

## Article

# Declining Effect of Precipitation on the Normalized Difference Vegetation Index of Grasslands in the Inner Mongolian Plateau, 1982–2010

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**Abstract:** Grasslands play an irreplaceable role in maintaining carbon balance and stabilizing the entire Earth's ecosystem. Although the grasslands in Inner Mongolia are sensitive and vulnerable to climate change, a generalized effect of climate change on the grasslands is still unavailable. In this study, we analyzed the effects of annual mean precipitation and annual mean temperature on the normalized difference vegetation index from 1982 to 2010 on the Inner Mongolia Plateau. Our results indicated that the normalized difference vegetation index was mostly affected by precipitation, followed by temperature. Spatially, temperature and precipitation had greater effects on normalized difference vegetation index in dry regions than in wet ones. In time series, the effect of precipitation on normalized difference vegetation index had significantly decreased from 1982 to 2010 ( $R^2 = 0.11$ ,  $p > 0.05$ ). However, the effect of temperature on normalized difference vegetation index remained stable. The high variation effect of precipitation on normalized difference vegetation index was due to the significant decrease in precipitation from 1980 to 2010. Thus, 35.47% and 0.56% of the dynamic of normalized difference vegetation index from 1982 to 2010 was accounted for by the precipitation and temperature, respectively. Our findings highlighted that grasslands are adaptable to the significant increase in temperature, but are sensitive to the decrease in precipitation on the Inner Mongolia Plateau.

**Keywords:** normalized difference vegetation index; temperature; precipitation; climate change; Inner Mongolian Plateau

## 1. Introduction

The global ecological environment is under a serious threat, such as loss of soil productivity due to global warming [1]. The relationship between vegetation and climate change is a hot point in global change studies because vegetation is an important component of the global terrestrial ecosystem [2]. Climate changes can lead to changes in vegetation coverage and productivity [3–5]. As an important ecosystem type, grassland ecosystems have important ecological functions, such as wind and sand fixation, water conservation, soil and water conservation, and biodiversity protection [6]. The normalized difference vegetation index (NDVI) can reflect the growth information of surface vegetation by remote sensing monitoring [7], which is calculated by the sum of the difference between the

reflection value of the near-infrared band and the red band [1]. NDVI is considered to be one of the best indicators for monitoring land vegetation cover and it has been widely used in the study of large-scale vegetation change [8]. The peak NDVI value reflects synthetically the photosynthetic activity of plants under current environmental conditions [9,10].

Hydrothermal conditions are the main factor that causing the difference in NDVI distribution [8]. The dynamic trend of NDVI in different areas is inconsistent. The relationships between NDVI and main climate factors (precipitation and temperature) vary from region to region due to different ecosystems and natural conditions [8]. For example, from 1982 to 1999, NDVI in arid and semi-arid areas of Western China showed an upward trend due to the change in climate from warm-dry to warm-wet [11]. Similarly, from 1982 to 2011, over 33% of the area of China with plants presented a significant increase trend [12]. However, the vegetation coverage in Northeast China showed a continuous downward trend [1]. Moreover, in different regions, the dynamic of NDVI in response to climate factors is also inconsistent. Specifically, the correlation between NDVI and precipitation ( $r = 0.75$ ,  $p < 0.01$ ) in Lhasa was higher than that of temperature ( $r = 0.63$ ,  $p < 0.01$ ) [13]. On the other hand, the correlation between NDVI and temperature ( $R^2 = 0.23$ ,  $p < 0.05$ ) of forests during 5 ~ 7 months in Northeast China was higher than that of precipitation ( $R^2 = 0.19$ ,  $p < 0.05$ ) [14] because the temperature in the eastern and central part of North China had increased significantly, which may promote the growth of vegetation [8,15]. Globally, the increase in temperature affected the increase in NDVI in the northern middle and high latitudinal zones, and the decrease in precipitation had an important effect on the decrease in NDVI in the semi-arid areas of the south [16].

