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# Changes in Water Retention and Carbon Sequestration in the Huangshan UNESCO Global Geopark (China) from 2000 to 2015

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**Abstract:** Geopark ecosystem function assessments form an essential knowledge base for natural resource conservation and sustainable development. In this study, we evaluated changes in water retention and carbon sequestration in forests in the Huangshan United Nations Educational, Scientific, and Cultural Organization (UNESCO) Global Geopark (HUGG), China, from 2000 to 2015. We analyzed the relationship between these ecosystem functions and various controlling factors. The ecosystem functions in HUGG experienced significant changes during the study period. Water retention function increased slightly (0.15 $m^3$ $hm^{-2}$ $year^{-1}$), while carbon sequestration increased sharply (25.57 g C $m^{-2}$ $year^{-1}$), with both showing increased spatial homogenization. Increased precipitation significantly enhanced the water retention function, whereas a temperature increase had a positive effect on the carbon sequestration. Both water retention and carbon sequestration decreased significantly with increased tourist disturbance. Pearson's correlation coefficient and variance partitioning analysis identified the climate factors and tourist disturbance controlling water retention and carbon sequestration, respectively. The fitted structural equation model showed that climate factors had a greater total impact on water retention than tourist disturbance, while the total impact of climate factors on carbon sequestration was far less than that due to tourist disturbance. This study untangled the relationship between ecosystem functions (water retention and carbon sequestration) and influential factors in the HUGG and clarified that climate factors and tourist disturbance were determinants of changes in these ecosystem functions. The results from this study provide scientific foundations for the sustainable management of natural ecosystems in the HUGG and other geoparks.

**Keywords:** ecosystem functions; carbon sequestration; water retention; tourist disturbance; climate factors; Huangshan UNESCO Global Geopark

## 1. Introduction

A geopark is a well-defined area containing one or more geoheritage sites that are selected based on scientific importance; rarity; scenic quality; or relationship with geological history, events, or processes [1,2]. Ecosystem functions in a geopark include regulating climate, fixing atmospheric $CO_2$, protecting natural resources, and so on [3,4]. However, with the rapid growth of tourism, ecosystem functions of geoparks are facing enormous challenges and may be greatly reduced in the future [5–7]. To cope with these ecological challenges, China is implementing a series of national policies and new initiatives. The conservation of geological sites in China can be tracked back to the early 1980s, and the establishment of geoparks has developed rapidly with strong support from both government agencies and nongovernmental organizations over several decades [8]. Since 2000, more than 200 geoparks in China have been upgraded as Chinese national geoparks, with 39 listed as United Nations Educational, Scientific and Cultural Organization (UNESCO) Global Geoparks. Thus, the proper quantification of ecosystem functions in geoparks is critical for protecting natural ecosystems and supporting sustainable development [9].

Earlier assessment studies reported that terrestrial ecosystem services and functions in China dropped slightly from 2000 to 2010 [10]. More studies have indicated that the degradation of forest and excessive human activities were among the leading reasons for the loss of ecosystem functions and services in terrestrial ecosystems [11–15]. Moreover, one particular study pointed out that the influence of climate variability has been identified as one of the most significant factors influencing ecosystem functions in certain places [9]. For example, the conversion of farmland to woodland or grassland could enhance soil retention and carbon sequestration functions, but reduce regional water yield under warming and drying climate trends [16]. Additionally, geographic variation among site conditions and plant species also affects changes and vulnerability of ecosystem functions under the changing climate [17]. However, to our knowledge, few studies of ecosystem services have focused on analyzing the complex temporal and spatial relationships among ecosystem functions and external disturbances [18,19]. Therefore, quantifying the ecosystem functions of geoparks and analyzing their main controlling factors aid in protecting the natural environments and functions of key ecosystems.

The ecosystem functions of geoparks play an essential role in carbon cycling and the conservation of biodiversity [20,21]. However, there are few studies on estimating ecosystem functions and interpreting their interference factors in geoparks [22]. Previous studies have focused on the natural geology but lacked analyses of ecological processes [23,24]. Thus, issues of particular interest and importance have been to determine how climate change and human disturbance affect a geopark's natural resources and ecosystem functions [9,25], and human disturbance depends on the level of tourism resource development [26,27]. Additional knowledge of geoparks' ecosystem functions will provide additional guidance for protecting geoparks [10,28,29]. Huangshan is not only a UNESCO Global Geopark [7,30–33], but is also one of the foremost tourist destinations in China [34–37]. A previous study in the Anhui Province assessed the spatiotemporal dynamic changes in forest ecosystem functions from 2009 to 2014 [38], but neither the effectiveness of environmental protection nor the change in ecosystem functions in Huangshan have been properly assessed.

