Spatiotemporal change of NDVI in the Arctic Caused by Global Warming and Its Impact on Carbon Stock——A Case Study of Alaska

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Abstract. Northern forests in Alaska store a large percentage of carbon. Besides, vegetation is quite sensitive to climate change. With the intensification of global warming, satellite images have observed a significant greening trend in the region (i.e., the growth of NDVI). In this paper, NDVI was applied to explore the spatiotemporal evolution of vegetation in Alaska and its links with climate variables. The trend of NDVI was estimated with linear regression and Theil Sen Median method. Besides, Pearson correlation coefficient between climate variables and NDVI was computed to explore the characteristics of vegetation in response to global warming. The carbon stock was estimated through Biomass Carbon Density Estimation Model. The results indicated that there was an uptrend in NDVI during 2000~2020. Precipitation was the dominant climate factor, more positively correlated with NDVI. On top of that, carbon estimation based on NDVI suggested that Alaska's average forest carbon stock is roughly 30.978t C/ha. According to the results, NDVI change is more susceptible to precipitation than temperature. The results can serve as a reference for monitoring local carbon dynamics.

Keywords: climate change, global warming, precipitation.

1. Introduction

In recent decades, the warming rate in Arctic is as twice as that of global level [1]. Climate change has a huge impact on ecosystems, increasing potential risks in several regions [2]. Monitoring vegetation with remote sensing data to is conducive to improving the perception of vegetation variations. The normalized difference vegetation index (NDVI) is one of the most prevailing vegetation index, which is extensively used at regional and global scales [3]. Extensive NDVI growth trends (usually termed as Arctic Greening) have been observed in high latitude regions, which are interpreted as signs of in situ increase in vegetation height, biomass, coverage and abundance related to warming [4]. In accordance with the Intergovernmental Panel on Climate Change (IPCC), the change of tundra vegetation, including the greening trend recorded by satellite, is one of the most pronounced examples of the influence of climate warming on land [5].

The high latitude ecosystem accounts for nearly 40% of the global terrestrial carbon, which is equivalent to the global atmospheric carbon sinks [6]. The large-scale vegetation climate feedback observed in this area related to greening may affect the local carbon dynamics, and even change the global soil carbon storage. Therefore, the study of the Arctic ecosystem is essential for management and monitoring of carbon stocks and the understanding of the trajectory of climate change. In recent years, satellite researches in some regions have shown that the greening speed has slowed down or reversed (sometimes termed as Arctic Browning) [4]. The current research shows that the responses of Arctic vegetations to global warming are quite heterogeneous. Nonetheless, there are conceptual and technical barriers in the analysis and comprehensive interpretation.

At present, NDVI has been used to measure biological responses to climate change, such as vegetation productivity, photosynthetic activity, biomass and carbon budget. The correlation between NDVI and climatic factors have also been broadly researched worldwide. The current research shows that precipitation and temperature are two primary elements of photosynthesis, which are closely connected with vegetation activities. Moreover, vegetation exerts a dominant role in the global carbon cycle, which is calculable through the difference of gain and loss with NDVI [7].

The temperature in Alaska is expected to rise 2~6 ° C in the next 50 years [8]. Vegetation growth is very sensitive to climate change. Alaska's northern forests store a large quantity of carbon, especially in the soil organic layer, which may be particularly vulnerable to interference related with climate change [9]. Therefore, it is very difficult to directly measure the carbon reserves in this area. Based on this, the purpose of this study consist in fully understanding the change of NDVI's spatiotemporal model and its impact on the carbon dynamics of Alaska region with the change of temperature and precipitation from 2000 to 2020. More specifically, the paper aims to explore the long-term NDVI trends in Alaska in order to conclude changing patterns of ambient, thus helping improve ecological management and environmental improvement. Secondly, the links between NDVI and climate variables are identified quantitatively so as to determine the impact of climate warming. Finally, NDVI is used to estimate Alaska's total forest carbon stocks and their trends.

2. Study Area and Data

2.1. Study area

Alaska is situated in northwest end of North American continent (60 ° N~70 ° N, 140 ° W~170 ° W), bordering Canada in the east, surrounded by oceans on the other three sides. The majority of the highest mountains in the US are located in the state. Besides, best part of the active glaciers in existence are sited here, of which the largest one is Maraspina Glacier with a drainage area of 5703 km².

