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Analysis of Spatiotemporal Variation Characteristics and Influencing Factors of Grassland Vegetation Coverage in the Qinghai–Tibet Plateau from 2000 to 2023 Based on MODIS Data

Xiankun Shi [1,2,3], Dong Yang [4], Shijian Zhou [5], Hongwei Li [6], Siting Zeng [3], Chen Yin [6] and Mingxin Yang [1,2,4,*]

[1] Xining Natural Resources Comprehensive Survey Center, China Geological Survey, Xining 810021, China; 2022120394@ecut.edu.cn
[2] Key Laboratory of Coupling Process and Effect of Natural Resources Elements, Beijing 100055, China
[3] School of Surveying and Geoinformation Engineering, East China University of Technology, Nanchang 330013, China; zengsiting@ecut.edu.cn
[4] School of Grassland Science, Beijing Forestry University, Beijing 100083, China; yd96062@bjfu.edu.cn
[5] School of Software, Nanchang Campus, Nanchang Hangkong University, Nanchang 330063, China; shjzhou@nchu.edu.cn
[6] Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100094, China; lihongwei@aircas.ac.cn (H.L.); yinchen22@mails.ucas.ac.cn (C.Y.)
* Correspondence: ymxin@bjfu.edu.cn

Abstract: Changes in grassland fractional vegetation coverage (FVC) are important indicators of global climate change. Due to the unique characteristics of the Tibetan Plateau ecosystem, variations in grassland coverage are crucial to its ecological stability. This study utilizes the Google Earth Engine (GEE) platform to retrieve long-term MODIS data and analyzes the spatiotemporal distribution of grassland FVC across the Qinghai–Tibet Plateau (QTP) over 24 years (2000–2023). The grassland growth index (GI) is used to evaluate the annual grassland growth at the pixel level. GI is an important indicator for measuring grassland growth status, which can effectively measure the changes in grassland growth in each year relative to the base year. FVC trends are monitored using Sen-Mann-Kendall slope estimation, the coefficient of variation, and the Hurst exponent. Geographic detectors and partial correlation analysis are then applied to explore the contribution rates of key driving factors to FVC. The results show: (1) From 2000 to 2023, FVC exhibited an overall upward trend, with an annual growth rate of 0.0881%. The distribution of FVC on the QTP follows a pattern of higher values in the east and lower values in the west; (2) Over the past 24 years, 54.05% of the total grassland area has shown a significant increase, 23.88% has remained stable, and only a small portion has shown a significant decrease. The overall trend is expected to continue with minimal variability, covering 82.36% of the total grassland area. The overall grassland GI suggests a balanced state of growth; (3) precipitation (Pre) and soil moisture (SM) are the main single factors affecting FVC changes in grasslands on the Tibetan Plateau (q = 0.59 and 0.46). In the interaction detection, in addition to the highest interaction between Pre and other factors, the interaction between SM and other factors also showed a significant impact on the changes in FVC of the QTP grassland; partial correlation analysis of hydrothermal factors and FVC of the QTP grassland. It shows that precipitation has a stronger correlation with QTP grassland FVC changes than temperature. This study has enhanced our understanding of grassland vegetation change and its driving factors on the QTP and quantitatively described the relationship between vegetation change and driving factors, which is of great significance for maintaining the sustainable development of grassland ecosystems.

Keywords: grassland FVC; spatiotemporal variation characteristics; trend analysis; driving force analysis; partial correlation analysis; QTP

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1. Introduction

Grassland ecosystems represent one of the most extensive and vital terrestrial ecosystems globally. As the second-largest grassland country in the world, China has approximately 40% of its land area covered by grasslands [1,2]. Grassland not only offer habitat for a wide range of animals, and microbial communities, but they also perform essential ecological functions such as climate regulation, soil conservation, biodiversity preservation, and carbon sequestration [3–5]. Grassland fractional vegetation coverage (FVC) is defined as the ratio of the area covered by vegetation to the total area within a grassland ecosystem [6]. Serving as a crucial indicator of grassland health, FVC reflects both the density and extent of vegetation, providing a clear insight into the ecosystem's overall condition and growth [7,8]. By monitoring FVC, it becomes possible to detect signs of grassland degradation early, enabling timely interventions to mitigate the decline of ecological functions and support the sustainable development of grassland ecosystems [7].

Before remote sensing technology emerged, grassland FVC estimation was primarily based on field surveys, which, while statistically accurate, were time-consuming, costly, and lacked spatial scalability, making them unsuitable for large-scale monitoring [8,9]. With the advancement of remote sensing, new methods for grassland FVC monitoring have become available. Due to its continuity, high timeliness, scalability, and low cost, remote sensing has become widely adopted for large-scale FVC monitoring [10,11]. Traditional remote sensing data processing often requires downloading large datasets and performing complex preprocessing steps like radiometric, atmospheric, and geometric corrections [8,9]. This approach can be time-consuming and limited by computational power and storage capacity, leading to inefficiencies. In contrast, cloud platforms such as Google Earth Engine (GEE) provide cloud-based solutions, allowing users to analyze data directly without using local resources [12]. GEE offers pre-processed, built-in data sources for easy analysis, making it an efficient tool for remote sensing data processing. Its convenience and efficiency have led to its widespread use in agriculture, ecology, environmental studies, and resource management [13,14].

The Qinghai–Tibet Plateau (QTP), known as the "Roof of the World" and the "Third Pole of the Earth", plays a vital role in the global climate system and significantly impacts global climate regulation and ecological balance due to its unique plateau climate [15]. Grasslands, which cover about 70% of the plateau's land area, are the main terrestrial ecosystem in the region. However, the fragile nature of this ecosystem makes it highly susceptible to external disturbances [16]. In the past, economic development and insufficient ecological protection awareness led to issues such as overgrazing and land reclamation, resulting in large-scale grassland destruction [17]. In response, the Chinese government launched various grassland protection and restoration initiatives in the early 21st century, with the QTP being a key region for these efforts [18]. Monitoring the FVC of QTP grasslands over an extended period allows for an assessment of the effectiveness of these initiatives. In addition to understanding the spatial distribution of FVC, identifying the factors that influence changes in grassland FVC is crucial for developing effective grassland policies. Numerous scholars have conducted research on the monitoring and driving factors of QTP grassland FVC [19,20]. However, most studies have only conducted annual statistical distribution of grassland FVC classification ratios and judged the growth of grasslands by the overall FVC coverage ratio of the QTP [21,22]. This method cannot determine the specific degree of recovery and degradation of grasslands compared with the early grasslands at the pixel scale. In addition, existing driving force studies have mainly discussed the impact of changes in major climate factors on grassland FVC in terms of indicator selection, such as precipitation (Pre), temperature (Tem), and other factors. However, there are still many indicators that play a key role in grassland FVC. For example, wind speed (VS) not only affects soil moisture evaporation, but may also change plant transpiration rate and local microclimate environment. Vapor pressure deficit (VPD), as a factor reflecting atmospheric humidity conditions, has an important impact on plant water balance and physiological activities and may also have a huge impact on QTP grassland FVC [23–25].

In addition, soil moisture (SM) and land use conversion (LUCC) also have a large impact on grassland FVC. Among them, soil moisture, as one of the most important physiological factors affecting grassland FVC, is still rarely discussed [26–28]. Soil moisture (SM) is a key factor influencing grassland fractional vegetation cover (FVC). It directly affects plant water uptake, photosynthesis, and growth [27]. When soil moisture is sufficient, plants grow well, leading to higher FVC. In contrast, insufficient moisture causes drought stress, resulting in a decrease in FVC [28]. Additionally, soil moisture is closely linked to climate factors, and climate change can alter moisture availability, further impacting grassland FVC [24,25]. Overall, there is still a lack of relatively comprehensive research on the FVC driving factors.

In order to address the above challenges, this study calculated the spatial distribution of grassland FVC in the growing season of the Qinghai–Tibetan Plateau from 2000 to 2023 through the pixel dichotomy model based on MODIS-MOD13Q1 images. Combining Mann–Kendall and Sen slope estimation and Hurst persistence test methods, the change trend of QTP grassland FVC in 24 years and the sustainability of future grassland FVC changes were analyzed. In addition, the grassland growth index (GI) is used to reflect the fine growth status of the grassland at the pixel scale. The coefficient of variation (CV) was used to explore the degree of spatial fluctuation of QTP grassland FVC in the past 24 years. Considering the limitations of the existing indicator systems in studies on the driving forces of the Tibetan Plateau, this study selects key climate variables (such as temperature and precipitation) while also taking into account the potential effects of soil moisture, wind speed, saturated vapor pressure difference, and land cover on grassland dynamics. And the contribution of influencing factors to FVC changes in grassland on the QTP was quantitatively explored through the geodetector method. At the same time, combined with partial correlation analysis and controlling other variables, the significant correlation between temperature and precipitation factors and QTP grassland FVC changes was analyzed.

