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Original Research

Spatiotemporal Variation of Vegetation NDVI and Its Climatic Driving Forces in Global Land Surface

Jinting Guo[1,2]*, Kaibo Wang[3], Tiejuan Wang[1,2], Nan Bai[1], Hui Zhang[1], Ya Cao[1], Hao Liu[1]

[1]College of Life Sciences and Technology, Inner Mongolia Normal University, Hohhot Inner Mongolia 010022, China
[2]Key Laboratory of Biodiversity Conservation and Sustainable Utilization at Universities of Inner Mongolia Autonomous Region, Hohhot Inner Mongolia 010022, China
[3]Center for Ecological Research, Northeast Forestry University, Harbin Heilongjiang 150040, China

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Abstract

Variations in the Normalized Difference Vegetation Index (NDVI) reflect the global land surface vegetation coverage, which is important for the analysis of the ecological environment. In this study, the spatiotemporal variation in global land surface vegetation NDVI and its climatic driving factors were analyzed for the period 1982-2014, using the GIMMS NDVI3g data set. The results show that the NDVI of global land surface vegetation was increasing during the study period. Although the NDVI of most areas in the southern hemisphere is generally higher than that of most areas in the northern hemisphere, the increase in NDVI in the northern hemisphere is higher than that in the southern hemisphere. Temperature and precipitation have different effects on NDVI at different spatiotemporal scales. Temperature is the driving factor for NDVI variation in most parts of the northern hemisphere, whereas precipitation is the driving factor for NDVI variation in the southern hemisphere.

Keywords: NDVI, global land surface vegetation, temperature, precipitation

Introduction

Vegetation, as an essential component of the global terrestrial ecosystem, plays a vital role in linking the ecosystem and climate systems [1, 2]. The considerable adverse impacts on the environment in recent years are clearly evident from global warming caused by increased emissions of greenhouse gases [3-5]. In the face of a deteriorating environment, we can precisely learn about surface vegetation coverage and reveal the pattern of surface spatial change by evaluating the influence of climate change and other factors on the process of vegetation growth. This is significant for identifying the causes of vegetation change and analyzing the regional ecological environment [6-8]. Therefore, studying the spatiotemporal changes in global terrestrial vegetation coverage and the factors that affect them is important in environmental restoration [9-11].

*e-mail: guojinting0517@163.com

The Normalized Difference Vegetation Index (NDVI) is the ratio of the difference between the reflectivity of near-infrared and red visible light to their sum. It is used to analyze the coverage and growth of land vegetation [12, 13]. It is widely used in the study of dynamic changes in large-scale vegetation activity because it reflects the luxuriance of vegetation and the change in its value over time corresponds to the growth and change in vegetation [14-17]. Based on NDVI data, Wu et al. reported that vegetation coverage was increasing in most provinces in China [18-20]. Li et al. evaluated the NDVI change in the arid region of Northwest China from 1981 to 2001 and reported that NDVI in the southern and northern parts of Xinjiang was increasing. Furthermore, their research showed that human activities had become an important factor driving significant changes in the ecological environment in the arid region of Northwest China [21].

Chen et al. observed that the vegetation coverage rate increased with fluctuation during 2001-2007 in Qinghai Province [22]. Li et al. reported that the NDVI of approximately 74% of the grasslands in Gannan and Northwest Sichuan increased in the growth period during 2000-2018 [23]. Guo et al. studied the spatiotemporal changes in NDVI of vegetation in the northeast frozen soil region and concluded that NDVI increased significantly during the growing season [24]. Furthermore, Myneni et al. found that vegetation coverage increased significantly during 1981-1991 in the northern hemisphere [25]. Bogaert et al. also observed a general increasing trend in the vegetation coverage of Eurasia from 1981 to 1999 [26]. Epstein et al. reported that the vegetation in Arctic and sub-Arctic regions turned green significantly as a result of climate warming [27].

Many ecological factors affect the growth of vegetation [28]. Climate has a considerable influence on vegetation growth because vegetation is extremely sensitive to the influence of temperature and precipitation. Therefore, studying global climate change is important [29]. In this study, spatiotemporal variations in the NDVI of global terrestrial surface vegetation from 1982 to 2014 were analyzed to investigate changes in vegetation in the ecological environment and the climate factors (temperature and precipitation) driving these changes.