Alaska, the largest state in the US, covers a total area of 1717854km², constituting 20% of the national area. According to figure 1, nearly half of the land in the state is located in the Arctic Circle, which has a polar climate with temperature below zero all year round, and the land use types here are mainly wetlands and grasslands. By contrast, the inland has a continental climate, with less precipitation. It can reach 26 ℃ in the polar day in summer and -15 ℃ in the polar night in winter. This part is mostly covered by forests and grasslands, while there is also a small part of cultivated land. The south part is affected by the ocean current, with strong cold wind and relatively more precipitation.

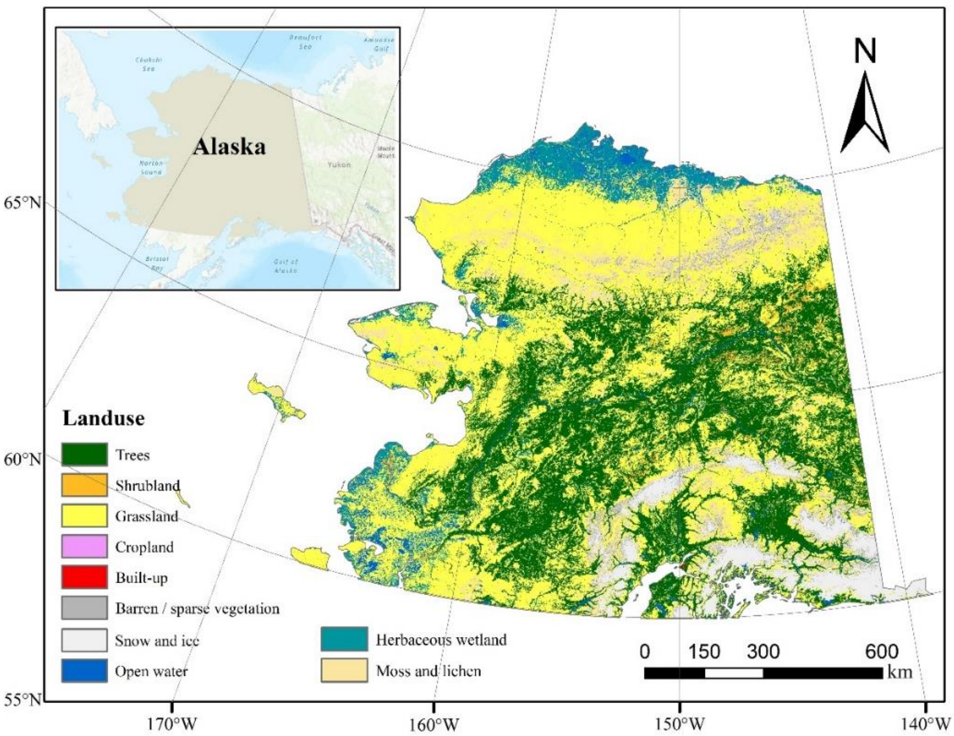

Figure 1. Alaska’s location and land use types

2.2. Data

NDVI, temperature and precipitation data from 2000 to 2020 are used in this study.

NDVI data comes from MOD13A2-V6 product, which provides vegetation index (VI) value on the basis of each pixel. There are two vegetation indexes, namely, NDVI and EVI. The NDVI value is derived from Advanced Very High-Resolution Radiometer (AVHRR) sensors of NOAA. The value is calculated by atmospheric corrected bidirectional surface reflectivity, which has shielded water, clouds, heavy aerosols and cloud shadows. MOD13A2 product has a 1km × 1km spatial resolution and a 16-day time resolution, which covers the period from 2000-02-18 to now.

The temperature and precipitation data come from ERA5 monthly average data set. This product is released by the European Medium Range Weather Forecast Center (ECMWF), which provides a summary of seven parameters. The total monthly precipitation is given in the form of monthly sum. Others are monthly averages. The spatial resolution of the product is 0.25 °, which covers 1979 -2022.

3. Methods

Using NDVI, temperature and precipitation time series data, this paper studies NDVI and its change trend with climate. Based on Google Earth Engine (GEE) platform, we downloaded NDVI images from 2000 to 2020, and synthesized 21 annual images according to the maximum value.

3.1. Linear Regression Method

This model is used to interpret the change trend of annual NDVI. LRM is a common method to assess the interdependence between two or more variables quantitatively based on regression analysis mathematical statistics model [10]. The slope derived from LRM represents the time trend of NDVI (as shown in equation 1). A positive slope means an uptrend, while a negative one indicates a downtrend.

$$Slope = \frac{n\times\sum_{i=1}^{n} i\times NDVI_i-\sum_{i=1}^{n} i\sum_{i=1}^{n} NDVI_i}{n\times\sum_{i=1}^{n} i^2-(\sum_{i=1}^{n} i)^2} \tag{1}$$

Where *Slope* reflects the tendency of NDVI, and n refers to the order number of year. Here, *n*=21. $NDVI_i$ represents the maximum annual NDVI value of the *i*th year.

