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Effects of Snowpack on Vegetation Phenology in the Hulunbuir Grassland Region of China

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Abstract

Currently, global warming has a significant impact on snow and vegetation in mid to high latitude regions. This paper primarily utilizes Fractional Vegetation Cover (FVC), snow phenological parameters, including the Start of Snow Cover Days (SCS), Melt of Snow Cover Days (SCM), and Snow Cover Days (SCD), complemented by soil temperature and moisture data. Employing partial correlation analysis, it was found that in this region, SCD is most closely associated with FVC. FVC was most strongly correlated with SCD and SCM. Additionally, the impact of snow cover on FVC is primarily reflected in temperature and moisture. The study's findings offer new insights into snow phenology and the growth of grasslands.

Subject Areas

Environmental Ecology

Keywords

Snowpack, Vegetation, Partial Correlation Analysis, Hulunbuir Grassland

1. Introduction

Currently, global anomalies are pronounced, with extreme temperature increases that have a more pronounced effect on snow cover, further impacting the growth of vegetation worldwide. Grassland vegetation, being widely distributed across the land, plays a crucial role in maintaining carbon storage and regulating regional climates [1] [2]. It is widely acknowledged that grasslands are highly sensitive and vulnerable to climate change.

Changes in snow cover can alter energy flow and the water cycle, thereby significantly affecting ecological processes [3]. Furthermore, snow cover provides essential moisture for vegetation, affects the soil freezing and thawing cycle, and promotes the growth of vegetation following cold seasons [4] [5]. For northern grasslands, during the snowmelt process, ground temperature is considered the most sensitive factor affecting the snowmelt response [6]. Fractional Vegetation Cover (FVC) can effectively capture the dynamic characteristics of vegetation [7]. For northern grasslands, during the snowmelt process, ground temperature is deemed the most sensitive factor in the snowmelt response [6].

The Hulunbuir grassland, situated in a semi-arid area, is vast and impractical for irrigation with water sources. Vegetation types in the Hulunbuir steppe are mainly influenced by geographical variables and climatic factors [8]. Moreover, the region's long and cold winters are mitigated by ample snowfall, which helps meet the area's water needs and protect vegetation through the winter. This study combines partial correlation analysis to fill the gaps in research on small areas. The main research objectives are as follows: 1) To analyze the degree of association between the three snow phenological parameters and FVC; 2) To elucidate the response of snow phenology in the Hulunbuir grassland to FVC. This study can provide insights for the sustainable utilization of snow in the future.

2. Data and Methods

2.1. Study Area

The Hulunbuir grassland, part of Hulunbuir City, is geographically located as shown in **Figure 1**. It is situated between 47˚20'N to 50˚51'N latitude, spans an area of 113,000 square kilometers, and is predominantly characterized by temperate grasslands. The belt vegetation of Hulunbuir Grassland is divided into three sub-zones from east to west. There are three main types of grassland in Hulunbuir grassland: Desert Steppe, Typical Steppe and Meadow Stepp from west to east [8].

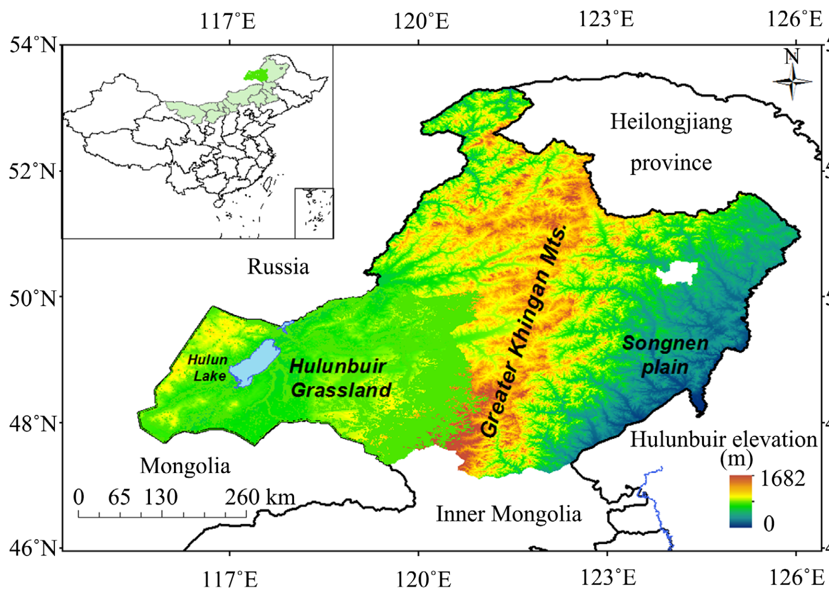


Figure 1. Location of the study area.