2. Materials and Methods

2.1. Study Area

The QTP is situated between 26°00′–39°47′ N and 73°19′–104°47′ E. It stretches approximately 2800 km from the Pamir Plateau in the west to the Hengduan Mountains in the east, bordered by the Kunlun, Altun, and Qilian mountains to the north and the Himalayas to the south. This vast region, with an average elevation exceeding 4000 m and covering around 2.5 million square kilometers (Figure 1), is one of China's primary permafrost areas, characterized predominantly by permafrost and glaciers [17]. As a significant source of major rivers in Asia and an important pastoral region, the plateau features extensive alpine grasslands. The diverse vegetation types on the QTP are influenced by its unique geographical conditions, resulting in relatively low and uneven grassland coverage. Annual average temperatures range from 20 °C in the southeastern areas to below −6 °C in the northwest. Due to the blockage of warm, moist air currents by multiple mountain ranges in the south, annual precipitation decreases significantly from 2000 mm to less than 50 mm, making the grasslands highly vulnerable to both human activities and environmental changes [18].

2.2. Data Source and Its Preprocessing

2.2.1. MODIS Remote Sensing Data

The remote sensing data were selected from MOD13Q of MODIS satellite products, with a spatial resolution of 250 m and a temporal resolution of 16 d. The products include NDVI band, red band, blue band, near-infrared band, mid-infrared band, etc., among which the NDVI band is widely used in the research related to vegetation cover [29], and in this study, the NDVI bands of the 2000~2023 growing season (June~October) were used to calculate FVC of QTP grassland based on the maximum synthesis method. In this study, we used GEE to retrieve the NDVI bands of the growing season (June to October) in each year from 2000 to 2023 and generated the maximum NDVI image of each year based on the maximum synthesis method to calculate the FVC of QTP grassland [30,31].

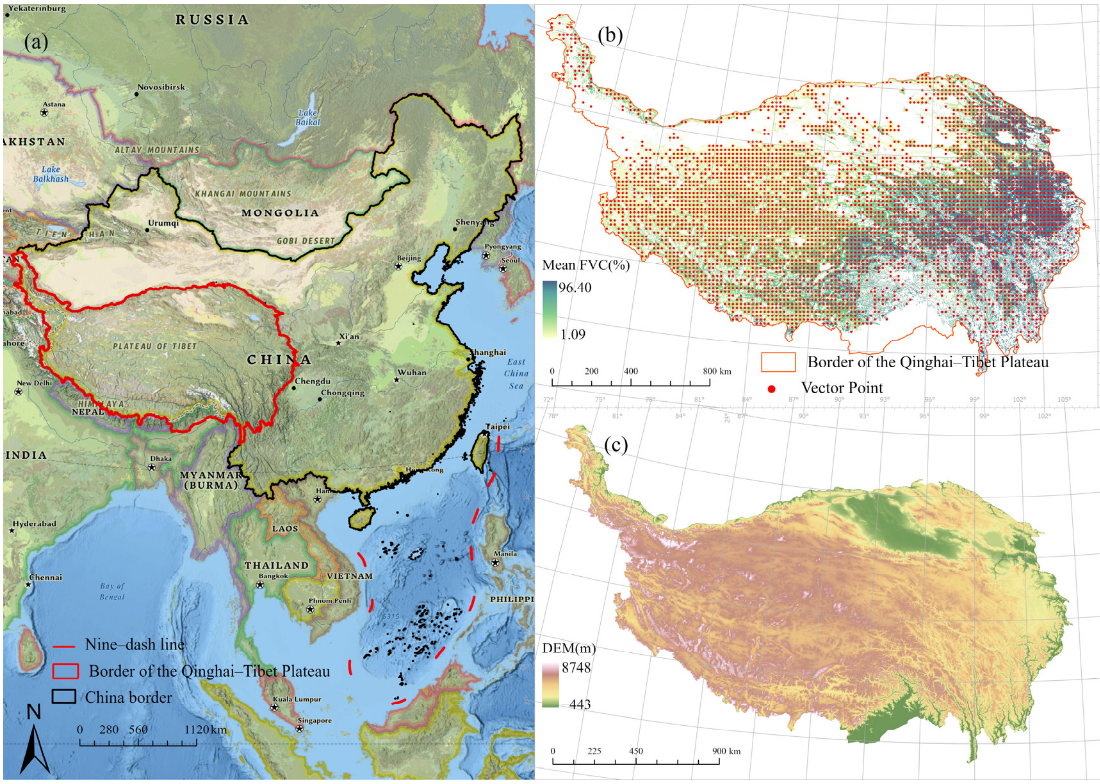

Figure 1. Study area. ((**a**): Geographical location of QTP in China; (**b**): mean FVC and fishing net points on the QTP; (**c**): elevation map of the QTP area).

2.2.2. Other Data

Table 1 lists the data sources of the driving factor indicators required in the experiment. The climate indicators selected the average annual precipitation (Pre), average annual temperature (Tem), wind speed (VS), and saturated vapor pressure difference (VPD) data. In addition to meteorological data, soil moisture (SM) and land use coverage type (LUCC) data were selected in this study to explore the impact on grassland FVC changes. To facilitate subsequent calculations, all data were unified in the coordinate system and resampled to 1 km. Since the independent variable data needs to be input into the category quantity in the geographic detector analysis, this study classified all factors into nine categories according to the natural breakpoint classification method and established a 10 km $\times$ 10 km grid for the QTP to generate fishing net points, extract the corresponding driving variable pixel values, and extract the fishing net points within the QTP grassland area according to the mask, and a total of 3860 sampling points were obtained for driving force research and analysis.

2.3. Methods

This study examined the grasslands of the QTP, using MOD13Q1 data from the Google Earth Engine (GEE) platform as the remote sensing source. Auxiliary data, including meteorological, soil, and land use information, were incorporated to identify driving factors. The pixel dichotomy model was applied to calculate grassland FVC from 2000 to 2023. We conducted a spatiotemporal trend analysis of the FVC results using the Mann–Kendall test, Sen slope estimation, and the Hurst persistence test. The annual growth of the grasslands was assessed at the pixel level through the growth index (GI), while the coefficient of variation (CV) measured the temporal volatility of FVC. Finally, geographic detectors and partial correlation analysis were utilized to identify the main factors influencing QTP grassland FVC. The overall workflow is depicted in Figure 2.

Table 1. Other data source types.

Category	Source	Spatial Resolution	Temporal Resolution
Precipitation data	National Earth System Science Data Center	1 km	2000–2023
Temperature data	National Earth System Science Data Center	1 km	2000–2023
Soil moisture data	TerraClimate—Climatology Lab https://www.climatologylab.org/terraclimate.html, accessed on 1 July 2024	0.04°	2000–2023
Wind speed pressure	TerraClimate—Climatology Lab https://www.climatologylab.org/terraclimate.html, accessed on 1 July 2024	0.04°	2000–2023
Saturated vapor pressure deficit	TerraClimate—Climatology Lab https://www.climatologylab.org/terraclimate.html, accessed on 1 July 2024	0.04°	2000–2023
LUCC data	https://zenodo.org/record/8176941, accessed on 1 July 2024	30 m	2000–2023