Materials and Methods

Data Sets

The NDVI data used herein, which were taken from the GIMMS NDVI3g data set acquired by AVHRR sensors on NOAA's polar orbiting satellite and published by NASA and the Model Research Group (GIMNS), can be obtained at https://ecocast.arc.nasa.gov/data/pub/gimms/ [30-32]. The spatial resolution was 8 km × 8 km, the temporal resolution was 15 days, and the time span was 1982-2014. A total of 396 images were downloaded. Meteorological data (temperature and precipitation) was provided by CEDA Archive, which is available from CRU TS 3.23 (http://badc.nerc.ac.uk/browse/badc/cru/data/cru_ts/cru_ts_3.23) with a resolution of 50 km × 50 km [33].

The monthly average of NDVI was calculated using the maximum value composite (MVC) method. Errors caused by solar altitude angle, sensors, and so on were corrected [34]. GIMMS NDVI data were resampled into data with a resolution of 50 km × 50 km to match the resolution of the meteorological data, thus allowing the data to be consistent and coherent without losing image information [35].

Methods

NDVI, temperature, and precipitation data of global terrestrial surface vegetation during 1982-2014 (33 years) were used to analyze changes in inter-annual and spatial dynamics. Firstly average NDVI, temperature, and total precipitation for each year were calculated using ArcGIS 10.3. Secondly, the temporal and spatial characteristics of NDVI and the climate factors of the 33 years were calculated using unary linear regression and trend-line analysis models, respectively. Thirdly, a correlation coefficient model was used to analyze whether the spatial pixel level NDVI was significantly affected by climate factors.

Analysis Method of Variation Characteristics of Vegetation NDVI and Climate Factors

The inter-annual change trend of NDVI and climate factors was analyzed using a unary linear regression model with NDVI and climate factors (temperature and precipitation) as dependent variable y and time (year) as independent variable x. The results were checked at the significance level of 95% (P<0.05).The unary linear regression formula is as follows [36]:

$$y = at + b + \varepsilon \tag{1}$$

$$a = \frac{\sum_{i=1}^{34}(y_i - \bar{y})(t_i - \bar{t})}{\sum_{i=1}^{34}(y_i - \bar{y}\,)^2} \tag{2}$$

In the formula, y represents NDVI or climate factor, a represents the inter-annual variation trend of NDVI or climate factor of global land, t represents time, b is the intercept and ε is residual error. The average of NDVI (climate factor) and time are represented by $\bar{y}$ and $\bar{\tau}$ respectively.

The trend analysis model was used to simulate the variation trend of each grid to comprehensively reflect the spatial change characteristics of NDVI and climate factors. The calculation formula is [37]:

$$Slope = \frac{n\times\sum_{i=1}^{n} i\times\bar{M}_i-\sum_{i=1}^{n} i\sum_{1}^{n}\bar{M}_i}{n\times\sum_{i=1}^{n} i^2-(\sum_{i=1}^{n} i)^2} \quad (3)$$

In the formula, *Slope* is the slope of a pixel in space which shows the change trend of NDVI or climate factor of the pixel, n is equal to the number of monitoring years, and $\bar{M}_i$ is the NDVI or climate factor value of the *i*-th year. In general, NDVI or climate factor changes as the function of Slope: *Slope*>0 increasing; *Slope* = 0 remaining unchanged; *Slope*<0 decreasing.

Analysis of the Correlation between Vegetation NDVI and Climate Factors

The correlation between vegetation NDVI and climate factors was analyzed using correlation coefficient. The correlation coefficient analyzes pixel-by-pixel correlation between average NDVI and climate factors (average temperature and total precipitation). The correlation formula is as follows [38]:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (4)$$

In the formula, r_{xy} represents the correlation coefficient of independent variable x and dependent variable y; x_i and y_i represent the values of x and y in *i*-th year respectively; $\bar{x}$ and $\bar{y}$ represent the average of the two variables, and n represents the number of monitoring years. The absolute value of r_{xy} is in the range of [-1, 1]; the larger the absolute value, the stronger is the correlation.