The terrain is relatively flat, and the region belongs to a typical temperate continental climate. The seasonal temperature varies greatly, and the average temperature in winter can reach about −20˚C [9]. The Hulunbuir region experiences long and harsh winters, often enduring deep snow for more than five months. Snowfall begins in late October and continues until March of the following year, or around early April.

2.2. Data Sources

A dataset of snow phenology in China based on MODIS from 2000 to 2020. The dataset is provided by National Cryosphere Desert Data Center. (http://www.ncdc.ac.cn). The data are in DOY (day of year) and have a spatial resolution of 500 m. China regional 250 m fractional vegetation cover data set (2000-2023), and scale factor of 0.0001; Global daily surface soil moisture dataset at 1-km resolution (2000-2020), the unit of the data is m^3/m^3; and Daily 1-km all-weather land surface temperature dataset for China's landmass and its surrounding areas (TRIMS LST; 2000-2022), the unit of the data is Kelvin. These dataset are provided by National Tibetan Plateau/Third Pole Environment Data Center (http://data.tpdc.ac.cn). Elevation data were obtained from the 2023 DEM (Digital Elevation Model) provided by GEBCO (https://www.gebco.net/), with a spatial resolution of 15 arc seconds.

2.3. Data Pre-Processing

All the data are based on the original data, using the Nearest neighbor interpolation method, and the resampling is unified to the same spatio-temporal resolution. The time scale of all data is selected from 2001 to 2020, and the resampling is a spatial resolution of 500 m. The time resolution of SCS, SCM, SCD and FVC was year. Uniform spatio-temporal resolution allows for more accurate results. ArcGis 10.4.1, R 4.3.1, OriginPro2024 and MATLAB R2016a were used for data analysis. All the data were studied only in the grassland region.

2.4. Trend Analysis

This study primarily employs a combination of Theil-Sen median trend analysis and the Mann-Kendall test to analyze extensive time series data. This methodology, highlighted in recent literature [9], offers a robust and stable approach compared to other statistical methods. The nonparametric nature of Theil-Sen median trend analysis enhances its resilience to outliers, making it particularly effective for long-term trend analysis. The calculation of the Theil-Sen median trend follows a well-established procedure.

$$\beta = median\left(\frac{X_j - X_i}{j - i}\right) \tag{1}$$

where "β" denotes the inter-annual trend of variable X, and j and i denote the time series data, and X_i and X_j denote the value of X in the i year and the j year, respectively, and median denotes the median function. We believe that there is an increasing trend when “$\beta > 0$”, and a decreasing trend when “$\beta < 0$”.

The Mann-Kendall test method is also used as a nonparametric test, which does not require the data to strictly follow a certain distribution, and has a broad generalization (See **Table 1**). For the sequence X_i, $i = 1, 2, \ldots, n$, the specific formula is as follows:

Table 1. Mann-Kendall test trend categories.

β	*Z*	*Trend type*	*Trend features*
$\beta > 0$	$2.58 < Z$	4	Dramatic significance increase
	$1.96 < Z \leq 2.58$	3	Significance increase
	$1.65 < Z \leq 1.96$	2	Slightly significance increase
	$Z \leq 1.65$	1	Insignificance increase
$\beta = 0$	Z	0	Unchanged
$\beta < 0$	$Z \leq 1.65$	−1	Insignificance decrease
	$1.65 < Z \leq 1.96$	−2	Slightly significance decrease
	$1.96 < Z \leq 2.58$	−3	Significance decrease
	$2.58 < Z$	−4	Dramatic significance decrease

First define the standardized test statistic Z:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, S > 0 \\ 0, S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, S < 0 \end{cases} \tag{2}$$

where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(X_j - X_i\right), \tag{3}$$

And

$$\operatorname{sgn}\left(X_j - X_i\right) = \begin{cases} 1, X_j - X_i > 0 \\ 0, X_j - X_i = 0 \\ -1, X_j - X_i < 0 \end{cases} \tag{4}$$

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

where X_i and X_j denote the X values in year i and year j respectively, n denotes the length of the time series, sgn denotes the sign function, and the range of Z is (−∞, +∞). It is generally believed that, at a given level of significance, if $|Z| > Z_{1-\alpha/2}$, it means that there is a significant change.