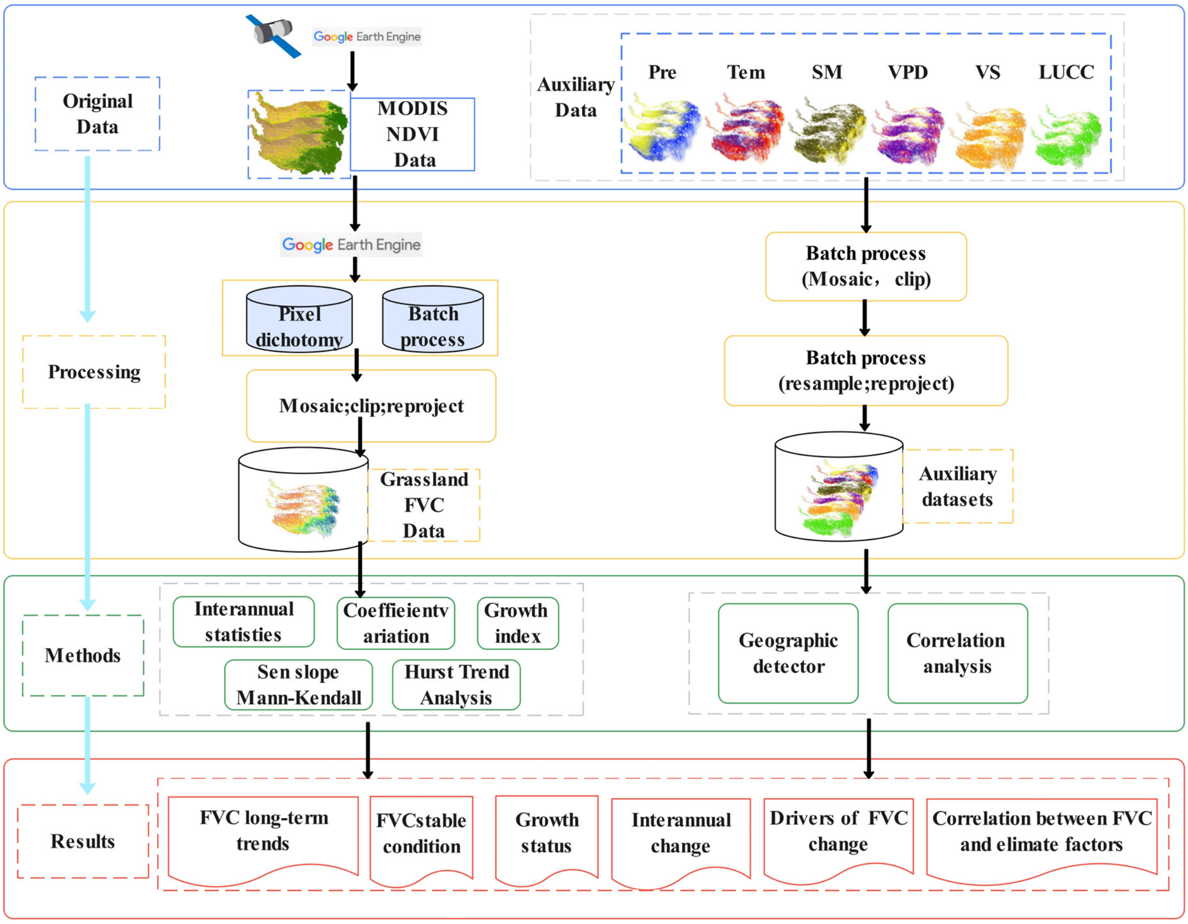

Figure 2. Flow chart.

2.3.1. Pixel Dichotomy Model

The pixel binary model serves as a straightforward and effective approach for estimating the FVC. Utilizing this model [32], the FVC for grasslands in the QTP is determined through an inversion model that relies on NDVI data. (The formula for these calculations can be found in the Supplementary Materials.)

In this study, the grassland vegetation coverage classification in the QTP region by Yan, K et al. [32,33] was used to divide the grassland coverage in this study into five levels (Table 2).

Table 2. QTP grassland FVC classification.

Grassland Vegetation Coverage (%)	Level Classification
0 < FVC < 20	Extremely low vegetation coverage
20 < FVC < 40	Low vegetation coverage
40 < FVC < 60	Medium vegetation cover
60 < FVC < 80	High vegetation cover
80 < FVC < 100	Extremely high vegetation cover

2.3.2. Grassland Growth Index

The grassland growth index (GI) is an important indicator of grassland growth changes and can effectively determine the changes in grassland growth each year compared with the base year [34]. The base year for this study was the average FVC value of the QTP over the past 24 years. GI classification is shown in Table 3. (The formula for these calculations can be found in the Supplementary Materials).

Table 3. QTP grassland growth index classification.

GI	Level Classification
$GI < -0.15$	Worse
$-0.15 < GI < -0.05$	Slightly worse
$-0.05 < GI < 0.05$	Balanced
$0.05 < GI < 0.15$	Slightly better
$GI > 0.15$	Better

2.3.3. Trend Analysis

This study uses the Mann–Kendall test and Sen's slope estimator for trend analysis, along with the Hurst persistence test, to investigate changes in grassland FVC of QTP grasslands over the past 24 years and evaluate their future sustainability. The criteria for these analyses are presented in Tables 4 and 5, with calculation formulas available in the Supplementary Materials [35–37].

Table 4. Changing trends.

Slope (S)	Z	Changing Trends
$S \geq 0.0005$	$Z > 1.96$ or $Z < -1.96$	Increased significance
	$-1.96 \leq Z \leq 1.96$	Insignificant increase
$-0.0005 \leq S \leq 0.0005$	Z arbitrary value	Constant
$S < -0.0005$	$Z > 1.96$ or $Z < -1.96$	Significance reduction
	$-1.96 \leq Z \leq 1.96$	Insignificant reduction

Table 5. Changing trends.

Slope (S)	Hurst (H)	Future Trend Changes
$S \geq 0.0005$	$0.5 \leq H < 1$	Persistence increase
	$0 \leq H < 0.5$	Anti-persistence increase
$-0.0005 \leq S \leq 0.0005$	H arbitrary value	Constant
$S < -0.0005$	$0.5 \leq H < 1$	Persistence reduction
	$0 \leq H < 0.5$	Anti-persistence reduction

2.3.4. Coefficient of Variation

The coefficient of variation (CV) is an important tool for evaluating vegetation cover in different time or space maps. By analyzing the relative sparseness of FVC [37,38], we can better understand the differences in vegetation cover in different time or space maps, as well as the stability and change patterns in different regions and different time periods [38,39]. The volatility level is shown in Table 6 [40]. (The formula for these calculations can be found in the Supplementary Materials.)

Table 6. Changing trends.

CV Value	Volatility
CV < 0.05	Extremely low volatility
0.05 < CV < 0.1	Lower volatility
0.1< CV < 0.15	Low volatility
0.15 < CV < 0.2	Medium-low volatility
CV > 0.2	High volatility

2.3.5. Geographic Detector

GeoDetector is a statistical tool designed to reveal spatial heterogeneity and identify the driving factors behind geographic phenomena. By examining the spatial distribution characteristics of various phenomena (such as environmental, social, and ecological data), this method quantitatively evaluates the impact and explanatory power of different factors on grassland FVC [41,42]. In this study, the GeoDetector model was applied to investigate the factors driving the spatiotemporal variation in grassland FVC on the QTP. The analysis involved six independent variables, including temperature and precipitation data from the National Earth System Science Data Center; soil moisture (SM), wind speed (VS), and saturated vapor pressure deficit (VPD) from TerraClimate—Climatology Lab; and LUCC data from https://zenodo.org/record/8176941, accessed on 1 July 2024. The reference dates of the above variable data are all from 2000 to 2023. Through factor and interaction detection, the model identified the key drivers of FVC variation. In addition, the q-value statistic was applied to evaluate how these independent variables explain the trend of grassland FVC on the QTP [43]. (For details on the specific calculation method and principle as well as the spatial distribution of factors, please see the Supplementary Materials.)

2.3.6. Partial Correlation Analysis

Partial correlation analysis is a statistical technique that examines the relationship between two variables while controlling for the effects of other variables [44]. This method is particularly valuable for investigating the influences of complex ecosystem factors, as it allows for a clear depiction of the relationship between the two primary variables, minimizing the interference from other variables. It has been widely utilized to evaluate the correlations between climatic factors and grassland FVC [45,46]. (The calculation formula can be found in the Supplementary Materials.)

3. Results

3.1. Analysis on Spatial Distribution and Temporal Variation in FVC in QTP Grassland

3.1.1. Spatial Distribution Characteristics

Figure 3 shows that, overall, grassland FVC shows a trend of gradually increasing from west to east. Specifically, areas with extremely low, low, and partially medium grassland vegetation coverage are mainly concentrated in the western part of the QTP, where the ecological environment is relatively fragile and grassland growth conditions are limited. Medium grassland FVC is mainly distributed in the central region, indicating that the region has relatively good growth conditions and relatively high vegetation coverage. In the eastern region, high and extremely high grassland FVC dominate, showing good ecological capacity. By analyzing the statistical proportions of different FVC categories, we can have a clearer understanding of the spatial distribution characteristics of grassland vegetation: extremely low FVC areas account for 31.39%, low FVC areas account for 25.49%, medium FVC areas account for 20.72%, high FVC areas account for 13.64%, and extremely high FVC areas account for only 8.76%. These data not only reflect the current spatial distribution status of grassland vegetation on the QTP but also provide important basic information for subsequent research on grassland ecological changes and their driving factors.