Although most previous research examined the correlation between NDVI and climate [12,16], the sensitivities of precipitation and temperature on NDVI are poorly understood, especially in Inner Mongolia. Most previous studies mainly focused on the temporal and spatial variation of NDVI under climate change [8,17], or other studies only analyzed the sensibility of alpine grassland in respond to precipitation [18]. These studies have improved our understanding of the NDVI-climate relationship, but the NDVI may respond differently to the climate condition in Inner Mongolia because the climate warming in Inner Mongolia is faster than the average global warming rate and vegetation in this area is very sensitive to climate change [19,20]. The Inner Mongolia Plateau is located in the northern frontier of China, which is considered as an amplifier after climate warming because of its sensitive grassland ecosystems. Inner Mongolia has a west-to-east climate gradient, making it an ideal region to explore NDVI in response to temperature and precipitation gradients [21]. Three vegetation types are meadow grassland, typical grassland, and desert grassland along the east-west precipitation gradient [22]. Whether the effects of climate on grasses are the same in arid and humid regions is still unknown. Moreover, with the improvement of people's requirements for the ecological environment, it is becoming increasingly important to understand the sensibility of NDVI in response to climate change.

Therefore, to better manage grassland ecosystems under global climate change, long-term time series of grassland NDVI and climate (1982–2010) were used to analyze the dynamic effect of climate on NDVI in Inner Mongolia. With satellite and climate data, our main purpose is to explore the interannual variation of NDVI and its driving mechanism. More specifically, we aim to address the following questions: (1) Is it temperature or precipitation that dominates the dynamic of NDVI? (2) How does the sensitivity between NDVI and climate vary temporally?

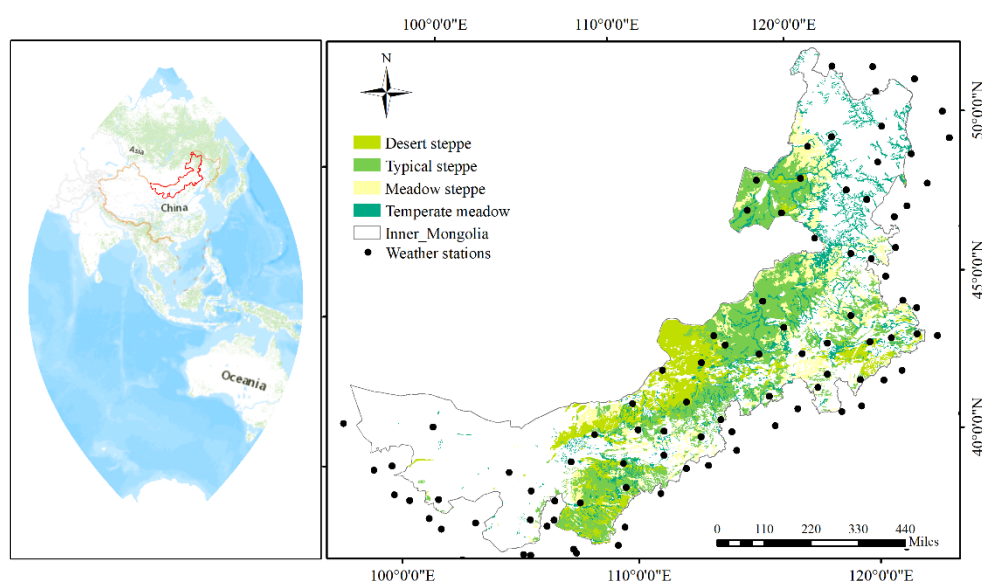
In this study, we innovatively used the linear regression model to find the variable relationships between NDVI and climate from 1982 to 2010. We not only revealed the dynamic effect of climate on NDVI temporally and spatially, but also quantified the contribution rates of temperature and precipitation on the changing of NDVI.

## 2. Materials and Methods

This section will elaborate on the information about the study area, data, and analytical method.