2.5. Partial Correlation Analysis

Partial correlation analysis evaluates the linear relationship between two variables while accounting for the linear influence of other variables. This method uses the correlation coefficient r as a measure, where a higher r value indicates a stronger correlation. The significance of the correlation is tested using the p-value, with a conventional threshold for significance set at $\alpha = 0.05$. In this study, three variables were selected to investigate the impact of various snow parameters on the Fractional Vegetation Cover (FVC). The specific formula is as follows:

$$r_{xy\times wz} = \frac{r_{xy\times w} - r_{xz\times w} r_{yz\times w}}{\sqrt{\left(1 - r_{xz\times w}^2\right)\left(1 - r_{yz\times w}^2\right)}} \tag{6}$$

The test statistic for partial correlation analysis is the t-test, with the specific formula as follows:

$$t_{n-k-2} = \frac{r\sqrt{n-k-2}}{\sqrt{1-r^2}} \tag{7}$$

In the formula, r represents the partial correlation coefficient, n is the number of observed variables, and k is the order of the partial correlation. A p-value less than 0.05 indicates significance.

3. Results

3.1. Spatiotemporal Trends of Snow Phenological Parameters, Auxiliary Data and FVC

For SCS, 62.71% of the regions showed an advanced trend, 16.04% showed a delayed trend, and 21.25% showed no change. Significant regions accounted for about 0.52%, among which 51.42% showed a trend of insignificant advance, while significant regions accounted for 11.81%. The regions with slightly significant advance, significantly advance and extremely significant advance accounted for 4.97%, 5.22% and 1.10%, respectively. In addition, 0.01% of the regions showed a very significant trend of delay; 0.22% and 0.29% of the regions showed a trend of significant delay and slightly significant delay, respectively. The areas with no significant delay accounted for 15.53% and 15.53% respectively. On the whole, it showed signs of gradually advancing from the surrounding areas to the interior. The advanced area is mainly distributed in the central vast area of Hulunbuir grassland. The area with no significant change is mainly located around Hulun Lake and has been very stable for 20 years. The delayed area is mainly located in the western part of the grassland. In the past 20 years, the overall trend is −3.9 days/10years (**Figure 2**).

For SCM, 75.58% of the area in advance is located in the vast area of the grassland; 4.72 percent of the regions were delayed, mainly in the western and north-central regions; 19.7% of the area showed no change trend and was relatively stable, mainly located in the west side of Hulun Lake and the southwest of the grassland. Among them, the significant regions accounted for about 13.77%, and the

0.0002% and 0.0027% regions showed a trend of significant delay and slightly significant delay, respectively. In addition, the proportion of extremely significant advance, significant advance and slightly significant advance was 0.7595%, 6.8491% and 6.1608%, respectively, and the proportion of non-significant advance was 61.8093%. In addition, the areas with no significant delay accounted for 0.0059%, the areas with clear significant delay accounted for 13.7694%, and the areas with clear significant delay accounted for 13.7694%. The areas with extremely significant delay were mainly located in the eastern region of the grassland, which was distributed in a narrow region. On the whole, the trend is ahead. On the whole, the trend of advance is −7.2 days/10 years (Figure 2).