In this study, we assessed two dominant ecosystem functions (water retention and carbon sequestration) in the Huangshan UNESCO Global Geopark (HUGG) and calculated their changes from 2000 to 2015. The main controlling factors of water retention and carbon sequestration were determined in the HUGG over the same period. In addition, we analyzed the impacts of climate factors and tourist disturbance separately on water retention and carbon sequestration. The aim of this study was to disentangle the relationship between ecosystem functions and controlling factors in the HUGG. The results can provide scientific foundations for better planning and sustainable management of the natural ecosystems in the HUGG as well as in other similar geoparks.

## 2. Materials and Methods

### 2.1. Study Area

This study was conducted in the Huangshan UNESCO Global Geopark (HUGG), which is located in Huangshan city, Anhui Province, China (Figure 1). The entire scenic area is approximately 40 km long from north to south and 30 km wide from east to west, and lies from 30°01′ N to 30°18′ N and from 118°01′ E to 118°17′ E, with an area about 160 km$^2$ and elevations ranging from 311.0 to 1826.0 m. Geographically, the dominant ecosystem type in the HUGG is forest, followed by grass, with two other land use types (cropland and water) representing smaller fractions (Figure 1c).

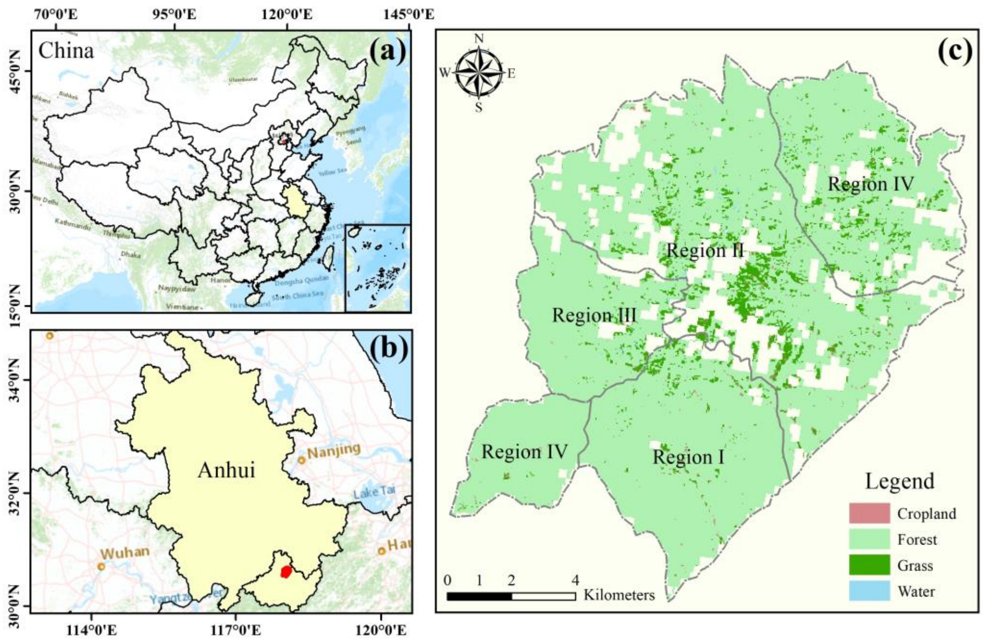


**Figure 1.** Overview map of the study area showing the location of the Anhui Province (**a**), the location of the Huangshan UNESCO Global Geopark (HUGG) (**b**), and the four types of ecosystems in the HUGG (**c**). Roman numerals in Figure 1c indicate the four levels of tourism resource development in the HUGG from 2000 to 2015.

