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The Spatiotemporal Variation of Tree Cover in the Loess Plateau of China after the 'Grain for Green' Project

Yuhang Wang [1,2], Muyi Kang [1,2], Mingfei Zhao [1,2,*], Kaixiong Xing [3], Guoyi Wang [1,2] and Feng Xue [1,2]

1. State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China; wyhhappy1990@163.com (Y.W.); kangmy@bnu.edu.cn (M.K.); wgy1119@mail.bnu.edu.cn (G.W.); 201421190046@mail.bnu.edu.cn (F.X.)
2. College of Resources Science and Technology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
3. Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; xingkaixiong@163.com

* Correspondence: Euler_mf@163.com; Tel.: +86-10-5880-9274

Academic Editors: Takuo Nagaike and Vincenzo Torretta
Received: 23 February 2017; Accepted: 28 April 2017; Published: 3 May 2017

Abstract: Analyzing spatiotemporal variation of tree cover could enhance understanding of the environment and promote a sustainable resource use of ecosystems. This study investigated the variation in tree cover in the Loess Plateau after an ecological restoration effort called the 'Grain for Green Project' (GGP). The results show that the proportion of tree covered area in the Loess Plateau changed from 73% to 88%, with the cumulative tree cover fluctuating from approximately 7% to 11%, and the average annual tree cover increased from 10% in 2000 to 12% in 2014. Based on tree cover values over the course of 15 years, the study area was classified into five regions, which provide much more information for spatial assessment of tree cover change in the Loess Plateau spatially. The increase in tree cover value was mainly in the core part of Loess Plateau, the mountains, and the edge of the mountain areas; whereas the values were stable in 36.21% of the area, and a decrease was noted in 5.63% of the area, primarily located in the low plain areas. Approximately 26.36% of the Loess Plateau will show a sustained increase in tree cover in the future. The results of this study will facilitate us to understand the current conditions and development of the GGP's effects, and offer a valuable reference for future detection of tree cover change through geographic information system (GIS) and remote sensing (RS) tools.

Keywords: tree cover; spatiotemporal; Loess Plateau; GGP; sustainability; MODIS vegetation continuous fields (VCF)

1. Introduction

Trees affect terrestrial energy exchanges such as photosynthesis, transpiration, and net primary production [1], and play an important role within and outside forest ecosystems (e.g., on farms and pastures, and in urban areas) [2,3]. Tree cover is defined structurally as the proportion of ground by, vertically projected area of woody plants (including leaves, stem, branches, etc.) above a given height [4]. The tree cover variable is important for ecosystem science [5]. Analyzing spatiotemporal tree cover distribution and variation could provide information to manage, conserve, and enhance production of trees within and outside forestland, which will promote sustainable resource use of ecosystems.

The Earth's surface has experienced intensive tree cover change [6], largely due to intense human activities. Urbanization, infrastructure construction and expansion of farmland bring about deforestation, leading to tree cover decrease [7]. On the other hand, ecological restoration policy such as afforestation and forest restoration promotes an increase of tree cover [8]. Previous studies focused on tree cover variation under the condition of deforestation [9]; however, the opposite process such as forest restoration and afforestation requires further study.

The Chinese government launched a large scale ecological restoration program called 'Grain for Green Project' (GGP) in 1999. The program's aims included conversion of marginal cropland to forestland, the mitigation of soil erosion, and provision of solutions to land deterioration problems [10]. Forestations, including afforestation and reforestation, are the main conservation programs of this project. The Loess Plateau in Northern China is a pilot region of the GGP. Evidence from RS and statistics data showed that vegetation cover has largely improved, and forest coverage increased [11,12]. Previous studies relied on the vegetation index derived from satellite data or land cover maps to reflect the influence of the project [13–15]. Nevertheless, these two ways both have some limitations in assessing the effectiveness of the GGP. The result from the vegetation index may overestimate effects by analyzing vegetation index variation at different times without excluding the large area of farmland in the Loess Plateau. On the other hand, by comparing forest land cover temporally, the result acquired from land cover maps overlooked the sparse newly planted trees, which were not included in forest land cover type. The tree cover variation is more likely related to the effectiveness of this project [16], whereas little is known about it, especially in a spatiotemporal sense.

In order to monitor tree cover dynamic temporally, multiple temporal tree cover data is needed. RS is superior to ground-based investigation in broad-scale tree cover change studies [17]. Through RS technique, tree cover can be represented directly as a 'continuous field', in terms of fractions or proportions of the total pixel area [4], which enables consistent long-term monitoring and quantification of tree cover changes. Among the continuous field data, Vegetation Continuous Fields (VCF) tree cover data produced from Moderated Resolution Imaging Spectroradiometer (MODIS) data are more objective and economical [18]. This data also has the best temporal resolution, offering much more information and reflecting the process when monitoring tree cover change in large scale [19].

Spatial analysis, trend analysis, and time-series analysis are widely used in spatiotemporal variation analysis. GIS is a powerful tool in spatial analysis, which could efficaciously help study the spatial heterogeneity of tree cover and its change [20,21]. Theil–Sen Median trend analysis and Mann-Kendall tests are robust trend analysis method [22,23]. The Hurst exponent could help quantitatively detect the sustainability of time series data [24]. These methods are effectively used in spatiotemporal variation of vegetation analysis indicated by vegetation index such as Normalized Difference Vegetation Index (NDVI) [25–28], but have rarely been adopted in tree cover variation analysis.

In this study, we utilized spatial analysis in GIS, trend analysis, and time-series analysis methods to analyze the tree cover variation in the Loess Plateau after the GGP. Analysis spatially and temporally based on MODIS VCF tree cover data is used to answering the following questions: (1) How does tree cover change spatiotemporally after the GGP in the Loess Plateau, and how will it change in the future? (2) Is tree cover an effective indicator in assessing the effectiveness and sustainability of the GGP?