Results

Change in NDVI of Global Land Surface Vegetation and Climate Factors

Spatial Distribution Characteristics of NDVI and Climate Factors

As shown in Fig. 1a), the average NDVI of the global terrestrial surface during 1982-2014 in the southern hemisphere is higher than that in the northern hemisphere. The NDVI of regions around the equator, such as northern Brazil and Congo, is maximum. In the northern hemisphere, NDVI shows a trend of "low-high-low", which means that the NDVI in mid-latitudes is higher than those in high latitudes and low latitudes. In the southern hemisphere, NDVI shows a decreasing trend from north to south. The global average temperature during the study period is highest around the equator and shows a decreasing trend from low latitudes to high latitudes, with the equator as the boundary (Fig. 1b). The average temperature in the southern hemisphere is generally higher than that in the northern hemisphere. As shown in Fig. 1c), regions with the highest annual average precipitation are mainly located near the equator. Moreover, precipitation in the southern hemisphere is generally higher than that in the northern hemisphere. Most coastal areas in the northern hemisphere witness higher precipitation than inland areas. For example, annual average precipitation in the east and west coastal areas of the United States is higher than that in inland areas, which is closely related to atmospheric movement and the distribution of land and sea. The trend of variation in temperature and precipitation is consistent for all global climatic zones.

Inter-annual Variation in NDVI and Climate Factors in Terms of Research Area

As shown in Fig. 2, the inter-annual NDVI variation range of global land surface vegetation is 0.149~0.165 from 1982 to 2014, which shows a trend of significant growth (*P*<0.01) overall, with an average of 0.158. During this period, though the inter-annual average global temperature and precipitation are fluctuating, they are still increasing significantly (*P*<0.01). By analyzing the variation trends of inter-annual NDVI,

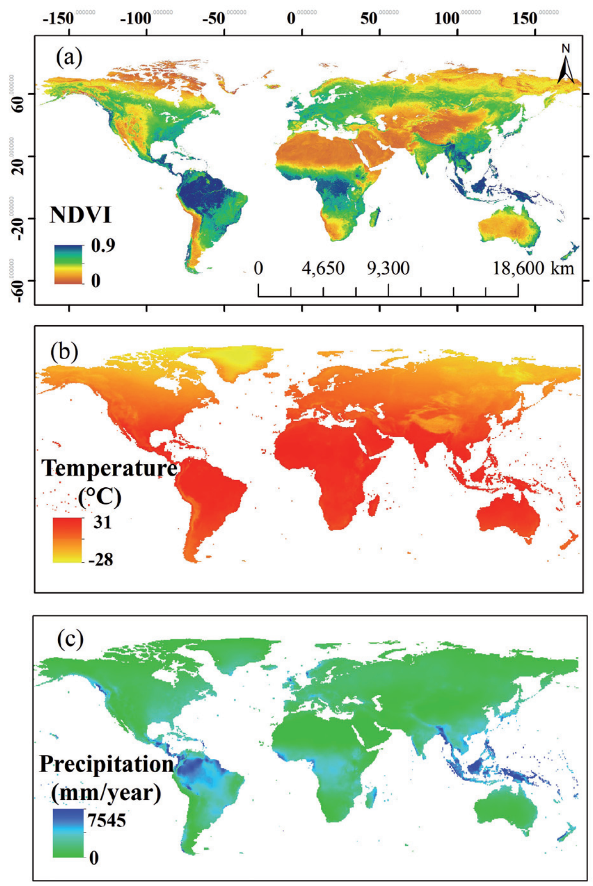

Fig. 1. Spatial variation in global average NDVI, temperature, and precipitation of land surface vegetation from 1982 to 2014.