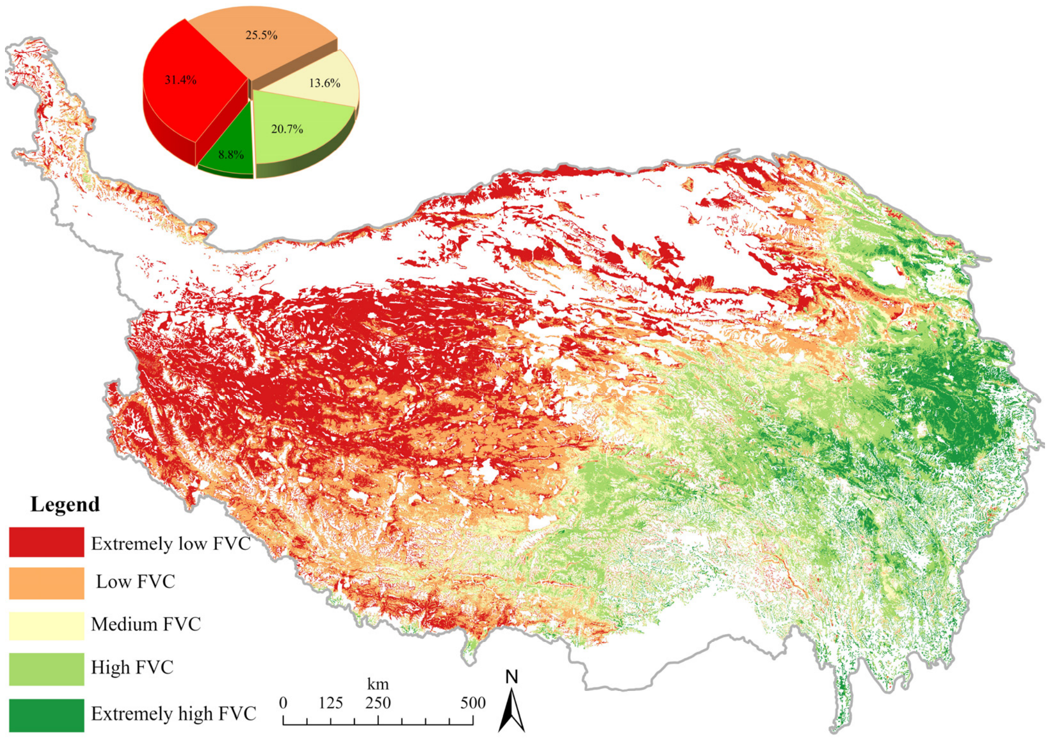

Figure 3. Spatial distribution and classification proportion of mean FVC grassland coverage in QTP grassland from 2000 to 2023.

3.1.2. Temporal Change Characteristics

Figure 4 uses the annual average FVC as a reference to analyze the changing trend of grassland over the past 24 years. The maximum value appeared in 2018, reaching 42.27%, while the minimum value was in 2015, at 38.41%. The data show that there have been two significant declines between 2015 and 2022. It dropped from 40.24% in 2014 to 38.41% in 2015. FVC showed a significant upward trend from 2015 to 2018, rising from 38.41% in 2015 to 42.27% in 2018. FVC will see a significant downward trend again in 2022, falling from 41.65% in 2021 to 39.39% in 2022. Despite this, the annual average FVC value of grassland on the QTP fluctuated between 38.41% and 42.27% from 2000 to 2023, and the overall change range was not dramatic. Overall, QTP grassland FVC showed a slow growth trend during this time period, with a Sen slope of 0.0881%/a, indicating the average annual growth rate. Figure S1 illustrates that over the past 24 years, the annual grassland FVC of grasslands on the QTP exhibits a spatial pattern of being lower in the west and higher in the east. This trend may be closely linked to the lower temperatures and reduced precipitation in the northwestern part of the plateau compared to the eastern region, leading to marked differences in grassland coverage.

As shown in Figure 5, the spatial and temporal distribution of QTP grassland FVC from 2000 to 2023 was quantitatively and qualitatively analyzed. Throughout the time series, more than 30% of the grassland area continued to show extremely low FVC values, while more than 40% of the area continued to show moderate to high FVC values. It is worth noting that although the FVC values of various types fluctuate every year, there is no obvious change in category proportions throughout the long time series. According to the data in Figure 4, vegetation coverage dropped significantly in 2015. About 60% of the regional area had an FVC value lower than 40%, while less than 10% of the regional area had an FVC value higher than 80%. The results reflect the dynamic characteristics of grassland vegetation coverage on the QTP, which can provide important references for ecological changes on the QTP.

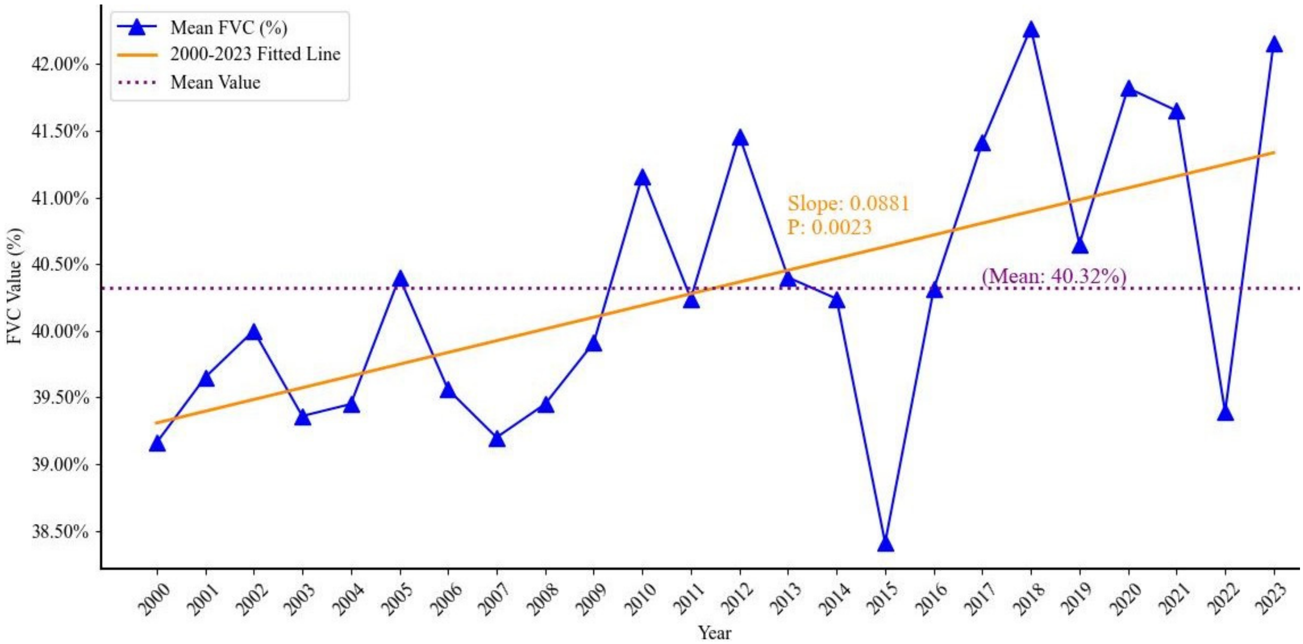

Figure 4. Trend of annual mean FVC in QTP grassland.

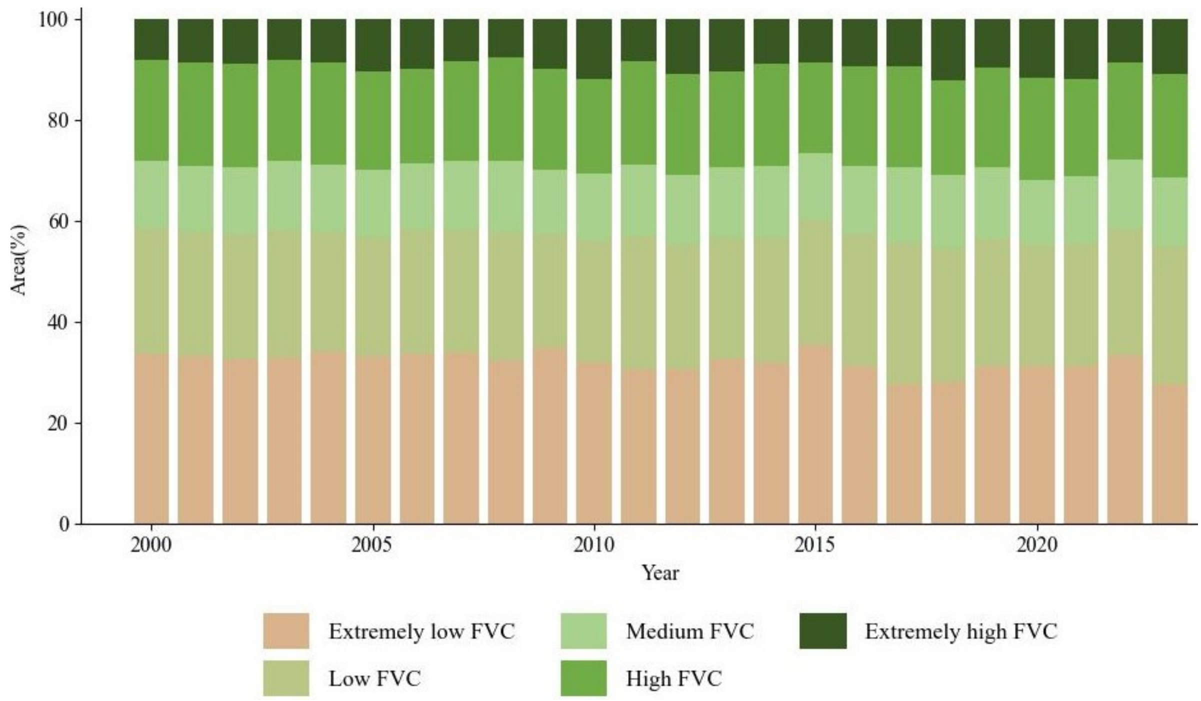

Figure 5. QTP grassland FVC category proportion statistics.