We hope the results will not only give a case for tree cover spatiotemporal variation analysis, but also potentially enhance understanding of current conditions and sustainability. This study also facilitates an assessment of the GGP's effects on environmental restoration, and offers a valuable reference for future detecting the tree cover change through GIS and RS tools.

2. Study Areas and Data

2.1. Study Area

The Loess Plateau is located at latitude of 34°–40°N and longitude of 103°–114°E, stretching across a region west to the Riyue Mountains, east to the Taihang Mountains, south to the Qinling Mountains, and north to the Yinshan Mountains in Inner Mongolia (Figure 1). The Plateau is approximately 1000 km long from east to west, and 700 km wide from north to south, spanning a total area of approximately 6.4×10^5 km^2. The Plateau is full of hills, basins, and alluvial plains where elevation ranges between 1000 and 1600 m above sea level, and is covered with continuous loess of 100–300 m in thickness. The loess was geologically transported from the northwestern Gobi desert by wind and has accumulated on the Loess Plateau since the beginning of the quaternary [29]. It is the largest area of loess deposition in the world, and lies in a semi-humid and semi-arid transitional zone that has an annual average temperature of 4.3 °C in the northwest and 14.3 °C in the southeast. Limited annual, rainfall, approximately 250 to 780 mm, is highly variable both spatially and temporally and concentrated during the summer months. Frequent storms, steep landscape, low vegetation cover, and highly erodible soil have led the Loess Plateau to be one of the most severely eroded regions globally [30,31]. After human disturbances over thousands of years, forest only primarily exists in some montane areas of the Plateau, with the majority of the Plateau undergoing heavy soil erosion.

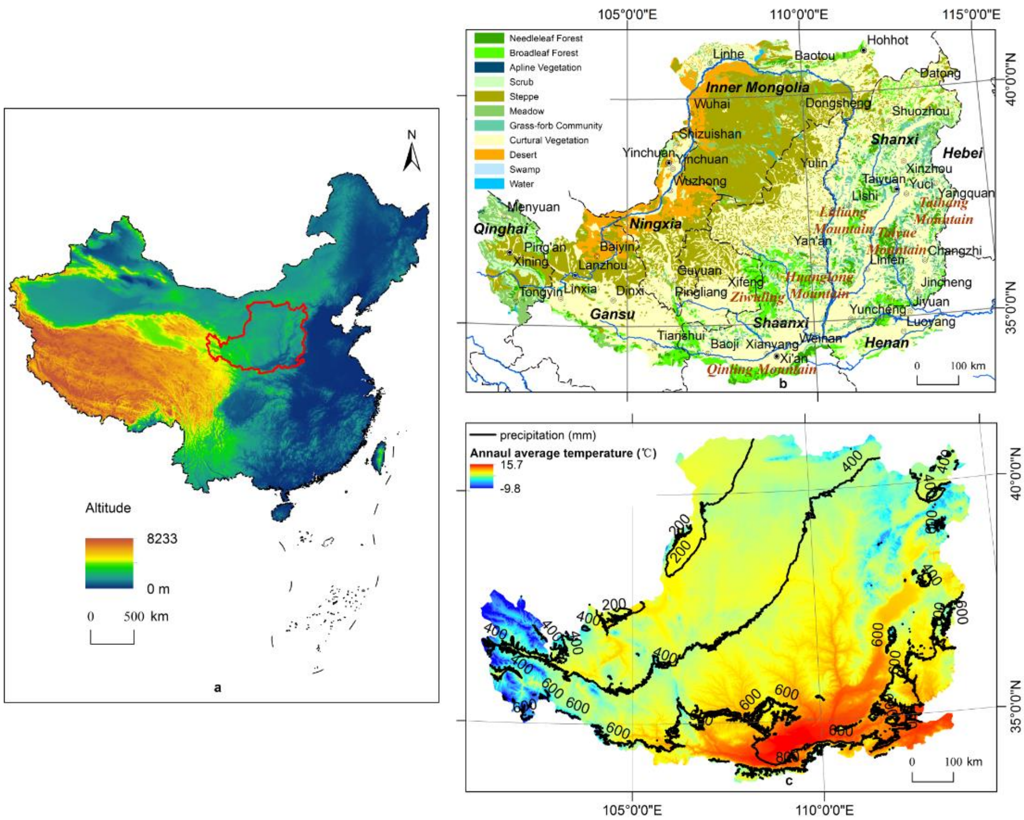

Figure 1. Location of the study area. The location of the Loess Plateau in China and elevation (**a**), vegetation type (**b**), and annual average temperature and precipitation in the study area (**c**). The elevation data was based on the advanced space borne thermal emission and reflection radiometer (ARTER) (http://www.gscloud.cn/) with a resolution of 1000 m. The vegetation type data is courtesy of the Institute of Botany, Chinese Academy of Sciences of 1:100 million Chinese Vegetation Map (2000), and the climate data was from the WordClim website (www.worldclim.org/) with a resolution of 1 × 1 km [32].

2.2. Data

2.2.1. Tree Cover Data

The study acquired tree cover data from the MODIS VCF product (MOD44B) Collection 5, at a spatial resolution of 500 m for the years 2000–2014 from NASA's Earth Observing System Data and Information System (EODIS, http://reverb.echo.nasa.gov/).

2.2.2. Other Data

The study used the digital elevation model (DEM) at a spatial resolution of 90 m, developed from advanced space borne thermal emission and reflection radiometer (ARTER) (http://www.gscloud.cn/). The DEM data was resampled and scaled up to 500 m to make it compatible with the MODIS tree cover data.