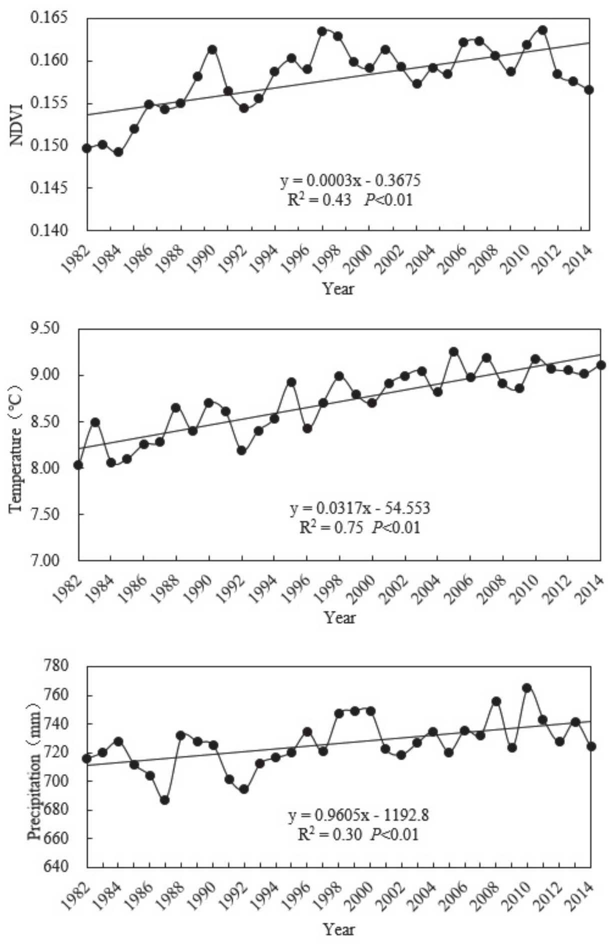

Fig. 2. Inter-annual variation in global average NDVI, temperature and precipitation of land surface vegetation from 1982 to 2014.

average temperature and precipitation, it can be seen that the variation trends of these terms are increasing, which is similar to each other.

Inter-annual Variation in NDVI and Climate Factors in Terms of Spatial Pixels

The inter-annual NDVI and climate factor series of the global land vegetation raster-by-raster data and their corresponding years were calculated using a single linear regression equation. The inter-annual variation trend maps of global vegetation (Fig. 3a, 3c, and 3e) were drawn and the variations were represented by slope in spatial aspect. As shown in these figures, during the study period, the slope is positive when global vegetation coverage increases and negative when it decreases. An ArcGIS 10.3 raster calculator was used to calculate related coefficients. Fig. 3 (b, d), and 3f were drawn by re-classification according to the significance level of the calculated raster data. Fig. 3a) shows that the NDVI of 67% of the global land areas is increasing. These areas are generally located in places with the tropical rainforest climate, tropical arid and semi-arid climate, humid subtropical climate, polar long cold climate, and the subarctic continental climate of Eurasia. 41% of the global land area witnessed an NDVI increase of 0-0.001 pixel. 42% of areas, primarily in the northern and southern parts of Eurasia and the northern and middle parts of Africa, witnessed significant growth in their NDVI; and 13% of areas, which are primarily in the northwestern parts of Canada and the southern parts of Kazakhstan and Argentina, witnessed significant decrease in their NDVI. These results show that areas with significant vegetation growth are more than the areas with significant vegetation decline. In general, global vegetation coverage has significantly increased over the past 33 years (1982-2014). Fig. 3c) shows that the temperature in 93% of the global land areas is increasing. The percentage of areas with a temperature increase of 0-0.02 (27%), 0.02-0.04 (32%) and over 0.06 (34%) are close to each other. In the meantime, temperatures have dropped in the mid-west of Colombia, the southeast of Angola, Indonesia, and the north of Australia. Fig. 3d) shows that 65% of the regions with temperature increases are in most of Europe, North America, Asia, South America, and the most of Africa. In general, the global temperature is increasing. Fig. 3e) shows that 58% of the global areas have witnessed an increase in precipitation, while the areas with 5 mm of annual precipitation decrease and 10 mm of annual precipitation increase account for 3% of the total pixel respectively. Areas with precipitation increase are mainly in Europe, Asia, Africa, and Oceania. Fig. 3f) shows that precipitation increased in 46% of the global areas (which are mainly in Africa) and precipitation decreased in 36% of the global areas; however, the change was not significant.

Correlation between Global Land Surface Vegetation NDVI and Climate Factor

The NDVI of vegetation is influenced by several ecological factors including climate, soil, and terrain. This study analyzed global land surface vegetation NDVI and climate factors to study the correlation between them (as shown in Fig. 4).