The HUGG contains 1805 species of higher plants which belong to 827 genera, consisting of 222 families. Species of higher plants include *Pinus taiwanensis*, *Rhododendron maculiferum*, and *Rhododendron ovatum*. The HUGG has a typical tropical monsoon climate, with a monthly mean temperature ranging from −2.1 °C in January to 17.8 °C in July, and the mean annual temperature is 8.3 °C. The mean annual precipitation is 2235.8 mm, most of which occurs from April to August. The mean annual relative humidity is 76.6% (Figure A1). From the low- to high-altitude areas in the HUGG, the soil types include quasi-red soil, quasi-yellow soil, and rot palm soil, with latent soils in some places. In addition, the classification map of HUGG tourism resource development drawn in 2005, which was provided by the HUGG Administrative Committee, shows that the development degree of tourism resources from Region I to Region IV decreased sequentially. Specifically, Region I is in proximity to the entrance of HUGG, and its tourism resource development is highest among the four. The next highest is Region II, due to many famous spots clustering in this region (Greeting Guest Pine, Flying-Over Rock, Yungu Temple, etc.), followed by Region III in an average degree of tourism resource development, where only a few famous spots in this area. Region IV barely experienced tourism development, and its tourism resource development is lowest among the four regions (Figure 1c).

### 2.2. Data Sources and Pretreatments

The image acquisition times were 17 April 2000 (Landsat 5 TM); 29 April 2010 (Landsat 5 TM); and 20 October 2015 (Landsat 8 OLI/TIRS). All the images were downloaded from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/). The cloud cover on the remote sensing images that we used was close to zero, allowing an accurate extraction of various vegetation indices. Following acquisition, all the images went through a preprocessing step, including orthorectification, radiometric calibration and atmospheric correction [39]. The processed remote sensing data eliminated the influences of atmospheric absorption and scattering on the surface reflectivity. Furthermore, we calculated four vegetation indices from remote sensing images using the formulae in Table 1. The normalized difference vegetation index (NDVI) determines the vegetation cover fraction and biomass in areas of low-density vegetation [40]. The ratio vegetation index (RVI) was used in mature forest phases with NDVI to study forest growth synergistically [41]. The use of Modified soil-adjusted vegetation index (MSAVI) resulted in a greater vegetation sensitivity than that of NDVI and RVI [42], and MTVI2 was used to a better predictor of chlorophyll content [43]. The abovementioned steps were completed using the ENVI 5.1 software.

**Table 1.** Equations for the vegetation indices used in this study. $\rho_{NIR}$, $\rho_{RED}$, and $\rho_{GREEN}$ represent the reflectances of the Landsat images in the near-infrared, red, and green bands, respectively.

| Vegetation Index | Equation |
|---|---|
| Normalized difference vegetation index (NDVI) | $NDVI = \frac{(\rho_{NIR} - \rho_{RED})}{(\rho_{NIR} + \rho_{RED})}$ |
| Ratio vegetation index (RVI) | $RVI = \frac{\rho_{NIR}}{\rho_{RED}}$ |
| Modified soil-adjusted vegetation index (MSAVI) | $MSAVI = \frac{[2\rho_{NIR} + 1 - \sqrt{(2\rho_{NIR} + 1)^2 - 8(\rho_{NIR} - \rho_{RED})}]}{2}$ |
| Modified triangular vegetation index 2 (MTVI2) | $MTVI2 = \frac{1.5[1.2(\rho_{NIR} - \rho_{GREEN}) - 2.5(\rho_{RED} - \rho_{GREEN})]}{\sqrt{(2 * \rho_{NIR} + 1)^2 - (6 * \rho_{NIR} - 5 * \sqrt{\rho_{RED}}) - 0.5}}$ |

We extracted the related climate factor data from a meteorological dataset provided by the National Meteorological Information Center of China (http://data.cma.cn/), including mean annual temperature (MAT) and mean annual precipitation (MAP) from 1998 to 2015. The meteorological data were from 41 ground monitoring stations near the HUGG in the Anhui Province. We calculated the MAT and MAP in 2000, 2010, and 2015. Spatial interpolation of the meteorological data was completed using the ANUSPLIN 4.4 software [44].

To quantitatively assess the disturbances to HUGG from 2000 to 2015, we downloaded a vector layer of roads and typical features (including attractions and villages) of the study area from OpenStreetMap (https://www.openstreetmap.org/). We modified the vector layer, and combined it with a scenic area survey conducted in July 2018 and a classification map of tourism resource development drawn in 2005 provided by the HUGG Administrative Committee. We calculated the Euclidean distance between the trail and the attractions and converted it to the disturbance [45]. Finally, we totaled them to generate the disturbance map of the HUGG.