3. Methods

3.1. Temporal Variation in the Tree Cover

We defined P, C and D as indicators of the tree-covered area, the cumulative tree cover and the average annual tree cover, respectively:

$$P_i = \frac{X_i}{A} \tag{1}$$

$$C_i = \frac{\sum_{j=1}^{n_i} T_j}{A} \tag{2}$$

$$D_i = \frac{\sum_{j=1}^{n_i} T_j}{n_i} \tag{3}$$

where, X_i is the tree covered area for year i ($2000 \leq i \leq 2014$); A is the area of the entire study area; T_j represents tree cover value of the j pixel of year i, and n_i is the number of tree-covered pixels of year i.

3.2. Spatial Variation in the Tree Cover

We calculated the average tree cover for each pixel for a 15-year period from 2000 to 2014 to analyze the distribution characteristics of the tree cover in the Loess Plateau. In order to detect the dynamic spatial distribution of tree cover variation, the study used the GIS tools to classify the annual tree cover into different levels based on each pixel. First, we adopted the most commonly used definition of forest, i.e., land with tree canopy cover larger than 20% with a minimum height of five meters [33] to extrapolate the forest area annually. The study area was then classified into forest, non-forest or water area. Second, the overlay method was used to determine the counts of every pixel classified as forest or non-forest from 2000 to 2014. To evaluate tree cover change in the forest study area, data were extracted on these two categories over the 15 past years. To evaluate tree cover change in the non-forest area, the 15 years of non-forest area data were assigned as one of three types (Figure 2).

The next step involved defining the classification system. Categories included, persisting forest region (I): cover value of every pixel was greater than 20% for each of the 15 years. Disturbed forest region (II): cover value of the pixel was less than 20% for 1 to 14 years, fluctuating between other region types. Persisting non-forest and tree covered region (III): the pixel was non-forest however, the tree cover value was larger than, but not equal to zero. This area was permanently non-forested but with some tree cover. Disturbed tree covered region (IV): the pixel was non-forest for 15 years and tree cover value was equal to zero for one to 14 years, which indicates that it fluctuated between being a tree covered and non-tree covered area. Persisting non-tree covered region (V): cover value of the pixel was the same for 15 years; no tree cover was identified in this area from 2000 to 2014.

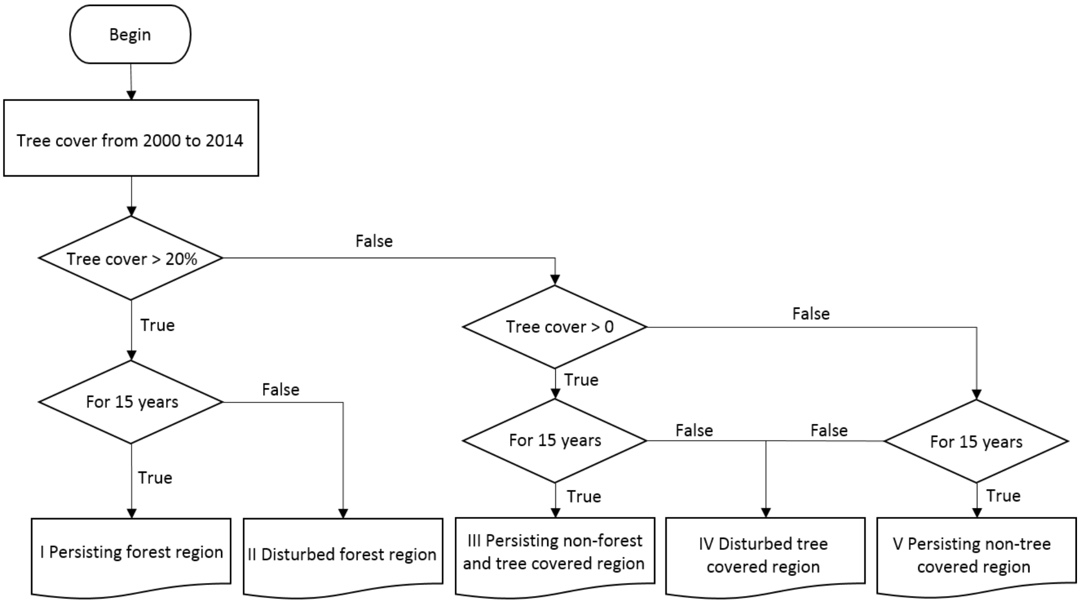

Figure 2. The process of determining tree cover classification.

After classifying the pixels in the study area, we compared the area, tree cover value and slope of the five regions and analyzed the characteristic of each level. The area was extracted by calculating the percentage of pixels at each level, and the slope was derived from the DEM data to overlay with the five levels.

3.3. Trend Analysis

The Theil–Sen Median trend analysis is a robust trend statistical method [22,23]. This analysis calculates the median slopes between all $n\ (n-1)/2$ pair-wise combinations of the time series data, which is particularly effective for the estimation of trends in small series [27]. The slope determined by the Theil–Sen Median analysis can represent the increase or decrease in the tree cover over the 15 years between 2000 and 2014 on a pixel scale and was calculated as follows:

$$slope = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \tag{4}$$

where, *slope* refers to the Theil-Sen median, and x_j and x_i represent the tree cover value of years i and j. When the $slope > 0$ the tree cover is characterized by a rising trend, alternatively when the $slope < 0$ the cover is in a decreasing trend.

The Mann-Kendall test is a non-parametric statistical test [34,35]. It has the advantage that samples do not need to obey certain distributions and is free from the interference of outliers [36]. The calculation formula of M-K test is as follows:

The variable Z is defined as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases} \tag{5}$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{6}$$

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1 \; x_j - x_i < 0 \\ 0 \; x_j - x_i = 0 \\ -1 \; x_j - x_i > 0 \end{cases} \tag{7}$$

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{8}$$

where, n is the number of the data, x_i and x_j are the data values in the times series i and j, respectively (in this study, x_j and x_j represent the tree cover value of years i and j, $2000 \leq i < j \leq 2014$); sgn is a sign function; and the Z value range ($-\infty$, $+\infty$). A given significance level, $|Z| > u_{1-\alpha/2}$, signifies that the times series have significant variations on the level of α. Generally, the value of α is 0.05, and here, we choose $\alpha = 0.05$ ($|Z| > 1.96$).