Correlation between Global Land Surface Vegetation NDVI and Temperature

As shown in Fig. 4a), the correlation between vegetation NDVI and temperature is positive in 66% of global land areas. 26% of these areas, located in northeast Canada, most of Europe, northeast Russia, a few regions in north and central Africa, and southeast China, witnessed a significantly positive correlation ($P<0.05$). NDVI increased in most of these areas. Furthermore, NDVI increased with an increase in temperature in most of the abovementioned areas.

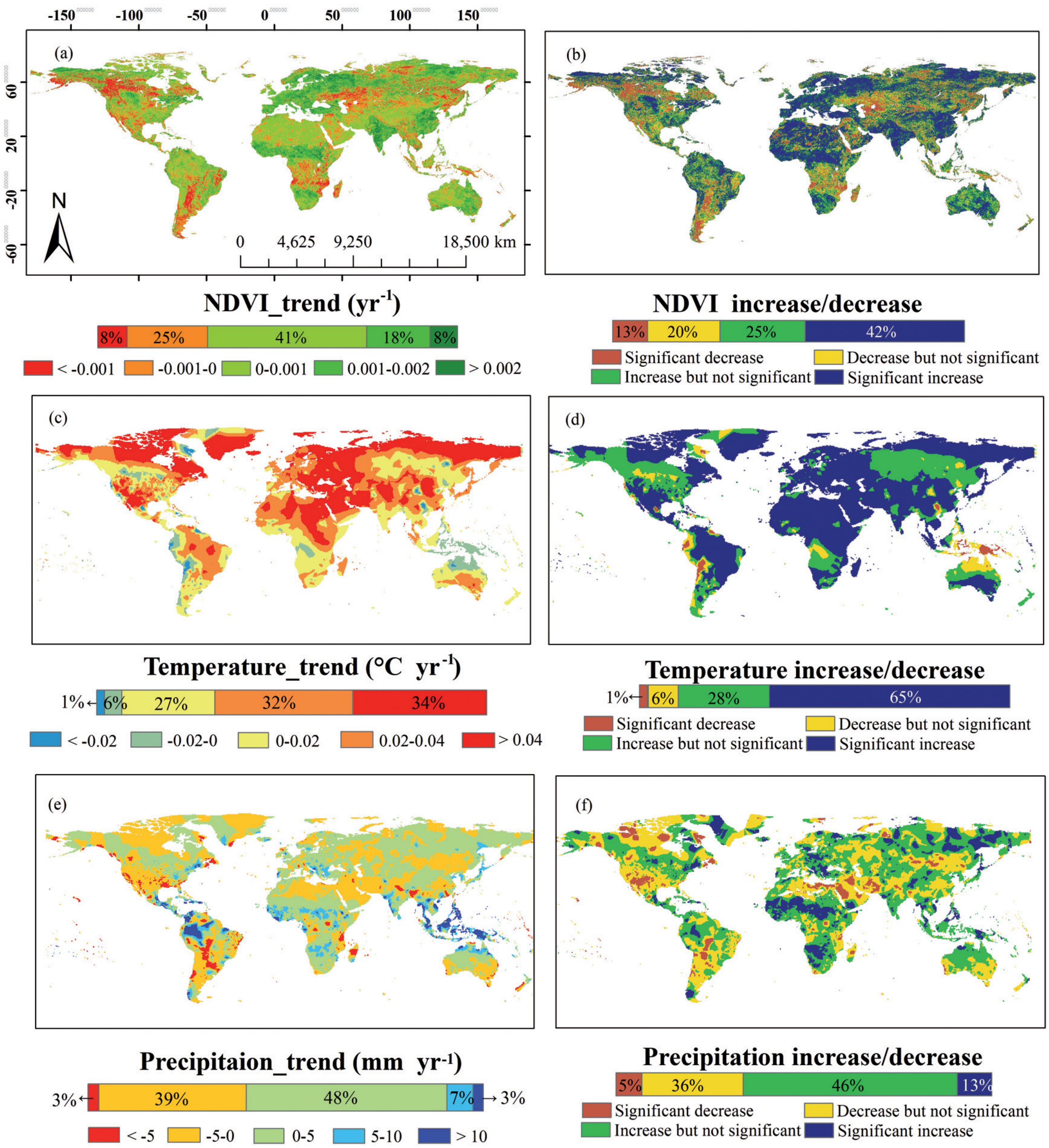

Fig. 3. Variation trend and significance of the global average NDVI, temperature and total precipitation of the global land surface vegetation from 1982 to 2014.