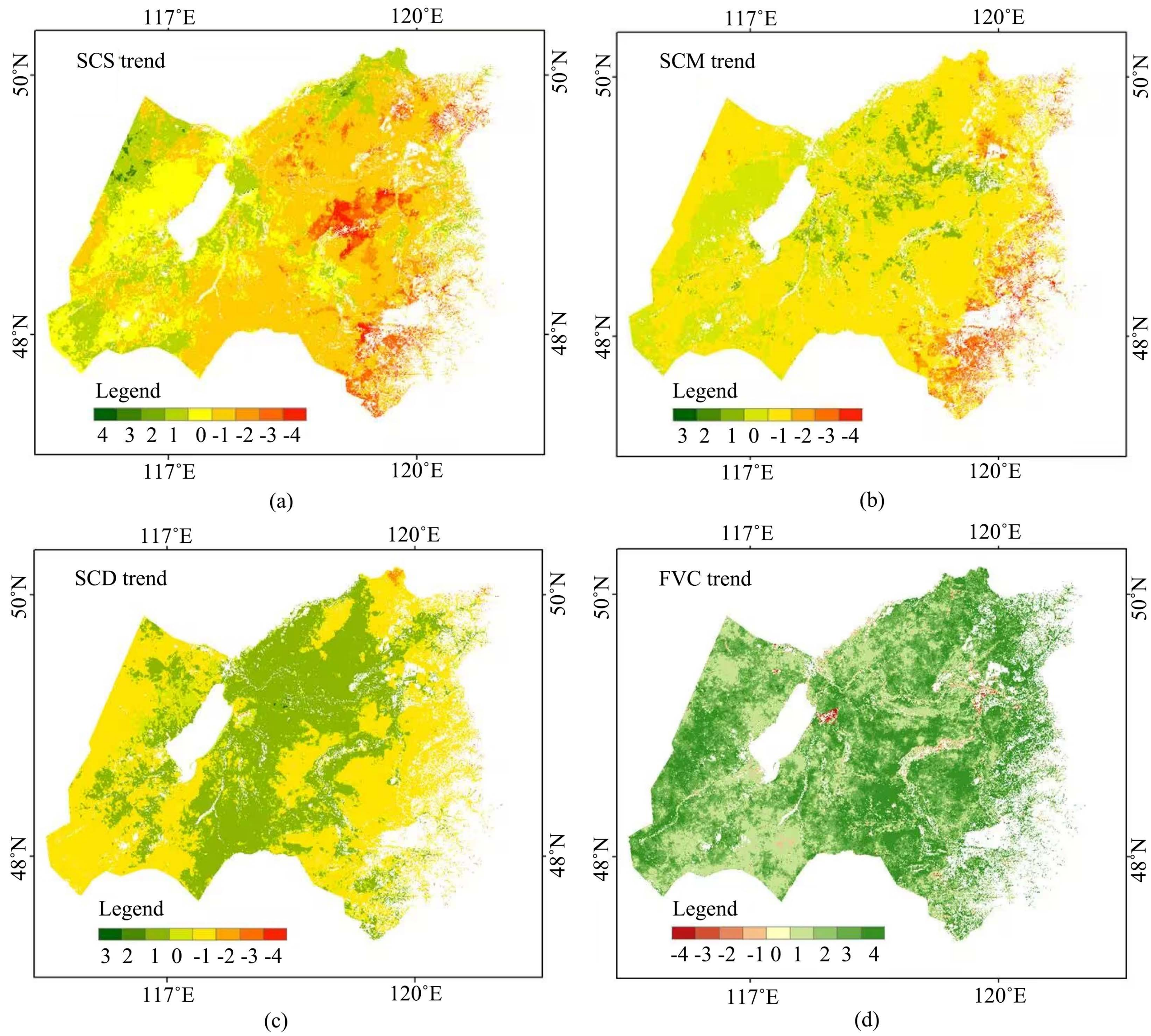


Figure 2. Pixel-by-pixel Spatial trend analysis diagram of SCS, SCM, SCD and FVC in Hulunbuir Grassland during 2001-2020, in which, 4, 3, 2, 1, 0, −1, −2, −3, −4 indicates dramatic significance decrease, significance decrease, slightly significance decrease, insignificance decrease, unchanged, insignificance increase, slightly significance increase, significance increase, dramatic significance increase.

For SCD, 52.27% of the areas showed a decreasing trend, mainly located in the surrounding areas. 36.03% of the regions showed an increasing trend, mainly concentrated in the central region; 11.7% showed no change. 0.80% of the regions showed a very significant decrease trend, and the regions with significant decrease and slight significant decrease accounted for 1.13% and 1.34%, respectively. In addition, the proportion of significantly increased and slightly significantly increased areas was 0.01% and 0.03%, respectively. In addition, the areas with no significant decrease and increase accounted for 49.00% and 36.00% respectively. On the whole, the center increased, the periphery decreased, and the region was regular. The most significant reduction was mainly in a narrow region in the northeast. On the whole, there is a decreasing trend in −3.9 days/10 years (**Figure 2**).