3.2. Theil Sen Median Method

In addition to LRM, Sen’s slope was also applied to study long-term NDVI trend in Alaska. It is a robust non-parametric method with high computational efficiency and insusceptibility to errors. Therefore, it is quite suitable to interpret the trend of long time series data. This method has extensive application in researches to vegetation dynamics [11]. Sen’s slope is calculated as equation (2).

$$Sen's\ slope = Median\left(\frac{x_j-x_i}{j-i}\right), \forall j > i \tag{2}$$

where x_i and x_j are the value of NDVI in ith and jth year, respectively ($i < j$). *Median* is an intermediate function. If Sen's slope is above 0, it means a positive trend, conversely, it’s a negative trend. After that, Mann Kendall method was introduced to evaluate the significance of results, with a confidence interval of 95% ($p<0.05$), which represents significant [12].

3.3. Relationship between Vegetation Index and Climate Change

Pearson correlation coefficient is used to evaluate the effects of climatic environment on plant growing. The method has been universally utilized to assess the correlativity between vegetation indices and climatic environments [13]. As in equation (3), *R* represents the correlation of *X* and *Y*, and the higher the absolute value of **R**, the stronger the relevancy.

$$R = \frac{\sum(X-\bar{X})(Y-\bar{Y})}{\left(\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})^2}\right)\left(\sqrt{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}\right)} \tag{3}$$

3.4. Biomass Carbon Density Estimation Model

The model is derived from satellite data, which estimates global biomass carbon density according to latitude and longitude and the corresponding maximum NDVI [14]. The calculation formula is as follows:

$$BCD = 111.521 \times ln(NDVI) - 0.452 \times lat - 20.034 \times lon + 0.08568 \times lon^2 + 1278.29 \tag{4}$$

where *BCD* means the biomass carbon density (Mg C/ha), *lat* and *lon* refer to latitude and longitude respectively. In this study, the corresponding value of the maximum NDVI was used as a predicted value of *BCD*, assuming that the maximum NDVI corresponds to the best measurement conditions. Therefore, the input variables of the model were the maximum NDVI, longitude and latitude of the region.

4. Results

4.1. Spatial Heterogeneity of NDVI

The annual mean NDVI image of Alaska is obtained by averaging the NDVI values from 2000 to 2020. As shown in the figure 2, the mean NDVI of Alaska has spatial differences. Annual average NDVI in the southeast region is pretty low, and values in some pixels are even negative. By contrast, the NDVI of the central region is high (higher than 0.4). The maximum lies between 0.7 and 0.8, distributed in areas occupied by coniferous forests in the sub cold zone.