3.4. Hurst Exponent

In order to predict the sustainability of the tree cover trends in the future, we calculated the Hurst exponent of every pixel base on a 15-year time series. The Hurst exponent is a method for distinguishing sustainability of time series data, which was proposed by British hydrologist Hurst (1951) [37], and improved upon by Mandelbrot and Wallis (1969) [38]. Recently, this exponent has been applied in the time series detection of vegetation variations [24,25]. The primary calculation procedures are as follows [39,40]: For a time-series, $\{\xi(t)\}$, $t = 1, 2, \ldots, n$; define another sequence, $\tau = 1, 2, 3, \ldots, n$; for a certain τ (in this study, $\xi(t)$ represents the tree cover value of year t, $2000 \leq t \leq 2014$, $2000 \leq \tau \leq 2014$). Define the mean sequence:

$$\langle \xi \rangle_\tau = \frac{1}{\tau} \sum_{t=1}^{\tau} \xi(t) \tag{9}$$

and calculate the cumulative deviation of time t:

$$X(t\,,\,\tau) = \sum_{u=1}^{t} (\xi(u) - \langle \xi \rangle_\tau) \; 1 \leq t \leq \tau \tag{10}$$

next, define the range sequence:

$$R(\tau) = \max_{1 \leq t \leq \tau} X(t\,,\,\tau) - \min_{1 \leq t \leq \tau} X(t\,,\,\tau) \tag{11}$$

then, define the standard deviation sequence:

$$S(\tau) = \left[\frac{1}{\tau} \sum_{t=1}^{\tau} (\xi(t) - \langle \xi \rangle_\tau)^2 \right]^{\frac{1}{2}} \tag{12}$$

and, calculate Hurst exponent:

$$\frac{R(\tau)}{S(\tau)} = (c\tau)^H \tag{13}$$

where, c is a constant, and H is Hurst index that can be calculated through observed data.

The value of the Hurst exponent (H) can be expanded from zero to one and is valued in three types: If $H = 0.5$, it means that the time-series is an independent random process without sustainability, indicating that the trend of the time series in the future would be unrelated with that of the study period (in this study, this refers to tree cover change is undetermined in the future). If $H > 0.5$, it means that the sustainability of the time series shows the same trend with the time series in the future (in this study, this refers to tree cover change shows the same trend in the future). When the value is less than 0.5, it refers to the anti-sustainability of the time series, representing the opposite of the time series in the future (in this study, this refers to tree cover change shows the opposite trend in the future).

4. Results

4.1. Temporal Variation of the Tree Cover in the Loess Plateau

From 2000 to 2014, the proportion of tree covered area (*P*) increased from 73% to 88% (Figure 3a). The cumulative tree cover in the Loess Plateau (*C*) revealed an increasing trend ($C = 0.30year + 7.07$, $R^2 = 0.75$, $p < 0.01$), fluctuating from approximately 7% to 11%. The average annual tree cover (*D*) also exhibited an increasing trend ($D = 0.22year + 9.55$, $R^2 = 0.67$, $p < 0.01$), and increased from approximately 10% to 12% (Figure 3b).

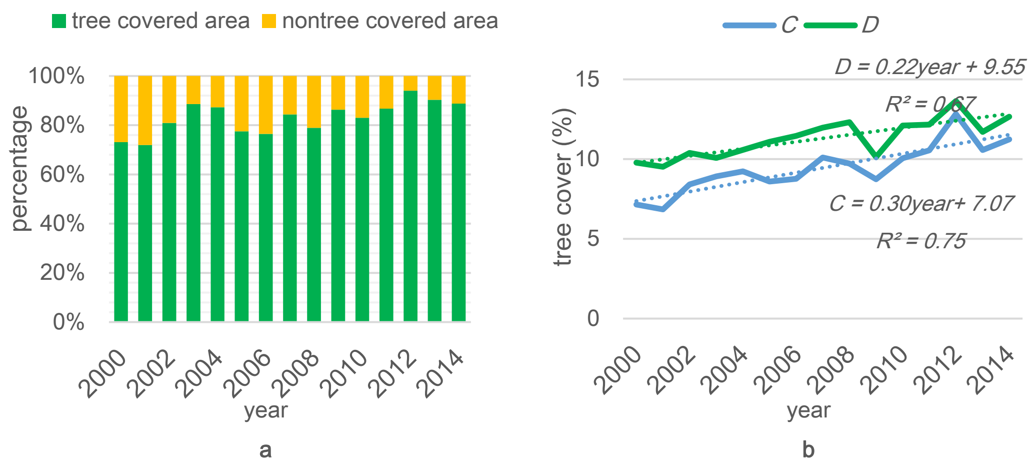

Figure 3. Temporal variation in the tree cover in the Loess Plateau. The annual variation in percentage of the tree-covered area (**a**), and the inter-annual cumulative tree cover change trend and the inter-annual average annual tree cover change trend (**b**).

4.2. Spatial Variation of the Tree Cover in the Loess Plateau

The tree cover spatial distribution in the Loess Plateau was mainly high in the southeast, especially in the mountainous areas (Ziwuling and Huanglong Mountains, Northern slope of Qinling Mountains along the Weihe River in Shaanxi Province, and Lüliang, Taiyue and Taihang Mountains in Shanxi Province). Tree cover spatial distribution was low in the northwest (Figures 1b and 4).