Considering the area of the HUGG, it is appropriate to use a square grid with a side length of 500 m to extract various types of data. Therefore, data extraction was performed in the following three steps. We created a 500 × 500 m fish net and then ruled it out using the vector boundaries of the HUGG. Data were prepared for extraction using these grids. The above processing steps were performed using the ArcGIS 10.1 software for Windows.

### 2.3. Calculations of Water Retention and Carbon Sequestration

Water retention is an important ecosystem function that not only indicates the ability of forest ecosystems to store precipitation and regulate runoff, it also reflects the integrated effects of vegetation, water, and soil in the study area [46–48]. Carbon sequestration is also an essential ecosystem function offered by plants, which reflects the ability of vegetation to mitigate climate change [49–53]. Moreover, the Ministry of Ecological and Environmental Protection of China carried out research on the environment, and proposed a division of functional districts in 2015. The HUGG was classified as an important area for water retention based on eco-functional regionalization. The ecosystem function calculation methods used in our study were provided by the ecosystem functions dataset of China (2010) [25]. Meteorological and net primary productivity data were used to calculate water retention and carbon sequestration. Using the formulae in Table 2, the changes in water retention and carbon sequestration among different years were calculated and displayed using the ArcGIS 10.1 software.

**Table 2.** Equations, abbreviations, and references used to calculate water retention and carbon sequestration.

| Ecosystem Function | Abbreviation | Equation | Reference |
|---|---|---|---|
| Water retention | EF_WR | $Q_{\text{Water retention}} = \sum_{i=1}^{j} A_i(P_i - R_i - ET_i)$ | [54,55] |
| Carbon sequestration | EF_CS | $NPP = APAR(x,t) \times \varepsilon(x,t)$<br>$NPP_{forest} = 0.50NPP$<br>$NPP_{grass} = 0.45NPP$<br>$C_{qave} = (NPP_{2010} - NPP_{2000})/10$<br>$(\text{or } C_{qave} = (NPP_{2015} - NPP_{2010})/5)$ | [56,57] |

$Q_{\text{Water retention}}$ represents the amount of water retention ($m^3$); $P_i$ represents the precipitation (mm); $R_i$ represents the storm runoff (mm); $ET_i$ represents the actual evapotranspiration (mm); and $A_i$ represents the area of ecosystem-i (forest, grass, cropland, or water) ($m^2$). APAR represents the absorbed photosynthetically active radiation (MJ $m^{-2}$ 10 $day^{-1}$); ε represents the actual light energy utilization rate of the pixel (g C $MJ^{-1}$); $C_{qave}$ is the average carbon sequestration amount from 2000 to 2010 (or 2010 to 2015); $NPP_{2000}$ ($NPP_{2010}$ or $NPP_{2015}$) is the total forest and grassland carbon sequestration in 2000 (2010 or 2015); $NPP_{forest}$ is the forest carbon sequestration; and $NPP_{grass}$ is the grassland carbon sequestration.

### *2.4. Multivariate Correlation Analysis and Variance Partitioning*

Prior to variance partitioning, Pearson correlation coefficient values (r) were calculated to determine the relationships among all observed variables. Relationships among different variables were analyzed to find key influences and drivers, which provided a basis for further data analysis and modelling [58,59]. A correlation coefficient matrix was constructed to analyze the correlations among variables, and a heat map was created to visually represent the correlation coefficient matrix.

Redundancy analysis (RDA) is a sorting method of regression analysis combined with a principal component analysis [60,61]. Variance partitioning quantifies the variance in a set of data, and these partitions can be divided into the variance explained by each variable alone or jointly [62]. We used variance partitioning to (1) explore the dominant factors for changes in water retention and carbon sequestration and (2) quantify the contribution of each factor that affects changes in carbon sequestration, water retention, and both of them. The results were presented using Venn diagrams to clearly see the impact of climate factors, tourist disturbance and vegetation growth on changes in water retention and carbon sequestration. All the analyses performed in this study were carried out using the "vegan" package in the R programming environment.