3.2. Analysis of Grassland Growth Status

The analysis presented in Figure 6 indicates that approximately 60% of the area remains in a balanced growth category, while 25% falls into the slightly worse or worse growth category, and only 15% shows slightly better or better growth. Overall, the growth performance of grassland FVC on the QTP is relatively stable. As highlighted in Figure 4, there was a significant decline in grassland coverage in 2015. Concurrently, Figure S2 reveals a notable increase in the proportion of areas with poor and slightly poor vegetation growth in 2015, while areas with better vegetation growth saw a marked reduction, reaching their lowest levels. This suggests that the ecological situation on the QTP was particularly severe in 2015, especially in the western regions, where unsatisfactory growth was concentrated. However, in 2017, 2018, and 2023, the proportion of areas with poor and slightly worse growth prospects significantly decreased, while areas with better growth prospects increased, indicating an improvement in spatial distribution. This positive change is primarily evident in the western and northern parts of the plateau and is crucial for the protection and enhancement of the northwest region, which has weaker ecological conditions. These findings not only highlight the dynamic characteristics of grassland vegetation coverage but also provide a vital foundation for promoting ecological changes across the entire QTP. There is a close relationship between grassland growth and coverage; enhancing growth will contribute to the overall health and sustainability of the ecosystem.

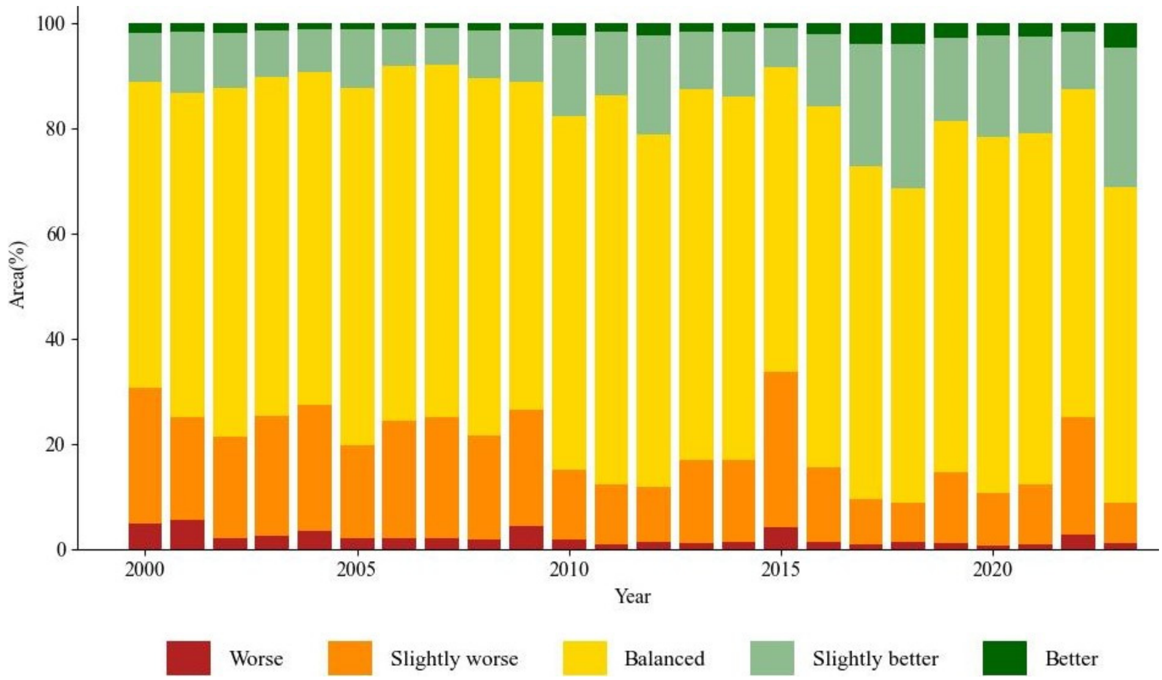

Figure 6. QTP grassland growth index classification and proportion statistics.

3.3. Analysis of Changing Trends

It can be seen from Figure 7. First, by superimposing the trend slope (Slope) and the significance Z value, Figure 7a is obtained, and the superposition result of Slope and Hurst index is shown in Figure 7c. Based on these analyses, the statistical trends and the classification proportions of future sustainable trends are presented in Figures 7b and 7d, respectively. According to the results of Figure 7b, in the past 24 years, QTP grassland FVC has shown a significant growth trend as a whole, with the growth proportion reaching 54.05%. Specifically, areas with significant growth accounted for 21.36%, areas with non-significant growth accounted for 32.69%, and areas that remained unchanged accounted for 23.88%. In comparison, the reduced areas accounted for 22.07% of the total, of which 18.76% were not significantly reduced and only 3.31% were significantly reduced.

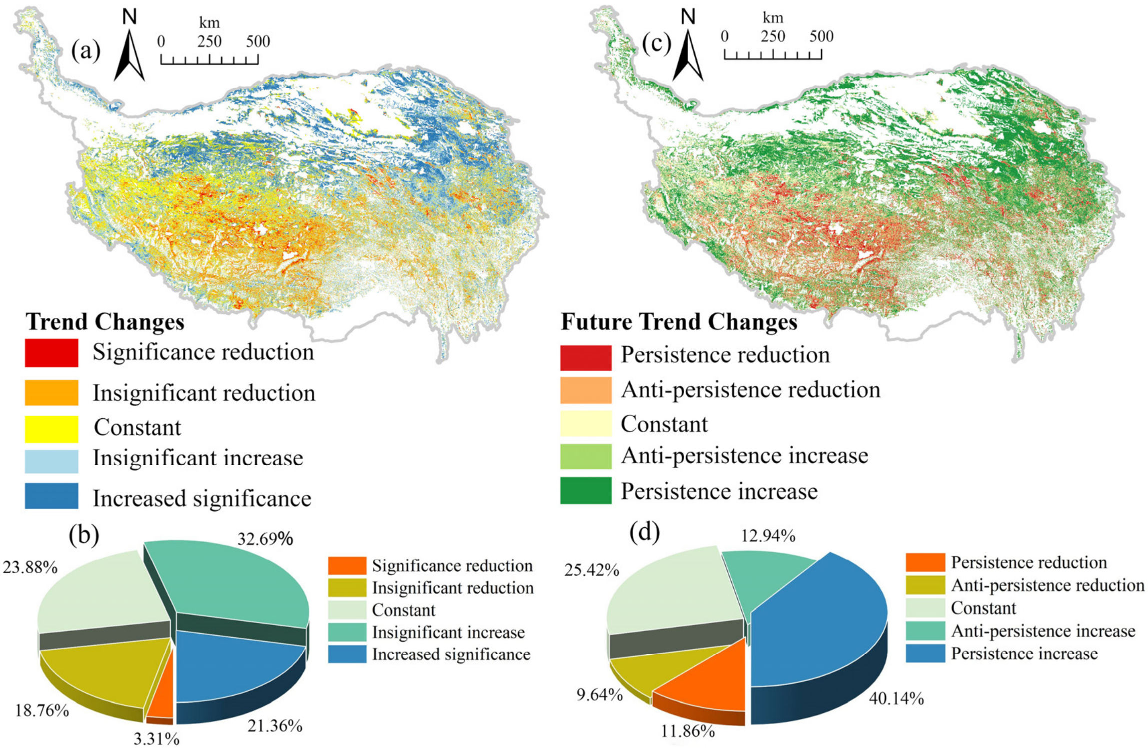

Figure 7. QTP grassland FVC change trend analysis. ((**a**): trend significance; (**b**): trend significance classification proportion; (**c**): future trend; (**d**): future trend classification proportion).