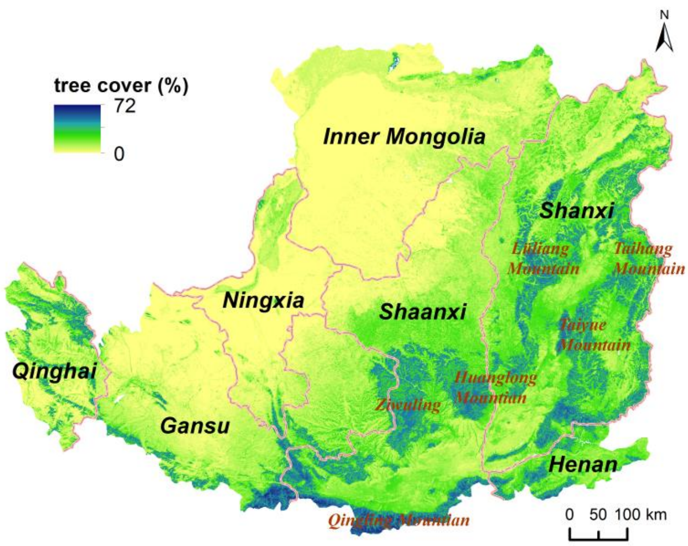

Figure 4. Spatial distribution of average tree cover value in the Loess Plateau from 2000 to 2014. Tree cover value is a percentage, ranging from 0% to 100%.

The study area was classified into five regions: Persisting forest region (I), Disturbed forest region (II), Persisting non-forest and tree-covered region (III), Disturbed tree covered region (IV) and Persisting non-tree covered region (V). Region I was located primarily in the mountainous area of the Loess Plateau; Region II mainly distributed around but outside the edge of Region I; Region III was in the southeast of the Loess Plateau, Ningxia Province in the northwest and Ordos in the north of the Loess Plateau. Region IV and V were in the northwest of the study area (Figure 5a).

Region III (43.36%) had the largest area among the five regions, and followed by Region IV (30.43%), Region II (13.55%), Region I (8.27%) and Region V (4.18%) (Figure 4b). From Region I to V, tree cover and slope decreased (Figure 5c,d).

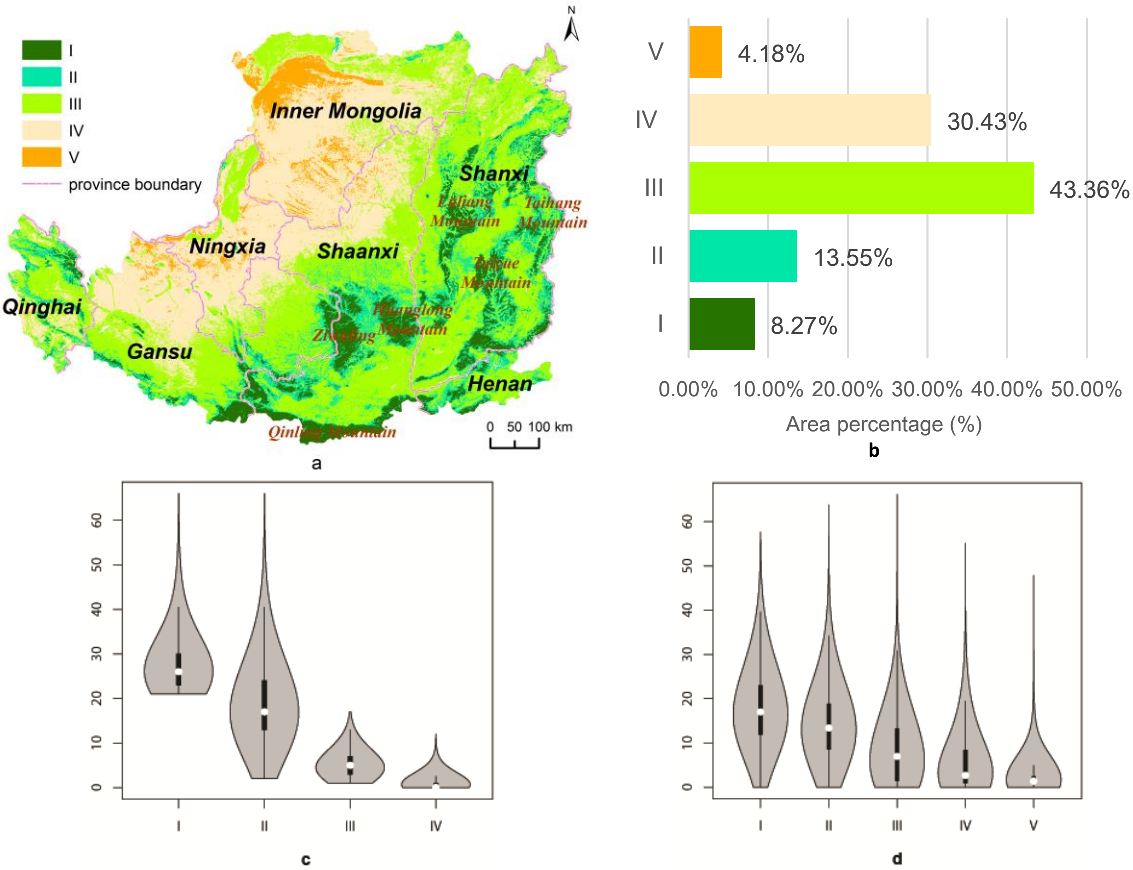

Figure 5. Five levels of tree cover regions in the Loess Plateau. Tree cover distribution of the five regions (**a**). Area percentage of the five tree cover classes (**b**). Violin plot for tree cover of the five regions (**c**), all the tree cover was zero in Region V. Violin plot for slope of the five regions (**d**).

4.3. Variation in Trends of Tree Cover Change

According to the real conditions of the slope of tree cover trend, we adopted Jiang's definition method to class the area into five classes [25]. The tree cover increasing area (58.16%) was considerably larger than the decreasing area (5.63%) from 2000 to 2014, and approximately 36.21% of the area in the Loess Plateau remained stable (Table 1).