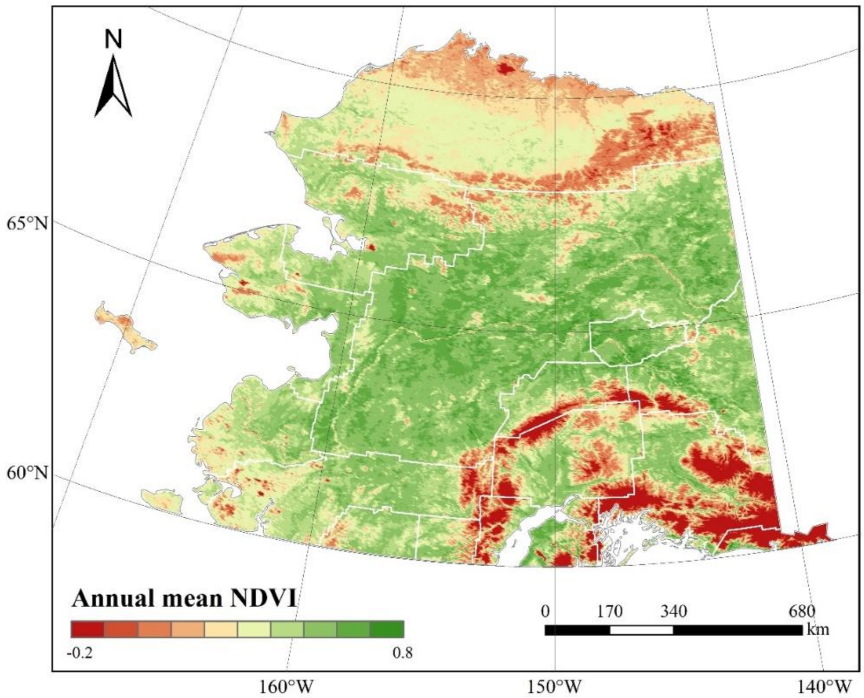

Figure 2. Distribution of annual mean NDVI

4.2. Spatial and Temporal Change Trend of NDVI

Figure 3 shows that from 2000 to 2020, NDVI had a positive trend, and the slopes estimated by the linear regression and Theil Sen Median were both positive. It means that greening was the main trend in Alaska, but there was also browning. The areas with obvious greening mainly occurred in the middle and northern polar regions of Alaska, while browning was principally reflected in the vicinity of mountains.

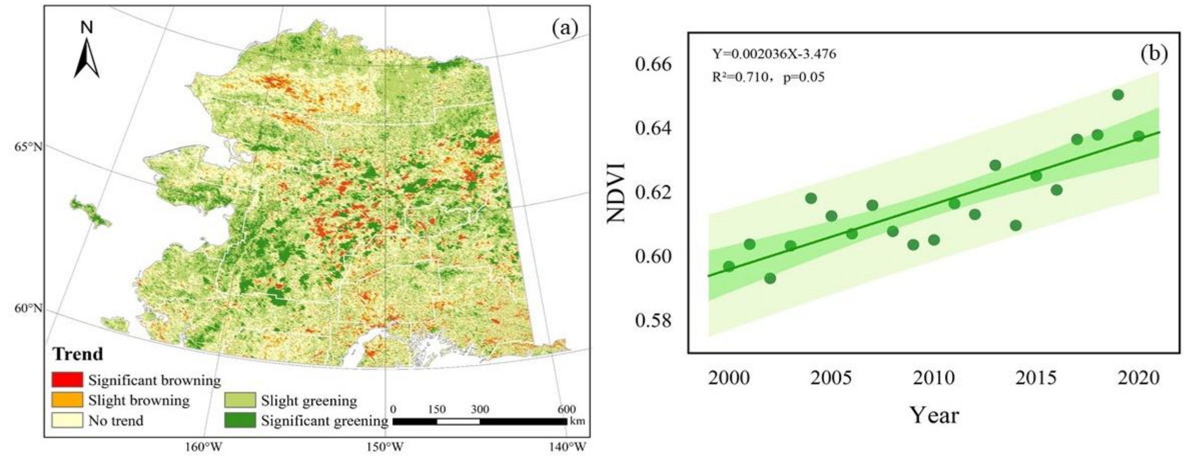

Figure 3. The spatiotemporal tendency of NDVI

4.3. Correlation between NDVI and Climate Change

As shown in figure 4, in general, vegetation growth in Alaska was more likely to be affected by precipitation than temperature. Areas strongly affected by precipitation were largely distributed in the north and southwest plains, while those strongly affected by temperature are primarily in the southeast and north mountains. The southeast of Alaska is mainly a mountain range. Therefore, the prevailing southerly westerly wind can bring rich water vapor from the Pacific Ocean, thus forming topographic rain on the windward slope of the eastern mountain range. At the same time, the warm current along the coast can also increase temperature and humidity. As a result, the precipitation in the eastern mountains is more than that in the plains, demonstrating that water required for vegetation growth in this area is sufficient, so the precipitation is not the main factor here. Hence, NDVI is more closely related to temperature. When it gets warmer, the photosynthesis of vegetation is promoted, thus promoting vegetation growth.

Similarly, in regions within the Arctic Circle, the temperature is below zero all the year round. When the temperature rises, the growth environment of vegetation improves, giving rise to the increase of NDVI. However, the precipitation in western Alaska is much lower than that in the east, so the precipitation is a principle factor limiting the local plant growing. When precipitation increases, the productivity of western vegetation will be enhanced.