Figure 7c,d shows that the overall trend points to continuous growth. Figure 7d shows that the future growth trend accounts for 53.08% of the total, of which continuous growth accounts for the highest proportion, reaching 40.14%, and anti-continuous growth accounts for 12.94%. The area that will maintain a relatively stable trend in the future accounts for 25.42%, while the future reduction trend accounts for 21.50%, of which the future continuous reduction and anti-continuous reduction account for 11.86% and 9.64%, respectively.

The analysis results of Figure 7a,c show that significant growth and future sustained growth are mainly concentrated in the northern region of the Tibetan Plateau. The dynamic changes and future development trends of QTP grassland FVC reflected in the results indicate that the grassland coverage in this region is showing signs of continuous improvement.

3.4. Volatility Analysis

Figure 8 is the result of quantitative statistics of the fluctuation range, in which Figure 8b shows that the FVC of QTP grassland is in a state of extremely low volatility and low volatility as a whole, accounting for 52.83% of the total. In contrast, the high volatility area accounts for only 6.33%. Additionally, Figure 8a illustrates the spatial distribution of FVC volatility in QTP grasslands. Higher volatility is primarily found in the western region of the QTP, while lower volatility is predominantly located in the eastern region.

Climate factors may be the key factor in grassland growth. The relatively warmer and more humid climate conditions in the eastern region provide a more favorable environment for grassland growth [38]. The results reflect the dynamic characteristics of grassland vegetation on the QTP and provide an important basis for in-depth research on the impact of climate factors on the grassland ecosystem on the QTP. By analyzing the fluctuation characteristics of FVC in QTP grassland, scientific guidance can be provided for ecological protection and sustainable management of the QTP.

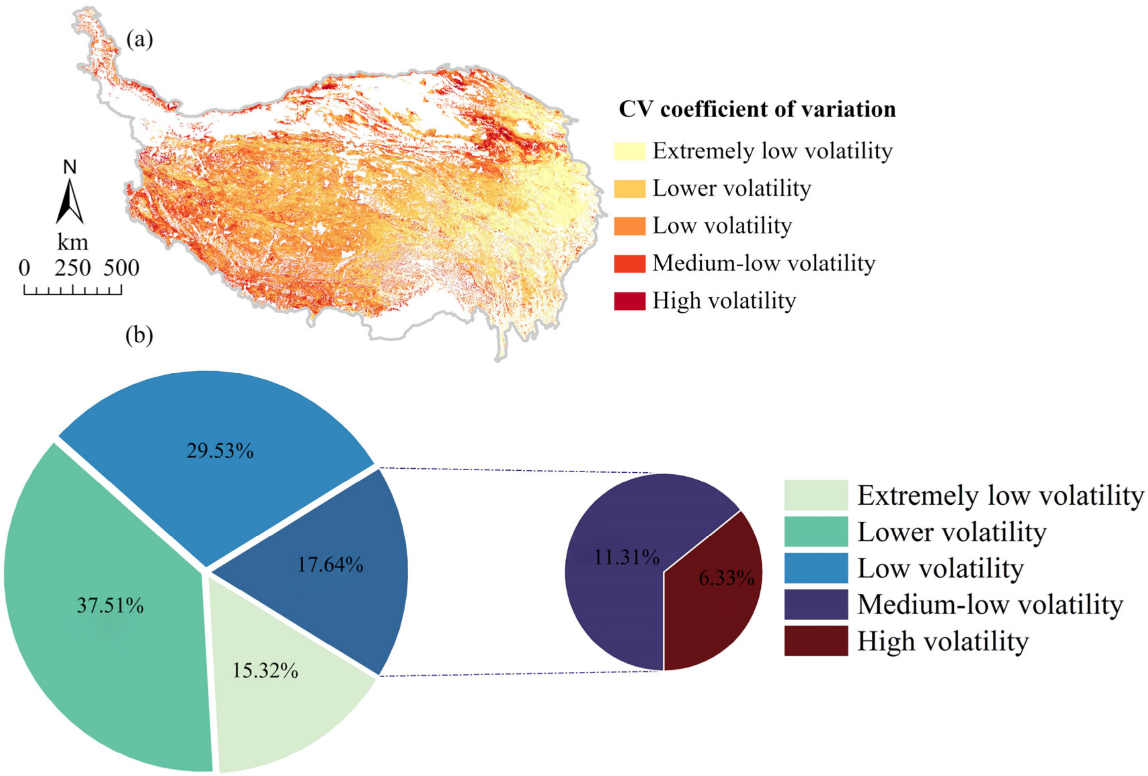

Figure 8. Spatial volatility of FVC in QTP grassland and the proportion of its volatility categories. ((**a**): spatial distribution of coefficient of variation; (**b**): proportion of different volatility levels).

3.5. Driving Force Discussion and Partial Correlation Analysis

3.5.1. Driving Force Analysis

Figure 9a shows the q-mean of each type of independent variable factor, which reflects the contribution value to the spatial variation in FVC of QTP grassland. The main contributions are concentrated on Pre and SM, and precipitation contributes the most, with an explanatory power of 0.59. When the explanatory power of a factor is higher than 0.20, it is considered that the factor has a positive effect on the change in FVC of QTP grassland. In this study, the dominant factor affecting FVC of QTP grassland is Pre, followed by SM, VS, and LUCC, and the explanatory power of these three factors exceeds 0.2. The explanatory power of Tem and VPD is less than 0.1, indicating that these two factors have no obvious effect on the spatiotemporal variation in FVC of QTP grassland. The average annual precipitation dominates the changing trend of FVC coverage of QTP grassland.

Figure 9b represents the contribution of 36 pairs of interactive factors to changes in QTP grassland FVC. Compared with a single factor, the influence of interactive factors is significantly enhanced. Among them, the interaction between Pre and SM and other factors has a high q value, especially the two-factor interaction of Pre, which is the most obvious (ranging from 0.59 to 0.66), indicating that Pre is the main driving factor of FVC changes in QTP grassland. This is followed by SM (ranging from 0.46 to 0.62). The q values of the interactions between other variables, Tem, VPD, VS, and LUCC, and other factors are 0.09 to 0.62, 0.03 to 0.60, 0.22 to 0.63, and 0.23 to 0.66, respectively, which shows that the other four factors also increase the FVC of QTP grassland. The situation has played a positive role. Although the effects of Tem and VPD were relatively small, their effects were strengthened after interaction with Pre and SM (q value >0.2). In comparison, the driving effects of VS and LUCC are smaller, but their minimum contribution values are still above 0.2.