Table 1. Trend in the tree cover changes in the Loess Plateau.

Trend of Tree Cover	Area Percentage (%)	Slope	Z Value	*p* Value
Significant increase	34.53	≥0.1	>1.96	≤0.05
Slight increase	23.63	0.0005–0.1	–1.96–1.96	>0.05
Stability	36.21	–0.0005–0.0005	–1.96–1.96	>0.05
Slight decrease	4.78	–0.1–0.0005	–1.96–1.96	>0.05
Significant decrease	0.85	≤–0.1	<−1.96	≤0.05

Note: the pixels with slope in −0.0005 and 0.0005 and Z > 1.96 or Z < −1.96 are classified as the stable.

In Region I, most of the area showed an increasing trend in tree cover (in total approximately 88.82% of this region showed an increase, of which 38.39% showed a significant increase and 50.23% showed a slight increase). Significant increases were most often observed in the northern region of the mountains in Shanxi Province (Lüliang and Taiyue Mountains), north of the Huanglong Mountain and northwest of Qinling Mountains, whereas a decreasing trend was observed mainly in the east of the Qinling mountains (Figure 6a).

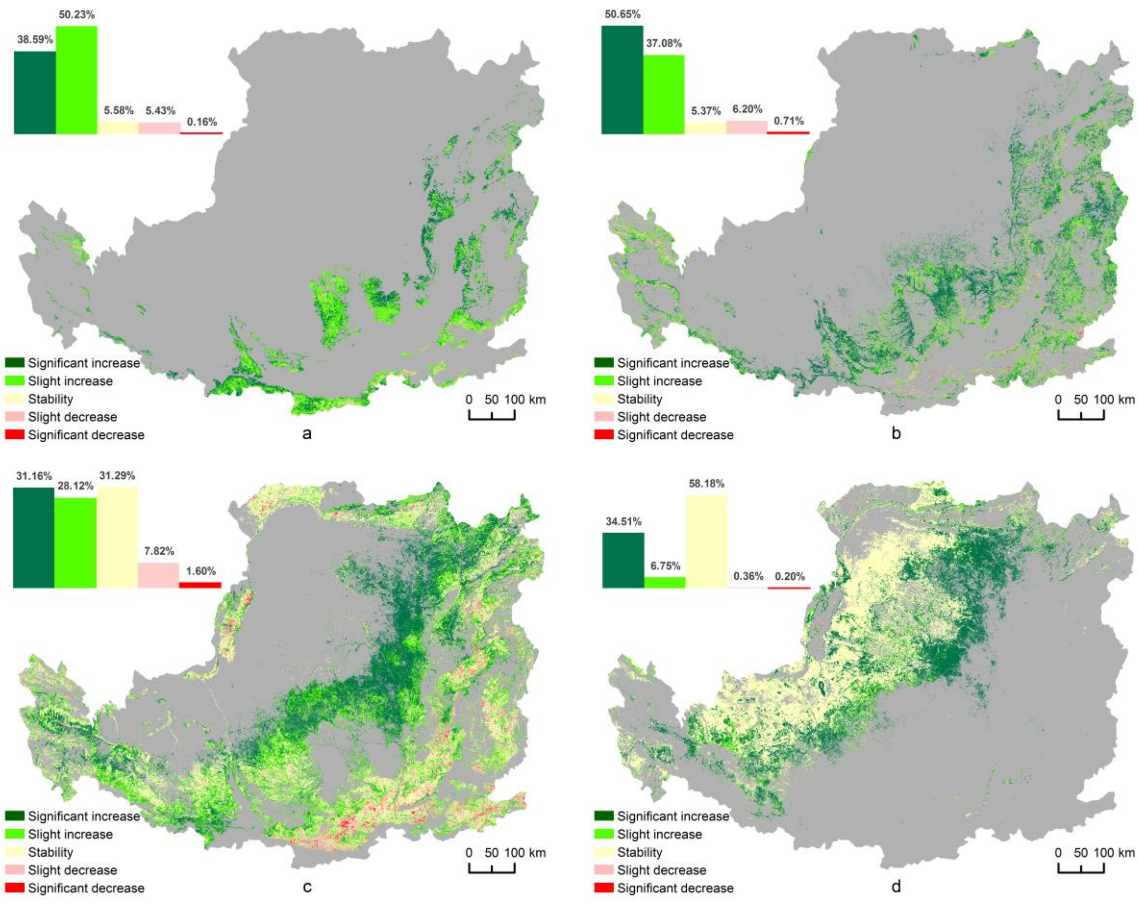

Figure 6. Trends of tree cover changes in Region I through IV (**a**–**d**) in the Loess Plateau from 2000 to 2014.

In Region II, the increasing trend in tree cover occurred across the majority of the area (in total, approximately 87.73% of this area showed an increase, of which 50.65% was characterized by a significant increase and 37.08%, by a slight increase). Only a few areas in the south were characterized by a decreasing trend in tree cover (in total approximately 6.91% of this region showed decreased cover, 0.71% of which was a significant decrease and, 6.20% slight decrease) (Figure 6b).

In Region III, approximately 59.28% of the area had an increasing trend, which mainly occurred in the north (31.16% of which was a significant increase and 28.12%, a slight increase). Tree cover maintained relative stability at 31.92% in this region, scattered mainly in the southeast. Around 9.42% of the region was characterized a decreasing trend in tree cover (of which 1.60% underwent a significant decrease and 7.82%, a slight decrease). This occurred mainly in the southeast of the Loess Plateau along the Wei River and Fen River Plains, as well as in the northwest where belonging to Ningxia Hui and Inner Mongolia Autonomous Regions (Figure 6c).