## 2.1. Study Area

Inner Mongolia is distributed in a narrow and long shape (Figure 1). From the northeast to the southwest, with the decrease in precipitation and the increase in temperature, forests, cultivated land, grassland, and desert are distributed, respectively. The climatic zone is distributed in a strip space, transitioning from arid to semi-arid areas (precipitation ranges from 30 to 200 mm, temperature ranges from 5.4 to 9.8 °C) from west to east to semi-humid and humid areas (precipitation ranges from 350 to 560 mm, temperature ranges from −3.9 to 7.5 °C) [23]. The main vegetation type in Inner Mongolia is grassland. The grassland in Inner Mongolia includes three climatic regions: semi-humid region, semi-arid region, and arid region. From east to west, according to China's vegetation classification system [10], it can be divided into the temperate meadow, meadow steppe, typical steppe, and desert steppe.



**Figure 1.** The grassland types in the study area.

## 2.2. NDVI and Climate Data

The long-term GIMMS3g NDVI data with a spatial resolution of 1 km were collected in our study [10]. During a half-month period, the GIMMS3g NDVI data were compiled by merging segments with the maximum value composites (MVC) method [10].

Climatic data of 86 weather stations (Figure 1) were downloaded from the China Meteorological Data Service Center (<http://data.cma.cn/> (accessed on 15 September 2021).) [10]. The primary climatic elements of annual mean temperature (AMT) and annual mean precipitation (AMP) from 1982 to 2010 were collected. Meanwhile, the spatial distribution of AMT and AMP was interpolated by Anusplin 4.2 (Centre for Resource and Environmental Studies, Australian National University, Canberra, Australia) [24], with a resolution of 1 km. Anusplin consists of a series of FORTRAN programs, which uses thin plate smoothing splines to generate continuous raster surfaces with climate records and elevation data [24].

## 2.3. Data Analysis

Firstly, fishnet points were established based on the grassland distribution area in Inner Mongolia by ArcGIS 10.2 (ESRI, Inc., Redlands, CA, USA). In addition, the values of NDVI, AMT, and AMP from 1982 to 2010 were extracted by these fishnet points in ArcGIS

10.2. Next, a simple linear regression model was used to analyze the effects ( $R^2$ ) between NDVI and AMT or AMP from 1982 to 2010, as follows:

$$R_2 = \frac{\sum_{i=1}^n y_i^2 - \frac{(\sum_{i=1}^n (y_i - Y_i))^2}{\sum_{i=1}^n y_i^2}}{\sum_{i=1}^n y_i^2} \quad (1)$$

where  $y_i$  is the actual value of NDVI and  $Y_i$  is the fitted value of NDVI.

Secondly, the effects of temperature and precipitation on NDVI across climatic gradients in Inner Mongolia were analyzed. Specifically, in terms of space, the climatic gradients of average temperature and precipitation from 1982 to 2010 were divided into  $< 1^\circ\text{C}$ ,  $1 \sim 2^\circ\text{C}$ ,  $2 \sim 3^\circ\text{C}$ ,  $3 \sim 4^\circ\text{C}$ ,  $4 \sim 5^\circ\text{C}$ ,  $> 5^\circ\text{C}$ ,  $< 100\text{ mm}$ ,  $100 \sim 200\text{ mm}$ ,  $200 \sim 300\text{ mm}$ ,  $300 \sim 400\text{ mm}$ ,  $400 \sim 500\text{ mm}$ ,  $500 \sim 600\text{ mm}$ ,  $600 \sim 700\text{ mm}$ ,  $700 \sim 800\text{ mm}$ , and  $> 800\text{ mm}$ , respectively. In addition, a simple linear regression model has been used to analyze the effects ( $R^2$ ) between NDVI and AMT or AMP across the climatic gradients.

Thirdly, the variable coefficient of the climate effect on NDVI was calculated by the standard deviation ( $SD$ ) and the mean ( $MN$ ) value of  $R^2$  between the adjacent year, as follows:

$$\text{Variable coefficient} = \frac{SD}{MN} \quad (2)$$

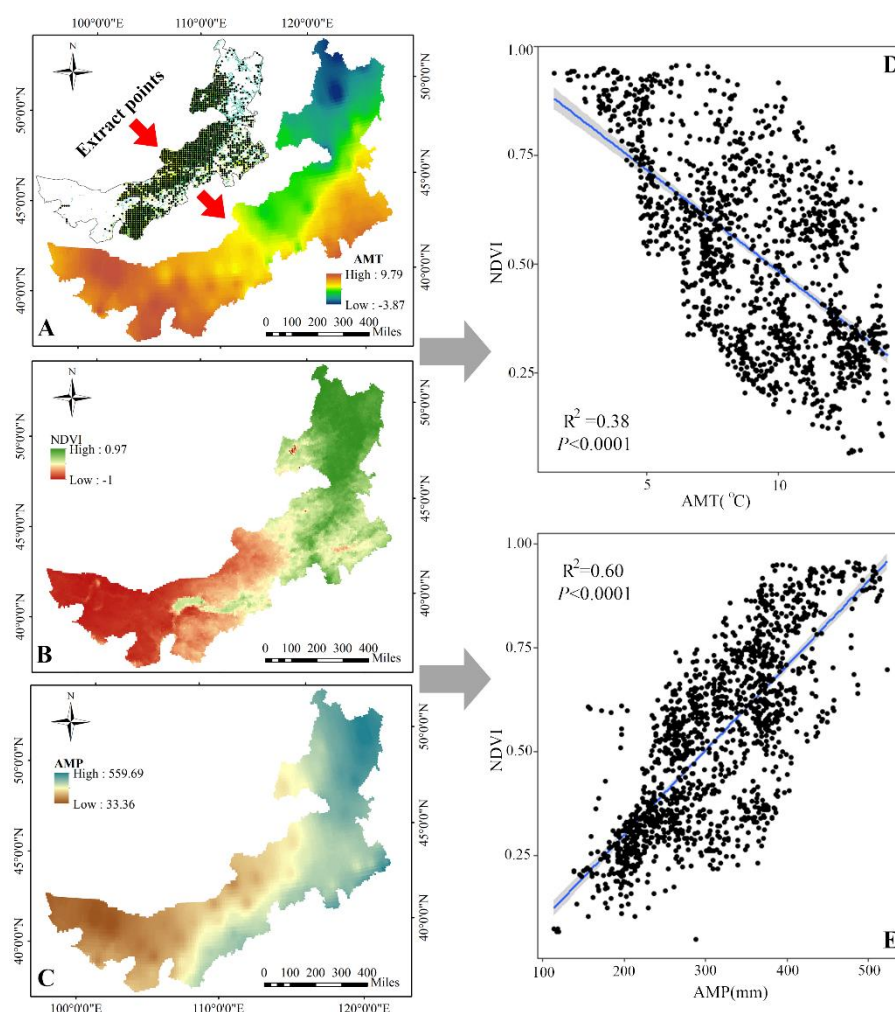
Finally, variation partitioning analysis was used to quantify the contributions of AMT and AMP to the dynamic of NDVI in R with the “vegan” package (R Core Development Team, R Foundation for Statistical Computing, Vienna, Austria) [25].

### 3. Results and Discussion

This section will elaborate on the relationship between climate and NDVI, further analyze the dynamic effect of climate on NDVI, and, finally, explore and discuss the driving mechanism of NDVI variation.

#### 3.1. Climate Relationship with NDVI

From the spatial scale, AMT, AMP, and NDVI exhibited variations in 1982, ranging from  $-3.87$  to  $9.79^\circ\text{C}$  for AMT (Figure 2A),  $-1$  to  $0.97$  for NDVI (Figure 2B), and  $33.36$  to  $559.69\text{ mm}$  for AMP (Figure 2C). Furthermore, AMT was significantly and negatively correlated with NDVI in Inner Mongolia ( $R^2 = 0.38$ ,  $p < 0.0001$ , Figure 2D). In contrast, a significant positive relationship between AMP and NDVI was observed ( $R^2 = 0.60$ ,  $p < 0.0001$ , Figure 2E). Vegetation status is one of the most important and sensitive indicators of climate change [26]. The northeast part of Inner Mongolia is semi-humid, with annual precipitation of more than  $500\text{ mm}$  [27], which is mainly affected by the East Asian monsoon [21]; therefore, a high NDVI value in the northeast of Inner Mongolia was observed. In contrast, the low temperature and the insufficient rainfall in the western region of Inner Mongolia would explain the low NDVI value (Figure 2B). Most of the western region belongs to desert steppe area and there are many bare lands with sparse vegetation cover [27]. Thus, the western region of Inner Mongolia is windy and dry with little rain, coupled with sufficient sunshine and strong evaporation, as a result of lower NDVI [21,23].