Correlation between Global Land Surface Vegetation NDVI and Precipitation

As shown in Fig. 4b), the correlation between NDVI and precipitation is positive in 63% of the pixels, among which 19% is significantly positive ($P<0.05$). These areas are in the southern part of North America, a small part of Europe and Central Asia, a small part of eastern and southern of South America, parts of central and southern Africa, and most parts of Australia. Furthermore, NDVI decreased with a decrease in precipitation in most of these areas.

Relative Importance of Climate Factors to NDVI

The effect of temperature on NDVI (58%) is greater than that of precipitation (42%); however, the difference between them is not significant (Fig. 5). By analyzing Fig. 5 and the characteristics of global terrestrial climate zones, we observed that precipitation has a dominant influence on NDVI in most hot areas with little rain and that temperature has a dominant influence on NDVI in most areas with low temperatures and heavy rain. These results are in agreement with Roerink's conclusions [39].

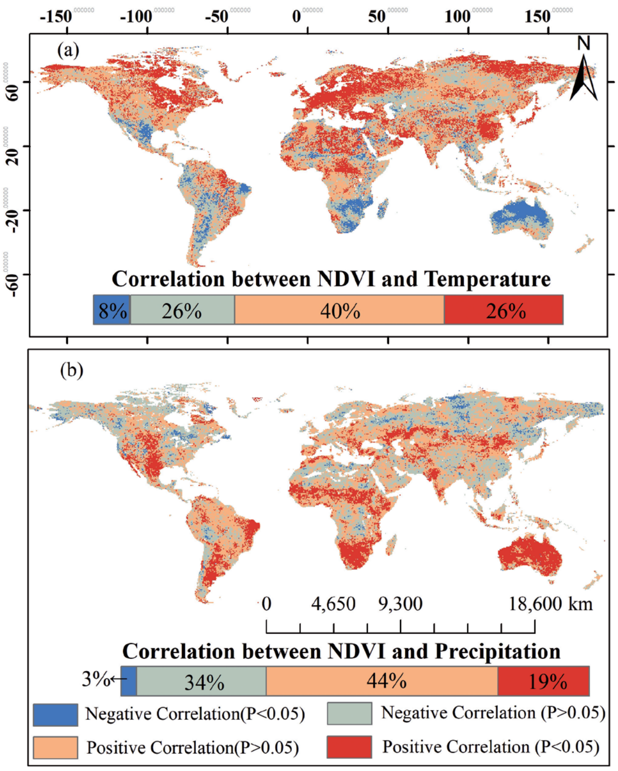

Fig. 4. Correlation between the global land surface vegetation NDVI and climate factors from 1982 to 2014.

Discussion

Temperature and precipitation changes are closely related to the growth of vegetation because they affect the growth and distribution of plants by controlling the photosynthesis and respiration of plants [40, 41]. However, the correlation between NDVI and climate factors is different due to the differences in time and space. According to a study by Su et al., the variation in NDVI is largely driven by hydrothermal conditions. Moreover, the dominant factors limiting the vegetation growth differs across latitude and longitude [42]. Chen et al. showed that the driving factors and intensity of NDVI dynamic variation are significantly different between the southeast and the northwest. Temperature is the main factor which affects NDVI in areas with heavy precipitation in west Xinjiang, while precipitation is the main factor in areas with low precipitation [43]. Temperature and precipitation in the suitable range for plant growth promote the physiological and biochemical reaction of the plant. However, high temperatures and drought inhibit the normal metabolic reactions of plants [44]. Fensholt et al. investigated the variation trend of vegetation greenness during 1981–2007 in semi-arid areas and reported that climate factors (both temperature and precipitation) affect the growth of global land vegetation coverage [45]. Temperature affects the efficacy of soil nutrients and precipitation affects the efficacy of soil moisture, both of which affect the growth of plants. The decomposition of soil organic matter and change in soil temperature are related to the lagging response of plants to temperature, whereas the time interval of plant growth is related to the delayed response of plants to precipitation [46]. Consequently, the effect of climate factors on NDVI changes depending on different spatiotemporal scales and other factors.

