-regions of east, central, and southwest. In these above zones, the rapid urbanization process, population growth rate and economic development had led to the intensification of the contradiction between man and land (Han et al., 2021). Although certain protection measures had been taken, the speed of social and economic development far exceeded the pace of ecological and environmental protection, so the change of vegetation cover was not obvious (Zhang et al., 2021). After 2000, the vegetation NDVI in most sub-regions showed an increasing trend, which was consistent with previous studies. During 1981-2019, the

gravity center of vegetation NDVI moved towards the south, which indicated that the grown rate and increment in the south parts were larger than that of the north parts. Although the vegetation NDVI in most regions showed an increasing trend due to the global warming (prolong vegetation growth period, accelerate the decomposition of soil organic matter and the release of nutrient elements) and human activity (improve the agricultural management and implement vegetation construction project), the rapidly rising temperature in North China also led to varying degrees of drought, especially in the northwest parts with scarce precipitation and water resource(Huo et al.,2021; Liu et al.,2021). Therefore, the grown increment of the vegetation NDVI was smaller than that of the south parts. For the sub-regions, the gravity center of the vegetation NDVI in northeast and north moved towards the south during the past 40 years because of the construction of “Three-north Forest Protection Project” and the rising temperature that were all both conducive to the grown and restoration of vegetation(Xu et al.,2021). The gravity center of the northwest showed a southward trend because that the climate in this area had been becoming warm and moist, especially in the northeast edge of Qinghai Tibet Plateau (Ning et al., 2021). In addition, the implement of “ecological environment protection project of Three-river Source Region” had also contributed to the restoration of vegetation in the southeast parts (Li et al.,2021). The gravity center of vegetation NDVI in east and central south both moved towards the south because of the implement of “Returning farmland to forest and grassland” and other ecological protection projects (Mu et al., 2020). The gravity center of vegetation NDVI showed a southwestward migration trend and it was because that under the stress of global warming, the rising temperature and increased precipitation had greatly contributed to the vegetation grown as well as the implement of “Returning grazing to grassland”(Liu et al.,2018;Jiang et al.,2020).

Dominant factors of different sub-regions in historical periods

Zones with positive relation between temperature and vegetation NDVI were mainly distributed in the southwest, east, and central parts of China, and the main

reason was that the rising temperature could prolong the growth period of vegetation and were conducive to the photosynthesis of vegetation(Sun et al.,2020). In addition, the higher temperature would accelerate the decomposition of soil organic matter and the release of nutrient elements, which improved the growth environment of vegetation (Ma et al.,2020). The temperature had negative relations with vegetation NDVI in the northwest and north parts, which was due to the fact that the rising temperature would lead to severe moisture evaporation that resulted in various degrees of drought (Jin et al.,2020). Zones with positive relation between precipitation and vegetation NDVI were mainly located in the Inner Mongolia Plateau and the middle and upper reaches of the Yellow River basin. The reason was that the grasslands were widely distributed in these areas, which was more sensitive to the change of soil moisture (Zhang et al., 2021). Zones with obvious positive correlation between sunshine and vegetation NDVI were mainly concentrated in the junction zones of Xinjiang-Gansu- Inner Mongolia and Yunnan. The reason was that sufficient light was conducive to the photosynthesis of plant, especially in the alpine region with lower temperature (Han et al., 2021). Zones with negative correlation with sunshine were mainly were mainly located in central parts of China, and its reason was that the prolonged sunshine hours would increase the surface heat, which intensified the surface evapotranspiration that increased drought risk(Sun et al.,2020). Zones with positive correlation of accumulated temperature were mainly located in the southern, southwestern (Qianghai-Tibet plateau), and eastern China. In these regions, the increasing accumulated temperature was conducive to prolong the grown period of vegetation (Ma et al.,2020).