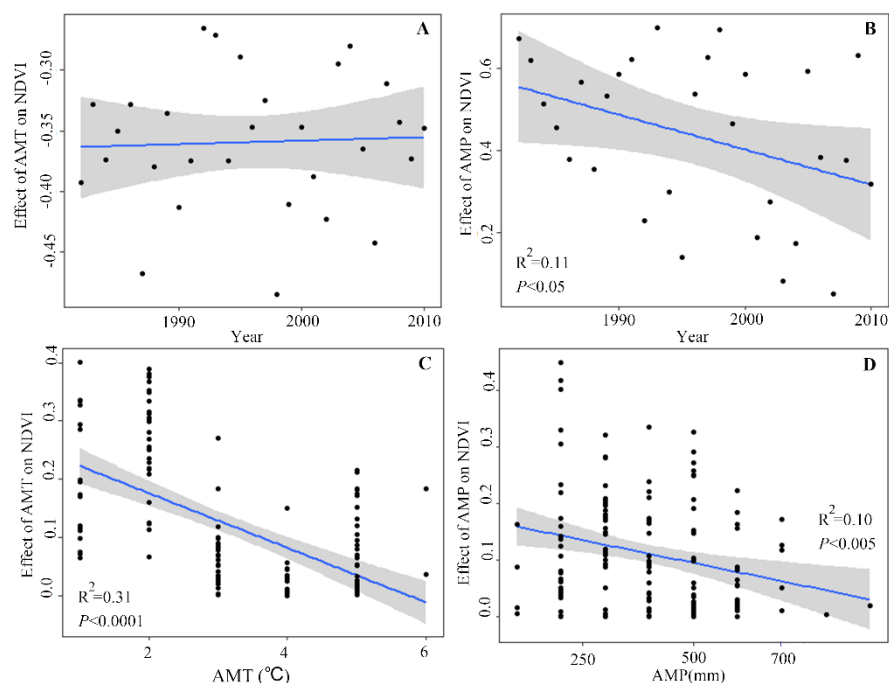
**Figure 2.** Spatial patterns of AMT (A), NDVI (B), AMP (C), and correlation between NDVI and temperature (D) and precipitation (E) in 1982. AMT, AMP, and NDVI represent the annual mean temperature, annual mean precipitation, and the normalized difference vegetation index, respectively.

### 3.2. Spatial and Temporal Analysis of the Effect of Climate on NDVI

From 1982 to 2010, the effect of AMT on NDVI showed no significant change (Figure 3A). In contrast, the effect of AMP on NDVI presented a significant decreasing trend ( $R^2 = 0.11$ ,  $p < 0.05$ , Figure 3B). From the spatial scale, with the increase in AMT, the effect of AMT on NDVI decreased significantly ( $R^2 = 0.31$ ,  $p < 0.0001$ , Figure 3C). Similarly, with the increase in AMP, the effect of AMP on NDVI also presented a decreasing trend ( $R^2 = 0.10$ ,  $p < 0.005$ , Figure 3D). Why did climate generate a greater effect on NDVI in dry regions than in wet ones? Here, we proposed three explanations. First, in dry regions, temperature and precipitation are the main factors that determined the growth of vegetation [28]. When the temperature is below  $0\text{ }^{\circ}\text{C}$  and coupled with low precipitation, the growth of plants would tend to stop [29]. However, once the temperature is above the plant growing threshold and coupled with an increase in precipitation, the priming effect of climate on plants would promote their growth [14]. Secondly, arid regions are associated with low ecosystem stability due to their low species diversity and hostile environment [30,31]. Therefore, the plants in dry regions are more sensitive to the dynamic of climate than those in wet regions. Thirdly, the little effect of climate on NDVI in wet regions (Figure 3C,D) might be because the growth of plants was more limited by soil resources than by climate in humid environments [32]. For instance, both nitrogen and phosphorus additions significantly promoted the biomass of grass in humid environments (e.g., AMP = 560 mm in Haibei [33], AMP = 620 mm in Maqu [34], and AMP = 747 mm in Hongyuan [35]). However, the increase in precipitation had a nonsignificant