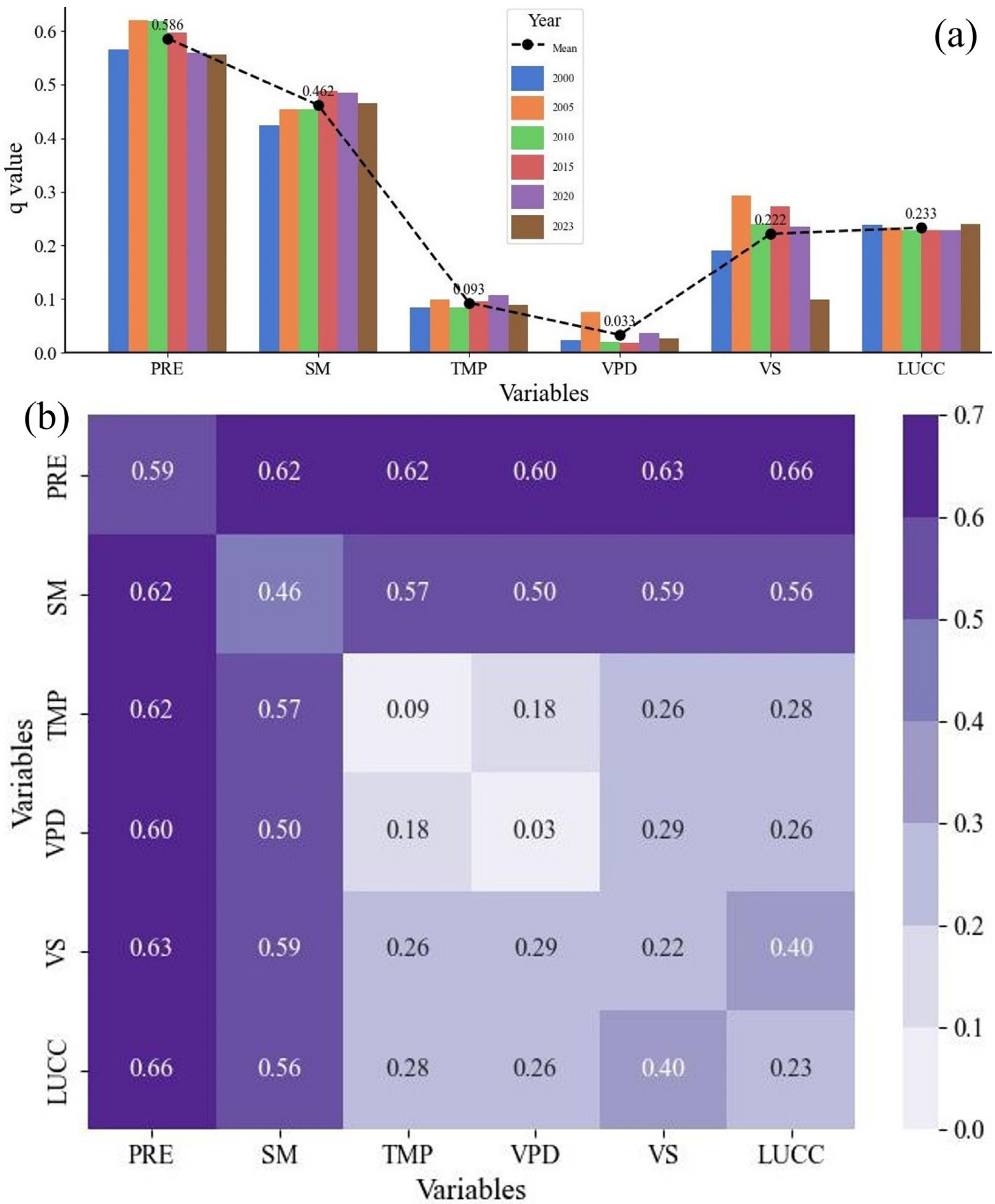

Figure 9. Driving force analysis ((**a**): single factor detection; (**b**): interactive factor detection).

3.5.2. Partial Correlation Analysis Results

In Figure 10, the partial correlation between precipitation and temperature and QTP grassland FVC changes was analyzed while controlling other variables. Figure 10a,c analyzes the correlation between precipitation and temperature on QTP grassland FVC, which specifically reflects the importance of these two factors in affecting QTP grassland FVC. The analysis results showed that the correlation between precipitation and FVC changes in QTP grassland was significantly higher than that of temperature, indicating that precipitation may be the main climate factor affecting changes in grassland coverage. When studying the significance of these two factors, 0.05 is used as the threshold; the results with a P value less than 0.05 are screened, and the red area is used to indicate the significance of these two factors on QTP grassland FVC, which can effectively highlight the impact of QTP main factors on grassland FVC. It can be clearly seen from Figure 10b,d that the correlation of precipitation on FVC of QTP grassland is higher than that of air temperature in the absolute values of the maximum and minimum values. This means that changes in precipitation have a more significant impact on grassland coverage under different climate conditions.

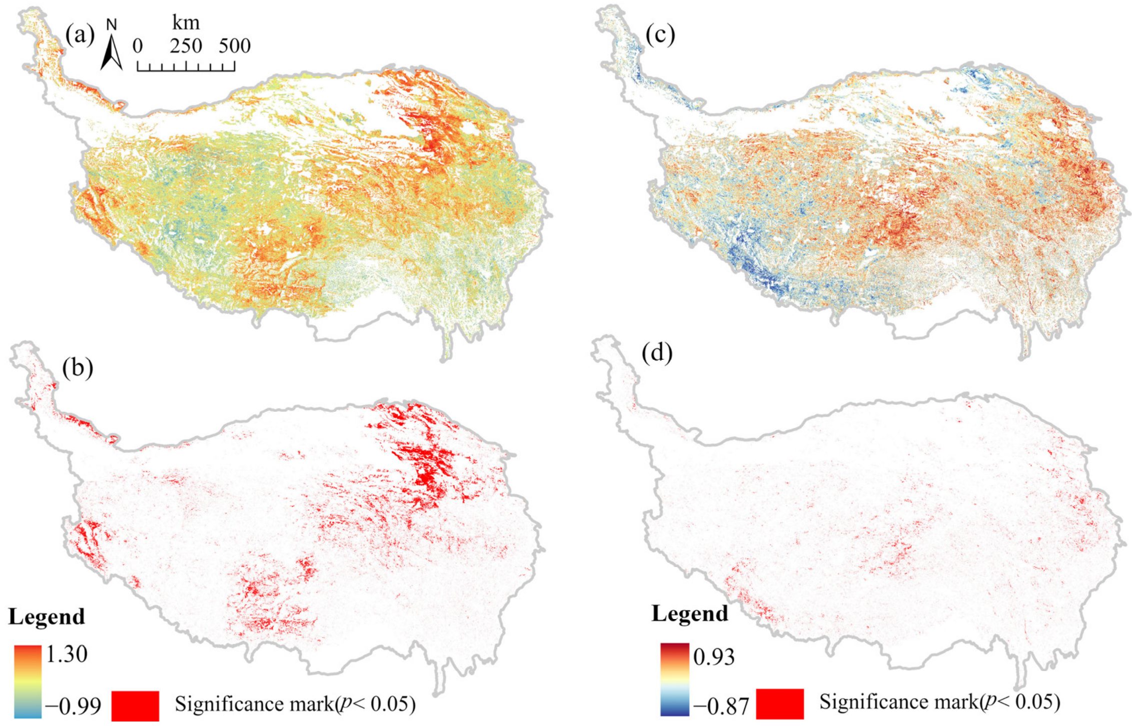

Figure 10. Analysis of correlation significance of QTP grassland FVC changes. ((**a**): partial correlation coefficient of QTP grassland FVC and precipitation factor; (**b**): partial correlation significance of precipitation factor on QTP grassland FVC; (**c**): representative QTP grassland FVC and temperature factor the partial correlation coefficient; (**d**): represents the significance of the partial correlation between the temperature factor and QTP grassland FVC.

In addition, in terms of significance, the correlation between precipitation and QTP grassland FVC is particularly obvious, mainly in the northern region, indicating that changes in precipitation may directly affect grassland growth and coverage in the northern region. The correlation and significance of temperature on FVC of QTP grassland are also high, with the maximum value as high as 0.93, showing that there is a significant correlation between the two. This result shows that although temperature also has an important impact on grassland FVC, the role of precipitation may be more prominent in the current study area. Comprehensively considering the impact of these two factors will help to better analyze and predict the changing trend of FVC in QTP grasslands.

4. Discussion

4.1. Temporal and Spatial Evolution Characteristics of FVC in QTP Grassland

This study conducts a detailed analysis of the spatiotemporal changes in FVC of QTP grasslands using MODIS-NDVI data from 2000 to 2023. Temporal analysis shows a significant overall increase in grassland FVC, with an annual growth rate of 0.0881%. This finding is consistent with the results of Guo et al. [47] and Su et al. [48], whose studies indicated a fluctuating upward trend in vegetation cover on the QTP, as shown in Figure 4. Additionally, our GI (growth index) analysis reveals an overall balanced growth state, with approximately 15% of the region showing slightly better or better growth trends (Figure 6), further indicating that grassland cover has increased over the 24-year period. Overall, these findings suggest that the vegetation cover of grasslands on the QTP has exhibited a steady upward trend over an extended period, reflecting an overall improvement in the regional ecosystem.

Spatially, this study finds that FVC on the QTP grasslands generally follows an east-high-west-low pattern (Figure 3), which aligns with the results of several other studies. For example, Deng et al. [49] observed an increasing trend in vegetation cover from the northwest to the southeast of Tibet. Similarly, Xu et al. and Liu et al. [50,51] reported a decreasing trend in vegetation cover from east to west and from south to north across the QTP. This spatial distribution pattern is closely related to factors such as climate and human activities in the region. The GI spatial distribution map for 2000–2023 (Figure S2) further explains why the southeastern region exhibits better growth conditions than the northwestern region, thus contributing to the east-high-west-low distribution of FVC. Previous studies have also shown that the eastern region, with its abundant precipitation, favorable temperatures, and optimal conditions for vegetation growth, tends to have higher FVC. In contrast, the western region, which is relatively dry with low vegetation coverage, exhibits a lower FVC. This spatial pattern, with higher FVC in the east and lower FVC in the west, is consistent with the findings of this study.