In the northeast parts of China in 1981, the dominant interactive factors were sunshine $\cap$ others, while in 2019, the land use $\cap$ other factors had played more important role in the evolution process of vegetation system. This was because that the sufficient sunshine could improve the grown environment and promote the plant photosynthesis (Li et al.,2021). With the implements of “Afforestation project” and

632 urbanization , the land use $\cap$ other factors gradually became the dominant interactive
 633 factors(Mu et al.,2020). In the north part of 1981, the sunshine $\cap$ temperature has the
 634 largest explanatory power while the land use $\cap$ precipitation was the dominant
 635 interactive factor. This was due to the fact that sunshine and temperature were both
 636 conducive to plant photosynthesis, especially in zones with low temperature (Liu e
 637 tal.,2018). In addition, the grassland was more sensitive to the change of temperature.
 638 However, under the stress of global warming and urbanization, the precipitation and
 639 human activity gradually became the dominant factors in the evolution process of
 640 vegetation system(Jiang et al.,2020). In the northwest parts, the precipitation $\cap$ other
 641 factors had the largest explanatory power in 1981, while the land use $\cap$ other factors
 642 played more important role in the change of vegetation NDVI. This was because that
 643 the water resources were one of the limiting factors for vegetation growth in arid and
 644 semi-arid areas, which were mainly derived from precipitation (Gao et al.,2019). And
 645 with the development of regional economic and social development, human activities,
 646 such as afforestation, returning grazing to grass, and urbanization, greatly weakened
 647 the influences of natural factors on the vegetation system(Sun et al.,2020). In the
 648 south part, the dominant interactive factor was soil type $\cap$ aspect in 1981, while the
 649 explanatory powers of land use $\cap$ other factors were larger in 2019. This was due to
 650 the fact that the sufficient water and heat sources were not the restrictive factors for
 651 vegetation grown, so that the soil type and terrain had played more important role in
 652 the evolution process of vegetation system (Li et al.,2012). In addition, the intensity
 653 of human interference severer during the past 40 year, which led to drastic changes of
 654 land use (Liu et al.,2015a). In the southwest part, the elevation and sunshine had the
 655 largest explanatory power in both 1981 and 2019. This was because that the eco-
 656 environment of these regions was characterized by high elevation and large
 657 topographic relief, which greatly influenced the spatial and temporal changes of
 658 vegetation NDVI (Li and Shi, 2000).

Conclusion

Base on the datasets of GIMMS NDVI and MODIS NDVI, gravity center model and geodetector had been introduced to quantitatively analyze and discussed the spatial-temporal evolution pattern of vegetation NDVI in different sub-regions from the perspective of geographical division, and furthermore clarified the dominant driving factors of vegetation NDVI evolution in different historical periods of each sub-region. The main conclusions were as follows:

(1) The spatial distribution of vegetation NDVI in China showed a decreasing trend from the southeast to the northwest as a whole. Prior to 2000, the average vegetation NDVI in most sub-regions of China showed a decreasing trend, while there was an obvious increasing trend in all areas after 2000.

(2) Zones with obvious increasing NDVI (change rate $> 30\%$) were mainly distributed in the middle reaches of the Yellow River Basin, the middle and upper reaches of the Yangtze River Basin and the Liaohe River Basin. The stable zones ($-10\% < \text{change rate} < 10\%$) was the most widely distributed and mainly concentrated in the south of Xinjiang, the west of Inner Mongolia and the north of the Qinghai-Tibet Plateau.

(3) During 1981-2019, the gravity center of national vegetation NDVI was mainly concentrated in Yan'an and Tongchuan in Shaanxi Province, showing a southward migration trend as a whole and which indicated that the increment and growth rate of the vegetation NDVI in southern part was greater than that of the northern part.

(4) There were significant differences in the correlation between vegetation NDVI and climatic factors in different sub-regions. The growth of vegetation in southern China was mainly affected by temperature, whereas that in the north was mainly affected by precipitation. In addition, the vegetation grown was comprehensively affected by temperature and precipitation in some zones, such as southern Xinjiang, and western Inner Mongolia.

(5) In 1981, the sunshine $\cap$ other factors in northeast China played a dominant role in the evolution process of vegetation, whilst in 2019, the explanatory power of land use $\cap$ other factors were the largest .The explanation power of precipitation, land use and soil types in north China was larger , whereas the explanation power of land use $\cap$ other factors was larger in east China and central south China. The explanatory power of precipitation $\cap$ various factors in northwest and southwest China was the largest .

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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