For FVC, 93.14% of the areas showed an increasing trend, almost all over the grassland; 3.41% of the area showed a decreasing trend, mainly in the east side of Hulun Lake and the northeast of the grassland. 3.45% showed no change and scattered in the middle of the grassland. Among them, 0.39% of the regions showed a very significant decrease trend, and the regions with a significant decrease and a slight significant decrease accounted for 0.33% and 0.20% respectively. In addition, the regions with extremely significant increase, significant increase and slight significant increase accounted for 26.22%, 28.92% and 13.77%, respectively. In addition, the areas with no significant decrease accounted for 2.49%, and the areas with no significant increase accounted for 24.23%. On the whole, there is an increasing trend. For FVC, significant increases were found throughout the grassland and significant decreases were almost non-existent. On the whole, there is an increasing trend in 0.3 days/10 years (**Figure 2**).

3.2. Partial Correlation Analysis Results of Three Snow Phenological Parameters

In the pixel-by-pixel partial correlation analysis between Fractional Vegetation Cover (FVC) and Start of Snow Cover days (SCS), the correlation coefficient r ranges from −0.87 to 0.87. Negative correlations account for approximately 52.51% of the total area, while positive correlations cover about 47.49%. Significant negative correlations are found in 45.61% of the analyzed pixels, predominantly in the southeastern part of the grassland. In contrast, most other regions, particularly the central and southwestern parts of the grassland, exhibit significant positive correlations, representing 54.39% of the pixels (**Figure 3(a)**).

There is a significant correlation between FVC and SCM across pixel regions. The correlation coefficient r falls within the range [−0.88, 0.8], indicating varying degrees of relationship strength. Negatively correlated areas account for 73.68%, predominantly covering the entire grassland. In contrast, positively correlated areas are mainly located in the southern, central, and western parts of the Hulunbuir grassland, accounting for 26.32%, with positive correlation r values generally ranging from 0 to 0.4. Among them, 38,358 pixel regions show a significant negative correlation, representing 91.23%. In comparison, 3689 pixel regions exhibit a significant positive correlation, with 8.77% of the regions showing a highly significant negative or positive correlation (**Figure 3(b)**).

Vegetation cover shows a significant correlation with Snow Cover Days (SCD) across pixel regions. The correlation is represented by the coefficient r, which ranges from −0.93 to 0.9. The negatively correlated areas account for 2.53% of the study area, mainly in the western and central regions of Hulunbuir. In contrast, the positively correlated areas constitute 97.47%, primarily located in the central and southwestern parts of the grassland. Significant negative correlations are observed in 58.22% of the regions. Conversely, 41.78% of the regions exhibit significant positive correlations. Extremely significant negative and positive correlations are noted within these proportions (**Figure 3(c)**).