### *2.5. Evaluation of the Structural Equation Model*

As a multivariate statistical method used to investigate the relationships among multiple factors in a natural system, the structural equation model (SEM) and its ecological application have received increasing attention in recent years [63–73]. An SEM was fitted by using the "lavaan" package in the R software [74–76]. Results were plotted for visual analysis. In this study, vegetation growth, climate factors, tourist disturbance, and water retention and carbon sequestration were set as the latent variables. The observed variables included four types of calculated vegetation indices (NDVI, RVI, MSAVI and MTVI2), calculated disturbance (DIS), mean average temperature (MAT), and mean average precipitation (MAP). The model was based on the following causal assumptions: (1) latent variables of vegetation growth, climate factors, and tourist disturbance directly impacted the latent variable of water retention and carbon sequestration; (2) latent variable of climate factors indirectly impacted the latent variable of water retention and carbon sequestration through the latent variables of vegetation growth; and (3) latent variable of tourist disturbance indirectly impacted the latent variable of water retention and carbon sequestration through the latent variables of vegetation growth.

## 3. Results

### 3.1. Dynamic Evaluation of Water Retention and Carbon Sequestration

The spatial distribution characteristics of water retention and carbon sequestration from 2000 to 2015 are shown in Figure 2. The water retention in the HUGG increased slightly from 2000 to 2010 (0.15 $m^3$ $ha^{-1}$ $year^{-1}$ on average) and basically remained almost unchanged from 2010 to 2015 (0.01 $m^3$ $ha^{-1}$ $year^{-1}$ on average) (Figure 2). From 2000 to 2010, the water retention significantly increased in 44.75% of the study area (58.54 $km^2$), 45.74% of the area remained unchanged (59.84 $km^2$), and 9.51% of the area decreased (12.44 $km^2$). From 2010–2015, only a small area of the HUGG decreased (0.42%), and the remaining area was unaltered (99.68%) (Figure A2 and Table 3).

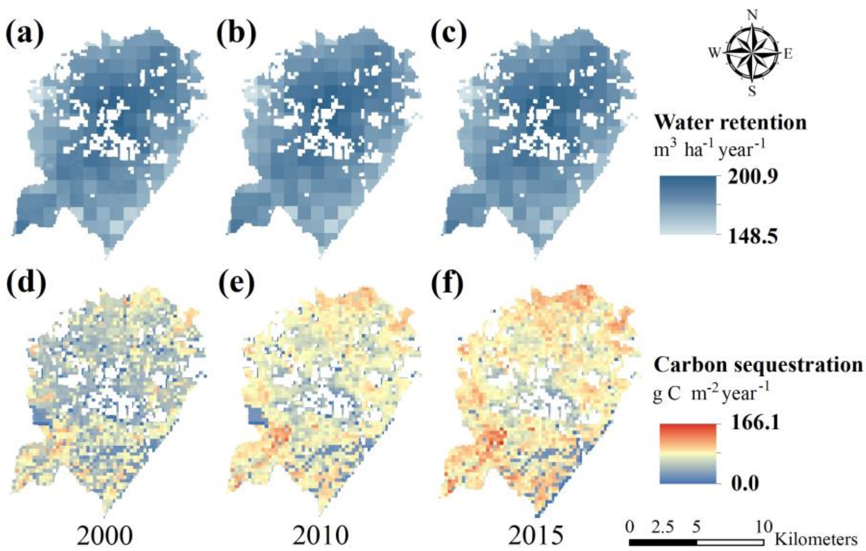


**Figure 2.** Spatial distribution of the water retention and carbon sequestration in the Huangshan UNESCO Global Geopark, showing water retention for 2000 (**a**), 2010 (**b**), and 2015 (**c**) and carbon sequestration for 2000 (**d**), 2010 (**e**), and 2015 (**f**).