In Region IV, the tree cover increased in approximately 41.26% over the region (34.51% of which was a significant increase and 6.75%, a slight increase) mainly located in the southeast of this region (Yulin in North Shaanxi, Guyuan in South Ningxia, and Pingliang in Northeast Gansu Province). More than half of this region remained stable, the majority (58.18%) of which was observed in the northeast of this region. Only a very small portion of this region was characterized by a decrease (0.56%) (Figure 6d).

4.4. The Sustainability of the Tree Cover Variation

The regions with Hurst exponent higher than 0.5, which were sustainable, accounted for 49.45% of the total area. Those lower than 0.5, which were unsustainable, accounted for 25.91% of the total area. There was little area with Hurst exponent equal to 0.5 in the Loess Plateau Region (Figure 7a, Table 2).

In order to reveal the variation in trends and the sustainability of the tree cover, the data obtained from the Theil–Sen Median trend analysis and the Mann–Kendall test were superimposed with the Hurst exponent results to yield the coupled information of variation in trends and sustainability. The coupling results were classified into six cases: (1) sustained significant increase; (2) sustained slight increase; (3) sustained stability; (4) sustained slight decrease; (5) sustained significant decrease; and (6) undetermined variation in trends in the future (Figure 7b).

The area showing sustained increase accounted for 26.36%, mainly distributed in the central and Northern Shaanxi and the Northeastern Gansu. The sustained stability region accounted for 8.25%, primarily scattered in the southern Region including of Shaanxi, part of Shanxi, and Henan Provinces. The area with sustained decrease accounted for 2.39%, mainly distributed in the same corner as the last except Henan Province. There existed areas where the variation trend in tree cover was unclear under the present situation. In total approximate 38.08% of the Loess Plateau Region, mainly located central areas, followed this trend (Figure 7b, Table 2).

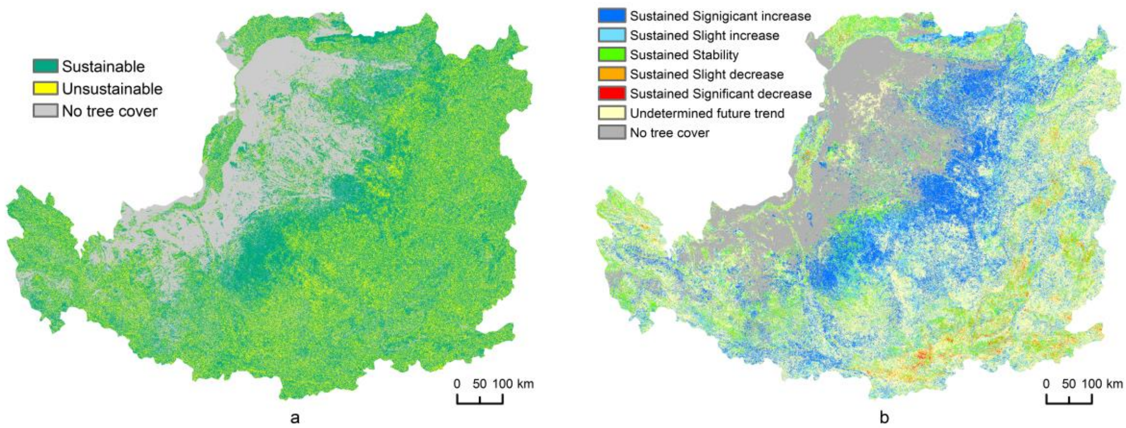

Figure 7. Sustainability of inter-annual tree cover change in the Loess Plateau from 2000 to 2014 (**a**), spatial distribution of the tree cover dynamics based on trends and the Hurst exponent (**b**).

Table 2. Trend in the tree cover changes in the Loess Plateau.

Variation Types	Area Percentage (%)	Slope	Z Value	H
Sustained Significant increase	16.31	≥0.1	>1.96	>0.5
Sustained Slight increase	10.05	0.0005–0.1	–1.96–1.96	>0.5
Sustained Stability	8.52	–0.0005–0.0005	–1.96–1.96	>0.5
Sustained Slight decrease	2.00	–0.1–0.0005	–1.96–1.96	>0.5
Sustained Significant decrease	0.39	≤–0.1	<−1.96	>0.5
Undetermined future trend	38.08	-	-	≤0.5

5. Discussion

5.1. Temporal Variation of the Tree Cover in the Loess Plateau

Tree covered area and tree cover values both increased in the Loess Plateau from 2000 to 2014 (Figure 4). Since the Grain for Green Project (GGP) launched in the Loess Plateau in 1999, a great number of trees were planted annually [41]. Furthermore, this project also helped protect natural vegetation [13]. Primarily due to the land-use policy implemented by the Chinese government, forest area increased in the Loess Plateau after 2000 [42]. Although vegetation is closely related to climate, it is a relatively short time period to evaluate any potential climate-influenced expansion of forested areas [15]. The GGP also enhanced forest coverage (older forest and newly forested land) [43]. The tree cover trend increased nearly 40-fold in the Loess Plateau, which was attributed to the GGP [11]. It is said that the GGP overemphasis on tree and shrub planting in environmentally fragile areas and failure to consider climate, soil, hydrology, and landscape factors are questionable [13]. The GGP dominantly resulted in the tree-covered area and tree cover value increased in the Loess Plateau.