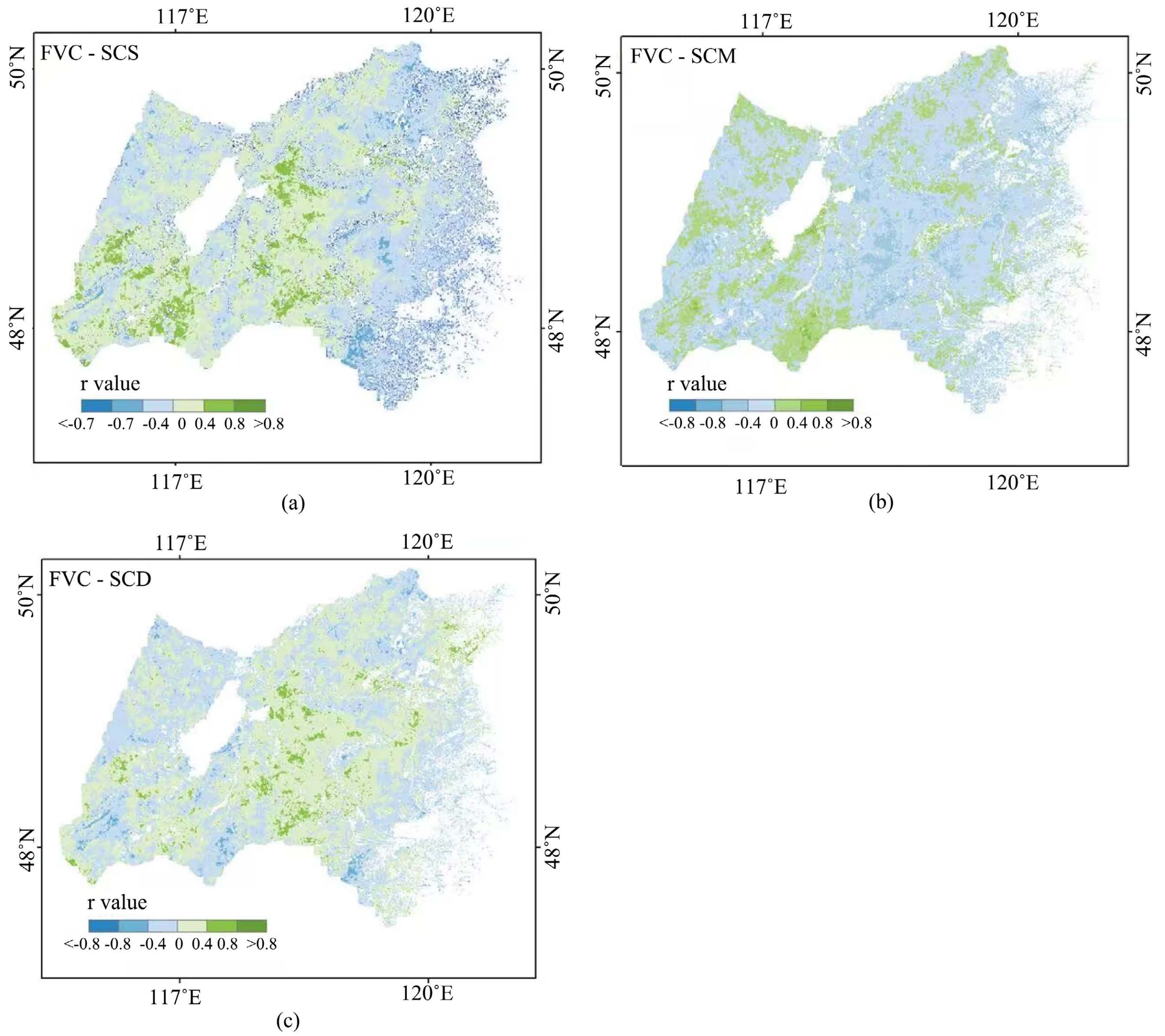
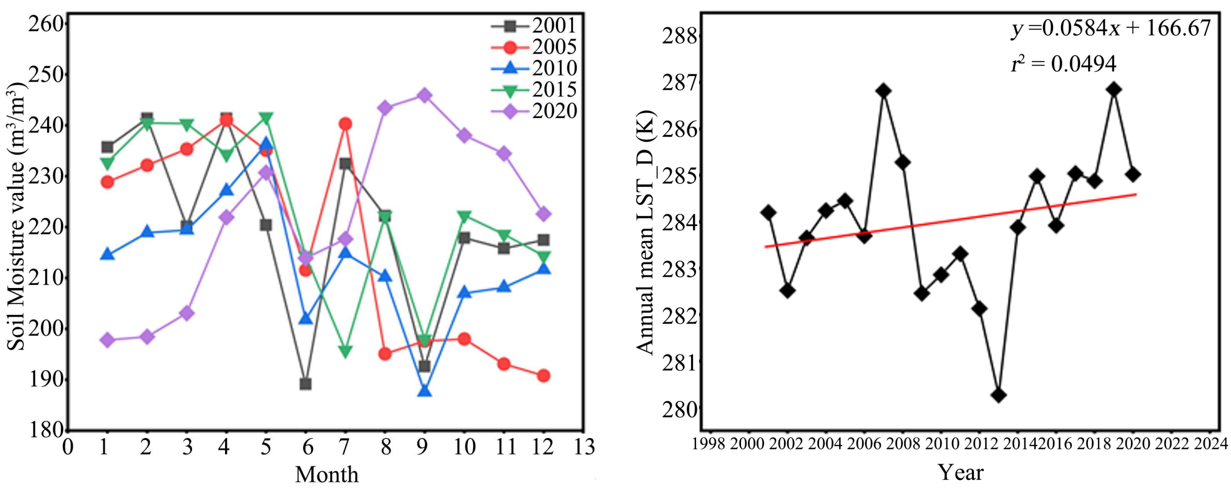


Figure 3. (a), (b), (c) Plots of r-values of spatial term-by-term meta-bias correlation coefficients of FVC with snowpack phenology parameters SCS, SCM, and SCD, respectively, for the years 2001-2020, where the term-by-term meta-data passed the t-tests at the significance level of $p < 0.05$, where $p < 0.05$ is considered significant.