In the spatial trend analysis, this study used Mann–Kendall and Sen slope estimation trend analysis and Hurst index analysis to find that QTP grassland FVC mainly showed an improvement trend (Figure 7a); the significant growth proportion accounted for 54.05% (Figure 7b); and it will maintain sustained growth in the short term in the future, with the sustained growth proportion accounting for 53.08% (Figure 7d), mainly distributed in the northern part of the QTP (Figure 7c). This conclusion aligns with the findings of Teng et al. [52], who observed that grassland vegetation in the northwest region of the QTP is experiencing more robust growth compared to the southeast. They noted that, over the past 17 years, the area with improved vegetation coverage has exceeded that of degraded land. In terms of stability analysis, the study uses the coefficient of variation, revealing that the overall fluctuation in FVC on the QTP grasslands is relatively low. Specifically, 52.83% of the region exhibits small fluctuations, while only 6.33% shows large fluctuations, indicating a stable grassland ecosystem. This finding is consistent with Duan et al. [53], who analyzed the spatiotemporal changes in vegetation cover in Qinghai Province, further emphasizing the stability of the ecosystem in the region. Additionally, the GI analysis indicates that approximately 60% of the area is in a balanced growth state, providing further evidence of the small fluctuation characteristic of FVC on the QTP. This stability is crucial for maintaining the ecosystem services provided by the grasslands, allowing them to better withstand external disturbances and climate change. The analysis of the Hurst index supports this conclusion, suggesting that future trends are likely to follow similar patterns, showing long-term positive correlation. By combining Sen's trend analysis with the Hurst index evaluation, this study predicts that FVC on the QTP grasslands will continue to increase. The GI analysis also reveals that 60% of the region is showing balanced growth, with 15% exhibiting better growth trends. These findings are consistent with expectations that vegetation cover on the QTP will likely continue to increase due to global climate change [52,53]. However, it is essential to recognize that future trends will still be influenced by various factors, including climate change, human activities, and natural disturbances. Therefore, ongoing attention and research into the impacts of these factors on FVC in QTP grasslands are necessary for developing effective grassland management policies and ecological protection strategies. Additionally, the analysis of grassland vegetation coverage over the past 24 years reveals that growth in this area remains stable, which corresponds with the findings on spatial volatility presented in this study (Figure 8), both indicating a relatively stable range of change. The reason for this phenomenon may be that the QTP is a multi-species region. As a key region for regulating the global climate, it is also the key to affecting the stability of biodiversity in the region. The growth of grassland and spatial distribution volatility maintain a balance.

4.2. Analysis of the Effects of Various Driving Factors on FVC in QTP Grassland

The analysis of precipitation in factor detection reveals that it has the highest contribution value to the FVC of QTP grasslands, reaching 0.59 (Figure 9a). This indicates that precipitation factors are among the primary drivers of changes in grassland FVC. Furthermore, the interaction between precipitation and temperature plays a significant role in influencing vegetation growth, with their combined contribution to changes in FVC in QTP grasslands amounting to 0.62 (Figure 9b). These findings align with the research conducted by Liu, et al. and Nie, et al. [26,54]. They pointed out that precipitation is a key factor in determining interannual changes and fluctuations in vegetation coverage in the plateau area. Increased precipitation can promote vegetation growth, thereby increasing coverage, while reduced precipitation may lead to vegetation degradation [53]. In addition, temperature changes also have an important impact on vegetation coverage, especially during the growing season. Global climate warming has caused the temperature on the QTP to continue to rise, which is conducive to extending the vegetation growing season and increasing vegetation coverage [55]. In addition, land use cover changes also significantly affected the changes in QTP grassland FVC, with a contribution value of 0.23 (Figure 9a). In addition to hydrothermal factors and human factors, we also considered the unique environmental conditions of the Tibetan Plateau and included factors such as soil moisture (SM), vegetation size (VS), and vapor pressure difference (VPD) into factor detection analysis. The single factor effect of SM plays an important role in FVC changes in the QTP grassland (Figure 9a), and the interaction between SM, VS, and VPD also shows a significant impact on FVC (Figure 9b). With population growth and economic development, human activities have increasingly disturbed the grassland ecosystem of the QTP. Activities such as overgrazing, irrational land use, and mineral development may lead to grassland degradation and reduce grassland vegetation coverage [56–58]. In addition to these, human settlement activities, particularly the expansion of residential areas and infrastructure development, further exacerbate the pressure on grassland ecosystems [57]. As human populations grow, more land is converted for residential, agricultural, and industrial use, reducing the available area for natural grasslands and leading to a decline in vegetation coverage. The spread of human settlements also increases the likelihood of overgrazing and other forms of land degradation, contributing to further reductions in FVC [56]. Therefore, when formulating grassland management and ecological protection policies, it is necessary to fully consider the impact of regional differences, time scales, and the effects of human settlement activities [58]. Targeted measures should be implemented to mitigate these impacts and promote the health and stability of grassland ecosystems.

4.3. Research Gaps and Future Prospects

This study has some limitations. It uses MOD13Q1 data to calculate the FVC of grasslands on the QTP, analyzes its changing trends, and predicts future changes. The application of geographic detectors and partial correlation analysis methods to explore the attribution and correlation of these changes provides valuable insights into the study of FVC in grasslands on the QTP. However, there are several shortcomings. For instance, the performance of FVC over a shorter time frame requires further investigation, and the selection of indicators, trend sorting, and the discretization process of factors may introduce subjectivity. Since FVC is influenced by multiple factors, including climate, meteorological conditions, and land cover, future research should focus on incorporating additional influencing factors, such as terrain, soil type, altitude, grazing, and economic and demographic data. The goal is to identify a more comprehensive and robust set of driving factors. Moreover, future studies could extend the time series, analyze different seasons, improve resolution, and conduct a more in-depth analysis of the trends and attributions related to changes in grassland vegetation cover.

5. Conclusions

Temporal change characteristics: Between 2000 and 2023, the average annual FVC of QTP grassland fluctuated between 38.41% and 42.27%. The overall change range is small, showing a slow growth trend, with an average annual growth rate of 0.0881%/a. Significant changes occurred in 2015 and 2022. In these two years, there was a downward trend in

FVC. The FVC value in 2015 dropped to 38.41%, while the FVC value in 2018 reached 42.27%. Despite inter-annual fluctuations, FVC has remained within a relatively stable range as a whole, with no obvious changes in category proportions. Future trend analysis shows that the overall trend of QTP grassland FVC points to continued growth, of which future growth trend accounts for 53.08%. This change indicates that despite fluctuations, grassland growth on the QTP is expected to continue to improve in the future.

Spatial variation characteristics: The FVC of QTP shows a spatial distribution characteristic that gradually increases from west to east. The areas of extremely low and low FVC in the western region account for 31.39% and 25.49%, respectively, while most of the central region has medium FVC, accounting for 20.72%. In contrast, the eastern region is dominated by high and extremely high FVC, accounting for 13.64% and 8.76%, respectively, indicating that the region has strong ecological capabilities. The results of the coefficient of variation analysis showed that the FVC of the QTP grassland as a whole was in a state of extremely low volatility and low volatility, accounting for 52.83% of the total. The high volatility area accounted for only 6.33% and was mainly concentrated in the western region. This result reflects the spatial distribution characteristics of grassland coverage and the differences in volatility in different regions.

Driving force influence characteristics: Pre was identified as the main driving factor affecting grassland FVC changes in the QTP, with an explanatory power of 0.59, showing the importance of precipitation on grassland growth. SM, VS, and LUCC also play a positive role in FVC changes, and their explanatory power exceeds 0.2. The explanatory power of temperature (Tem) and VPD is lower than 0.1, indicating that their impact on FVC changes is small. In the interaction factor analysis, the interaction between precipitation and soil moisture had a significant impact on changes in FVC, indicating that the interaction between these two factors plays a key role in grassland growth.

Partial correlation analysis: The correlation between precipitation and FVC changes is significantly higher than that of temperature. In the northern region, changes in precipitation have a more obvious impact on grassland growth and coverage, with the maximum value reaching 1.30. The maximum correlation of temperature is 0.93, indicating that there is a significant correlation between the two. Comprehensive consideration of these factors will help to better analyze and predict the changing trends of grassland FVC on the QTP and provide a scientific basis for ecological protection and sustainable management. This result indicates that changes in precipitation may be the main driver of dynamic changes in grassland ecosystems on the QTP.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13122127/s1, Figure S1: Annual spatial distribution of FVC in QTP grassland from 2000 to 2023; Figure S2: Annual spatial distribution of growth index; Figure S3: Spatial distribution of independent variable factors; Table S1: Statistics on the annual average value of FVC in QTP grassland from 2000 to 2023; Table S2: The proportion of different types of QTP grassland FVC in 2000-2023; Table S3: Statistical table of area proportion of different growth index categories from 2000 to 2023.

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