effect on biomass in Hongyuan [36]. Meanwhile, in areas with concentrated precipitation, excessive precipitation during the rainy season may lead to soil erosion and nutrient loss [37]. Therefore, the effect of climate on NDVI in the wet regions was lower than that in the dry regions.



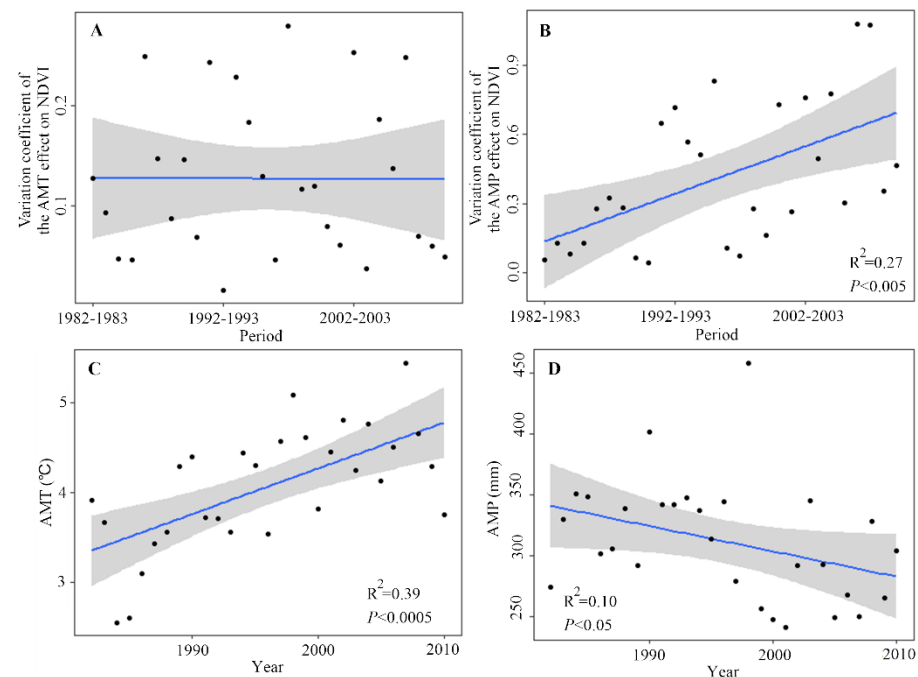
**Figure 3.** The dynamic effects of temperature (A) and precipitation (B) on NDVI in Inner Mongolia from 1982 to 2010. In addition, the dynamic effects of temperature (C) and precipitation (D) on NDVI across climatic gradients in Inner Mongolia. AMT, AMP, and NDVI represent the annual mean temperature, annual mean precipitation, and the normalized difference vegetation index, respectively.

### 3.3. The Variation Coefficient of Climate Effect on NDVI

The variation coefficient of the AMT effect on NDVI showed no significant change in trend (Figure 4A). This result indicated that the NDVI was not sensitive to the significant increase in temperature during 1982–2010 ( $R^2 = 0.39$ ,  $p < 0.0005$ , Figure 4C). In contrast, the variation coefficient of the AMP on NDVI exhibited a highly significant increasing trend ( $R^2 = 0.27$ ,  $p < 0.005$ , Figure 4B). From this result, it can be concluded that the NDVI was sensitive to the significant decrease in precipitation during 1982–2010 ( $R^2 = 0.10$ ,  $p < 0.05$ , Figure 4D). Similar to our results, previous studies also found that the grasses during 1982–1999 in North China were strongly affected by the change in precipitation, but the sensitivity of grass growth to increasing temperature declined [17]. For temperate grassland, water is the key factor of plant growth [28]. For example, in the arid sub-humid area of northern China, precipitation has a positive impact on NDVI [38]. Precipitation is also the main influencing factor of NDVI in the growing season in Northeast China [39].