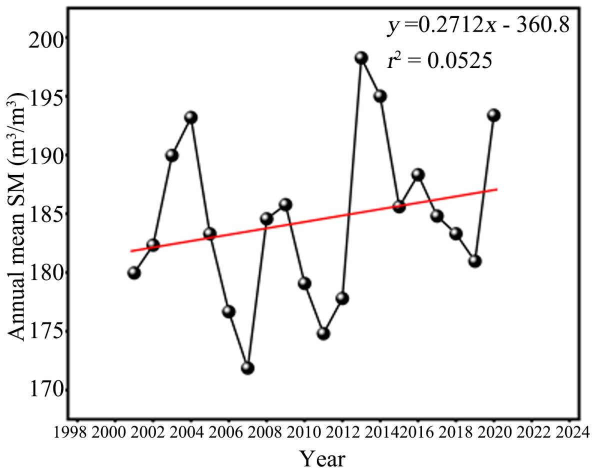
4. Discussion

For the positive correlation between FVC and SCS, it may be due to the central area's flat and broad terrain, which is easily influenced by the cold northwest monsoon. The earlier the snowfall, the more snow accumulates, ensuring that the root systems can survive the winter. The negative correlation might be attributed to the area at the foot of the Greater Khingan Range, which is relatively less affected by the fluctuations of the cold northwest monsoon compared to the central region. In the case of FVC and SCM, the majority of areas show a negative correlation, likely because as the weather warms in the following year, earlier snowmelt is more conducive to the grass receiving the influence of warm air currents, promoting early greening. Long-term trends also indicate signs of earlier snowmelt (SCM) in the area. For FVC and SCD, there is a predominantly positive correlation, as the relatively arid conditions in the area require moisture and insulation for grass growth, which snow provides during the cold and lengthy winter. Traditionally, on snow-covered lands in the Northern Hemisphere, SCD is considered the main factor affecting vegetation. More than half of the study area shows that SCS and SCM are advancing at a rate of 5.33 and 5.74 days of the year, respectively [10], which is similar to our findings.

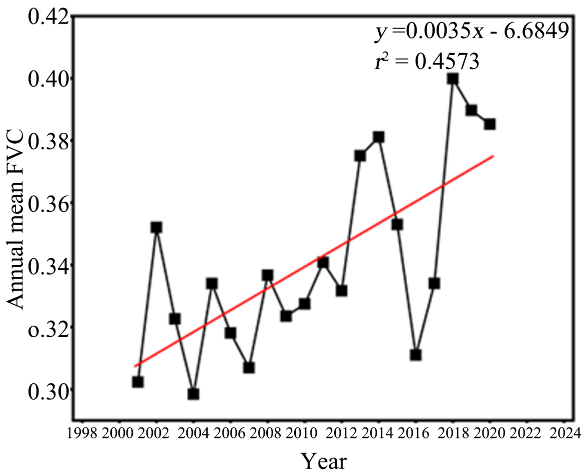
In mid to high latitude regions, snow cover typically leads to a decrease in soil temperature, which hinders vegetation growth [11]. However, the Hulunbuir Plateau is an exception. Here, winter snow cover maintains soil temperature to some extent, supporting vegetation recovery, as evidenced by the increase in local soil surface temperatures. Additionally, when analyzing the relationship between Fractional Vegetation Cover (FVC) and snow phenology, including local soil moisture and Land Surface Temperature_Day (LST_D) is crucial [12]. The study found that local soil moisture (SM) and LST_D are increasing at rates of 2.7/10 years and 0.5 K/10 years (**Figure 4**), respectively, illustrating the "thermal effect" and "moisture effect" of snow cover. It can be deduced that snow cover contributes to the increase in FVC through these thermal and moisture effects.



(a) (b)



(c)



(d)

Figure 4. (a) Line chart of monthly soil moisture content in Hulunbuir Grassland in 2001, 2005, 2010, 2015, and 2020. (b), (c) and (d) are the annual average trend charts of LST_D, SM, and FVC, respectively.

5. Conclusion

In the past, when studying large areas, there was no strict distinction made between different types of vegetation. Here, we only mask grasslands and select them as the subject of our study. Through partial correlation analysis, it can be observed that while the proportion of positive and negative correlations between FVC and SCS is not significantly different, the correlations between SCD and SCM with FVC are strong, mainly showing negative correlations with coefficients reaching −0.32 and −0.42, respectively. Overall, although both SCS and SCM have occurred earlier, they both have a promoting effect on the local FVC. This promoting effect is mainly reflected in the "thermal effect".

Conflicts of Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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