The tree covered area tended to increase from 2000 to 2014, but with some fluctuations (Figure 3). It experienced a rapid increase at first, and decreased, and slightly increased again, which may have been caused by the different stages of GGP implementation. At the beginning of the GPP, many trees were planted, and the tree covered area continued to increase, peaking in 2003. However, after 2003, it decreased and reached the minimum in 2006, which may have been due several reasons. First, trees cultivated in an inappropriate environment place may not grow well or even die. For example, many trees planted in the typical steppe zone or desert steppe zone were termed 'small-aged trees' characterized by much smaller sizes than what would be expected in another environment [44]. The failure of afforestation in desert steppe or desert zones also demonstrated this size discrepancy. Second, planting inappropriate tree species may also cause other problems [45]. For instance, cash trees (e.g., apricot and apple trees) did not always grow well due to water scarcity and unfavorable climate in the Loess Plateau [46,47]. Other detrimental conditions in the Loess Plateau may also lead to trees death. In arid and semiarid areas, soil moisture is generally deficient in planted forests due to low rates in annual precipitation, and has led to large-scale of plantations mortality during drought years [48]. This decrease in forested area was regarded as the second stage of the project. Even though the three reasons above have led to a decline in tree cover, as the project expanded, the tree covered area increased, and the number of trees planted annually decreased [41]. Thus, the tree covered area did not change drastically on an annual basis after 2006, tending to be stable. In 2014, it was greater than that in 2000 at the beginning of this project.

5.2. Spatial Variation of Tree Cover Change in the Loess Plateau

From Region I to V, tree cover and slope decreased, and had a spatial pattern from northeast to southwest (Figure 5). The five types of tree cover regions were based on the 15 year tree cover value, providing the spatial distribution and limitation of trees in the Loess Plateau. The spatial pattern of the five regions had a close relationship with the vegetation zone distribution in the Loess Plateau. From the southeast to northwest of the Loess Plateau are the forest zone, forest steppe zone, typical steppe zone, desert steppe zone and desert zone. Trees could survive in the forest zone, forest steppe zone and to a limited extent in the typical steppe zone, but could not live in the desert steppe zone or desert zone [49]. The ranges of Region I, II and III were very close to the forest zone and forest steppe zone and the scope of Region IV and V were comparable with typical steppe zone, desert steppe zone and desert vegetation zone, which matched well with the classification of the five tree cover regions. This showed the accuracy of the ecological meaning of the five tree cover regions.

In the five tree cover regions, the proportions of tree cover change showed big tending differences (Figure 6). Tree cover increased occurred mainly in Region I to IV, but were due to different processes. In Region I, II and III, the increase trend represented the tree cover value of a tree covered pixel increase. In Region IV, the former process existed, but it was more likely to be a non-tree covered pixel change to tree covered. Overall, under the GGP, restoration and afforestation both promote the increase of tree coverage and tree covered area increase. Even though most of the regions were experiencing tree cover increase, tree cover decrease also existed. The proportion was much higher in Region III, where the slope was flatter and trees could persist but not forest. Human activities were more detrimental due to the urbanization in this region during the past 15 years [42], which were the dominating reasons causing tree cover decrease.

An increasing trend of tree cover distributed in Northern of the Shaanxi Province, the east and west of the Shanxi Province, the north of Ordos Plateau, Northern of Pingliang in the Gansu Province and Northern of Ningxia. This was consistent with shifts observed in vegetation cover in most regions except in the Ningxia plain, Inner Mongolia and Liupan Mountains, where grasses and shrubs were the dominant vegetation [13,50]. A sustained increase in tree cover were found mainly in Region III and IV, including all the potential revegetation regions (Huangfuchuan, Kuyehe, Wudinghe, and Yanhe watersheds) discussed in previous research [13]. The result regarding sustained and increasing of tree cover was based on the current situation. However, some studies had showed that afforestation in unsuitable regions leads to deterioration of soil ecosystems, decrease of land surface temperature and water shortage as a result of increased transpiration [16,51,52]. In order to predict tree cover change in the Loess Plateau more accurately in the future, further studies need to take the influence of environment change into account.

5.3. Uncertainty

The MODIS VCF tree layer is among the most useful and reliable global datasets representing Earth's woody vegetation, and many studies have used it to analyze tree cover and its change [53]. However, drawbacks of this data include coarse levels of resolution, which could cause uncertain conclusions to be drawn. Much of this uncertainty is systematic, due to the overestimation in sparsely treed (e.g., agricultural) regions and underestimation in dense forests [54]. Some studies show that the MODIS VCF product confuses trees with shrubs [55–57]. Few studies have attempted to validate the MODIS VCF against independent reference data since this work require substantial financial support [57]. Until now, there has been nearly no validation in China. In comparison to other data sets, MODIS VCF data are very promising, as it is more objective and economical [18]. Even though other tree cover data sets with higher spatial resolution were produced, most of them represent measurements taken over one year and lack temporal resolution [2,54]. In the future, in order to evaluate tree cover change accurately, validation need to be made.

6. Conclusions

In this study, we investigated the temporal and spatial variations of the tree cover characteristics from 2000 to 2014 after the GGP in the Loess Plateau, China. With regard to temporal variations, the proportion of tree covered area, the cumulative tree cover and the average annual tree cover all increased, and their fluctuation reflected the different stages of the GGP. Concerning variation in tree cover trends, except few areas where significant human disturbance resulted in a decreasing trend; more than half of the Loess Plateau had an increasing trend. Categories based on temporal tree cover value determine the fitness and limitation of tree distribution, and enhance spatial understanding of tree cover variation and sustainability. Hence, further ecological instruction and restoration should take the categories into consideration in future policies or measures. The study also found that the spatiotemporal variation analysis of tree cover assists in assessing the effectiveness and sustainability of the ecological restoration projects.

Acknowledgments: This research was supported by the National Science Foundation of China (No. 41630750, 41271059), and the National Key Basic Research Special Foundation of China (No. 2011FY110300). The MODIS VCF data product was obtained from NASA's Earth Observing System Data and Information System (EOSDIS; http://reverb.echo.nasa.gov). We would like to thank the PIs and other research personnel of this product for developing and making them available to the research community. We also thank the three anonymous reviewers for their constructive comments on the manuscript.

Author Contributions: Yuhang Wang, Muyi Kang and Mingfei Zhao designed the paper; Yuhang Wang collected the data; Yuhang Wang and Mingfei Zhao analyzed the data; Yuhang Wang wrote the paper. Others were advisors. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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