**Table 3.** Area statistics of ecosystem function changes in the Huangshan UNESCO Global Geopark.

| Ecosystem Function | Change | 2000–2010 | | | 2010–2015 | | |
|---|---|---|---|---|---|---|---|
| | | Area ($km^2$) | Area Percent (%) | Average Change ($m^3$ $ha^{-1}$ $year^{-1}$ or g C $m^{-2}$ $year^{-1}$) | Area ($km^2$) | Area Percentage (%) | Average Change ($m^3$ $ha^{-1}$ $year^{-1}$ or g C $m^{-2}$ $year^{-1}$) |
| Water retention | Increased | 58.54 | 44.75 | 0.15 | 0.00 | 0.00 | 0.01 |
| | Decreased | 12.44 | 9.51 | | 0.42 | 0.32 | |
| | Unchanged | 59.84 | 45.74 | | 130.39 | 99.68 | |
| Carbon sequestration | Increased | 102.93 | 78.68 | 16.29 | 128.83 | 98.48 | 9.28 |
| | Decreased | 25.25 | 19.30 | | 1.92 | 1.47 | |
| | Unchanged | 2.63 | 2.01 | | 0.06 | 0.05 | |

For the carbon sequestration in the HUGG, the growth period could be subdivided into two phases, with first period from 2000 to 2010 (16.29 g C $m^{-2}$ $year^{-1}$ on average), and second period from

2010-2015 (9.28 g C $m^{-2}$ $year^{-1}$ on average) (Figure 2). From 2000 to 2010, carbon sequestration showed significantly increases in 78.68% of HUGG (102.93 $km^2$), 19.30% of the area decreased (25.25 $km^2$), and only 2.01% of the area remained unchanged (2.63 $km^2$). However, almost all the HUGG area (98.48%) increased over the observation period (Figure A2 and Table 3).

Regional statistical results of the changes in ecosystem functions from 2000–2015 are shown in Figure 3. There were similar change trends for both water retention and carbon sequestration in the HUGG. For water retention, the changes in Region III (0.37 ± 0.12) were higher than those in Region II (0.21 ± 0.01), Region IV (0.08 ± 0.03) and Region I (-0.02 ± 0.03). Similar to water retention, the changes in carbon sequestration were also different among regions. The greatest changes in carbon sequestration were also observed in Region III (30.65 ± 1.21), followed by Region II (28.20 ± 0.75), Region IV (25.85 ± 0.75), and Region I (18.20 ± 0.91). The results were statistically significant ($p < 0.05$).

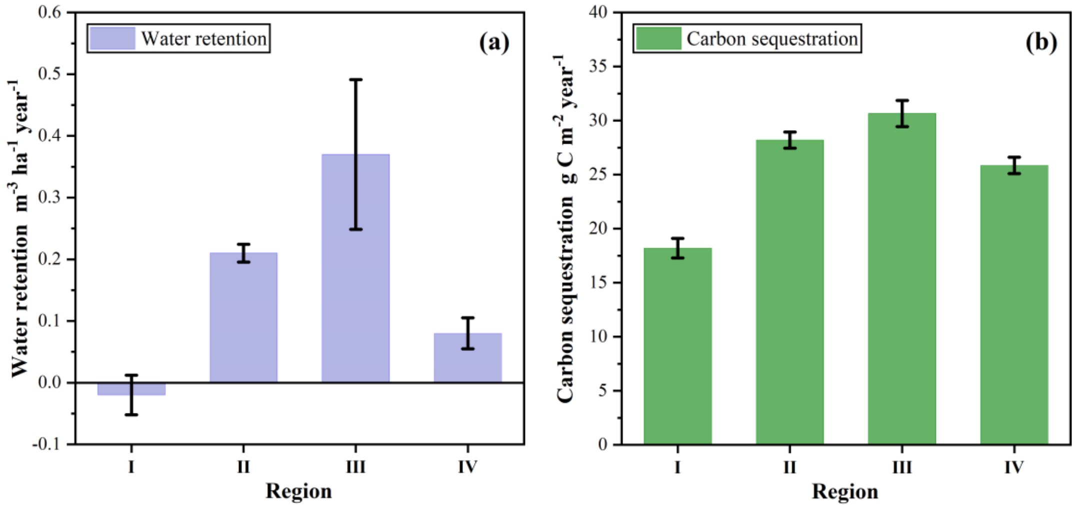


**Figure 3.** Mean changes (±SE) in the water retention (**a**) and carbon sequestration (**b**) among the four tourism resource development regions from 2000 to 2015 in the Huangshan UNESCO Global Geopark.