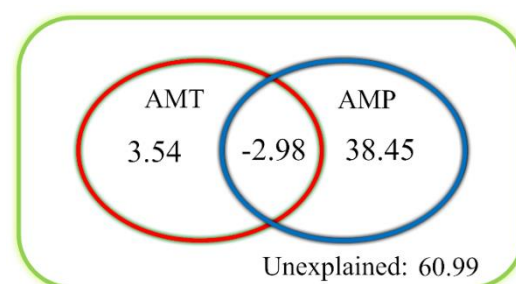
However, the effect of precipitation on NDVI had significantly decreased from 1982 to 2010 ( $R^2 = 0.11$ ,  $p < 0.05$ , Figure 3B). The precipitation is unevenly distributed during the vegetation growing season. The high variation effect of precipitation on NDVI (Figure 4B) was due to the significant decrease in precipitation from 1980 to 2010 (Figure 4D). Previous studies also found that grasslands in the Tibetan Plateau [18] and the US Great Plains [40] were sensitive to the dynamic of precipitation. In Konza, both the drought and high temperature reduced grass productivity [41]. Generally, on a global scale, the grasses in alpine zones worldwide, Central Asia, southeast of South America, and eastern areas of Australia were sensitive to the variability of precipitation. However, the plants in the

Arctic tundra, central South America, and the north of North America were sensitive to the variability of temperature [42].



**Figure 4.** The variation coefficient of the climate effect on NDVI from 1982 to 2010 (variation coefficient of the AMT effect on NDVI (A) and variation coefficient of the AMP effect on NDVI (B)); and the dynamic of AMT (C) and AMP (D) from 1982 to 2010. AMT, AMP, and NDVI represent the annual mean temperature, annual mean precipitation, and the normalized difference vegetation index, respectively.

Quantitative analysis demonstrated that 39.01%, 35.47%, and 0.56% of the dynamic of NDVI from 1982 to 2010 was accounted for by the factors of AMT and AMP, AMP, and AMT, respectively (Figure 5). Water shortage caused by the decreasing precipitation from 1982 to 2010 is an important environmental factor that affects the photosynthetic physiological process and NDVI of grasslands [29,43,44]. The negative effect of water deficit on plants is greater when the decreasing precipitation is coupled with the increasing temperature [28], because water and heat availability are the key factors that mediated the growth of grasslands [21,44]. After sensing water stress, plants resist and adapt to stress through a series of physiological and ecological changes to reduce stress damage, such as stomatal closure, reduction in photosynthesis and transpiration water consumption rate, growth restriction, and so on [43,45]. In order to survive, plants will evolve to be more and more drought resistant [6,42,46]. That is to say, plants need to reduce the impact of precipitation changes on them, so plants are less affected by the precipitation in 2010 than that in 1982 (Figure 3B).



**Figure 5.** Relative contributions of annual mean temperature (AMT) and annual mean precipitation (AMP) to the dynamic of normalized difference vegetation index from 1982 to 2010.

#### 4. Conclusions

By studying the relationship between NDVI and temperature and precipitation sensitivity, we have a better understanding of global climate change and the vegetation response of grassland ecosystems. In this study, we found that the grassland NDVI in Inner Mongolia was affected more by precipitation than by temperature. In terms of space, the climate had a greater impact on NDVI in dry areas than in wet regions. NDVI was most affected by climate when the temperature and precipitation were  $\sim 2^{\circ}\text{C}$  and  $\sim 200\text{ mm}$  in space, respectively. In time series, as the temperature increased, the effect of temperature on NDVI was almost unchanged. As precipitation decreased, the impact of precipitation on NDVI decreased.

Although our finding demonstrated that the NDVI was more sensitive to the change in precipitation than the temperature change, more factors that can affect the NDVI should be considered, such as the soil nutrients, soil microbes, and the percentage of cities, fields, terrain, etc. Moreover, more attention should be paid to the potential effect of climate on plants in arid and semi-arid regions during different seasons.

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