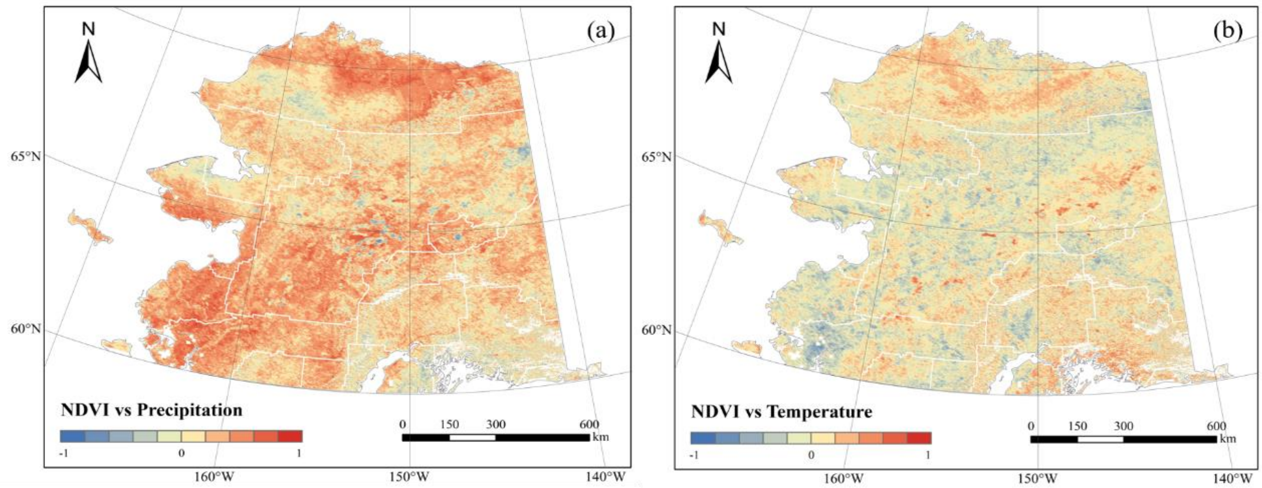

Figure 4. Correlation between NDVI and precipitation or temperature

4.4. Influence of NDVI on Carbon Stock

The average forest carbon storage in Alaska is 30.978 t C/ha. What's more, the carbon stock shows an increasing trend, especially in the past decade (as shown in figure 5). The low value occurred in 2008-2012. In 2008, a serious "zombie fire" occurred in Alaska. At that time, the fire burned more than 33000 acres of land, equivalent to 38% of the total area of land burned by the fire in that state. The extremely low temperature and heavy snow cover in high latitudes can put out most of the fires, but under special conditions, there will still be fires that will not be extinguished. The peat soil under the snow slowly smolders, depending on the thin air under the snow. Even if the naked flame on the ground is extinguished, the fire that will not be extinguished can continue to burn for a long time. Forests in the state are burned, and local carbon reserves are affected, which may last for several years.

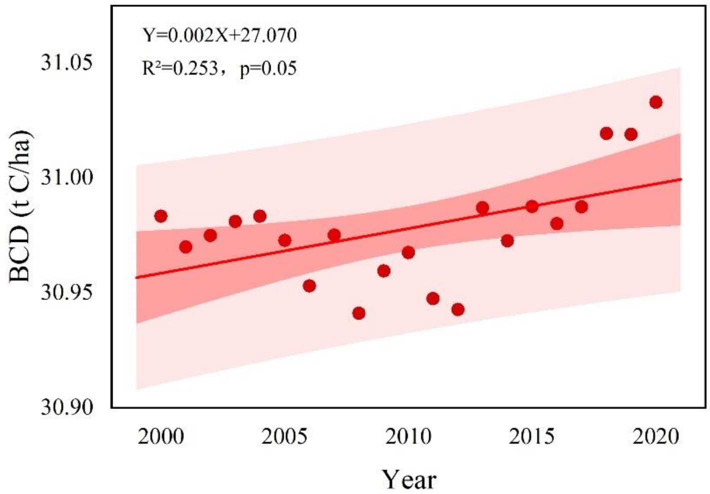

Figure 5. Trend of BCD

5. Conclusions

This paper explores the spatiotemporal variation trends of NDVI in Alaska from 2000 to 2020, and the relevancy between NDVI and climate variables on annual scale. Moreover, forest carbon stocks and its temporal trends are calculated with NDVI. We found a positive trend in both NDVI and carbon storage. In terms of space, most parts of Alaska experienced a significant NDVI growth trend, which is so-called "Arctic Greening" phenomenon. Among them, the NDVI growth rate in the interior and central regions of the Arctic Circle was relatively higher. Besides, the carbon stock analysis based upon NDVI showed that the carbon stock also had a growing trend, especially in the past decade. The low value appeared in 2008~2012, which is considered to be affected by the huge wildfires in 2008. In addition, this study also found that the increase of NDVI was mainly connected with the increase of precipitation, which was the uppermost climatic factor affecting NDVI in Alaska. The overall findings of this study are hopeful to be conducive to understand the links between NDVI trend and climate variations, and the impact of NDVI on carbon cycle can aid in providing theoretical knowledge for Alaska's ecological and environmental management.

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