Conclusions

The following conclusions were drawn from the analysis of the correlation between the spatial-temporal change in NDVI of the global land surface vegetation

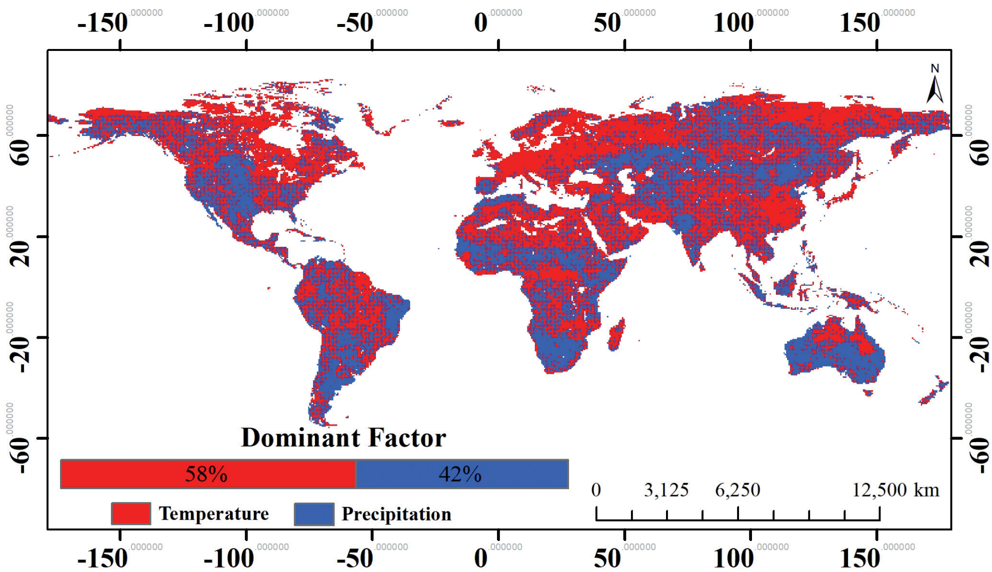

Fig. 5. Leading factors of global land surface vegetation NDVI changes from 1982 to 2014.

and climate factors based on GIMMS NDVI3g data during 1982-2014:

(1) During 1982–2014, the variation in NDVI, temperature, and precipitation of the global land surface were similar; they presented an increasing trend, on the whole. In this period, the NDVI, temperature, and precipitation of equatorial regions were relatively higher than those of other regions, and were generally higher in the southern hemisphere than in the northern hemisphere at the same latitude. However, the NDVI increase in most regions in the northern hemisphere was larger than that in the southern hemisphere. The areas where NDVI decreased significantly were clustered in northern North America, Central Asia, and southern South America.

(2) Temperature and precipitation influences NDVI, and the effect varies under different conditions of temperature and precipitation. The correlation between temperature and NDVI is positive in most areas in the northern hemisphere; that between precipitation and NDVI is positive in most areas in the southern hemisphere; and the correlation between temperature, precipitation, and NDVI is positive in some areas in Central Africa. Compared to precipitation, temperature has a greater effect on NDVI. In China, temperature is the driving factor influencing NDVI variation in southern areas, whereas precipitation is the driving factor influencing NDVI variation in northern areas. In Australia, temperature is the driving force influencing NDVI variation in a few areas in the north, whereas precipitation is the driving force influencing NDVI variation in most areas in the south. Ichii et al. analyzed the NDVI variation during 1982–1990 and reported that the NDVI increase in the middle and high latitudes of the northern hemisphere is related to temperature rise and the NDVI decrease in semi-arid areas of the southern hemisphere is related to precipitation decrease [47]. The findings of this study are consistent with similar research conducted in China and abroad [48-51]. Other ecological factors were not analyzed in this study. Therefore, the conclusions obtained herein may vary from the conclusions obtained in other studies [52].

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Conflict of Interest

The authors declare no conflict of interest.

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