### 3.2. Correlation Among Observed Variables

All the vegetation growth indices (NDVI, RVI, MSAVI, and MTVI2) of the HUGG fluctuated between 2000 and 2015, with the worst vegetation growth occurring in 2010 (0.62 on the average value of vegetation growth indices) and the best in 2015 (1.07 on the average value of vegetation growth indices) (Figure A3). The mean annual precipitation (MAP) ranged from 1761.1 (2010) to 2768.7 mm (2000). The mean annual temperature (MAT) range was 9.0 to 15.9 °C (Figure A4). MAT decreased with increasing altitude, while MAP increased with increasing altitude.

From 2000–2015, the disturbance in HUGG ranged from 0.01 to 2.00, which represents an increasing influence (Figure 4). Disturbance was concentrated in Regions I, II, and III, where the landscape attractions were concentrated, and the tourist trails were dense (e.g., Greeting Guest Pine, Stone Monkey Watching the Sea, Flying-Over Rock, etc.). Region IV had a lower tourist disturbance due to its limited tourism resource development.

The correlations among all variables are presented in Figure 5. The results indicated that water retention (EF_WR) was positively correlated with mean annual precipitation (MAP), and negatively correlated with vegetation growth indices (NDVI, RVI, MSAVI and MTVI2), mean annual temperature (MAT), and tourist disturbance (TD). Additionally, TD and MAP had negative effects on carbon sequestration (EF_CS), while MAT and MTVI2 had positive effects on carbon sequestration. All the vegetation growth indices had significant positive relationships with MAT, but were negatively correlated with MAP. Moreover, with the increase in TD, vegetation growth indices increased while EF_CS and EF_CS decreased (Figure 5).

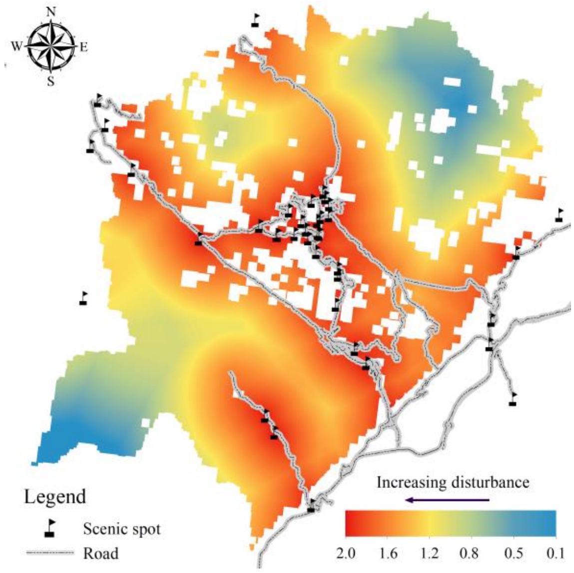


**Figure 4.** Distribution of disturbance across the Huangshan UNESCO Global Geopark ranging from 0.1 to 2.0, which represents an increasing influence.

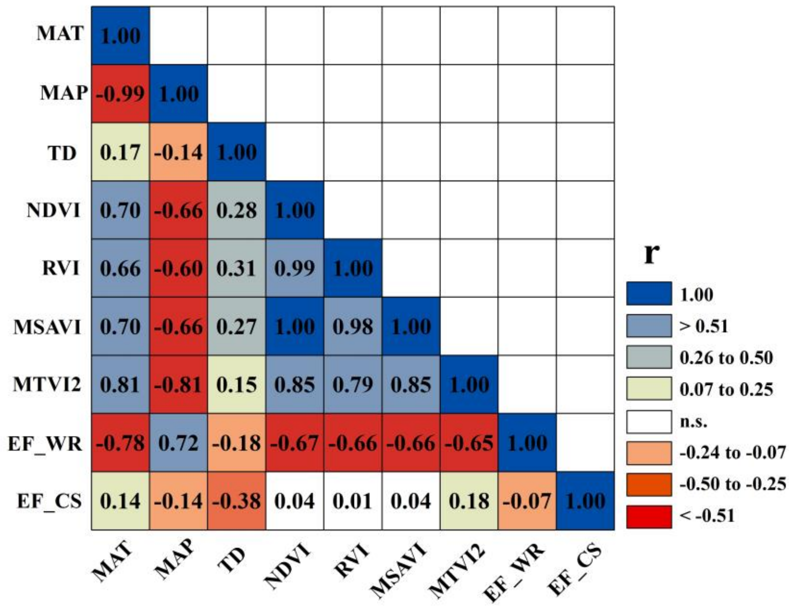


**Figure 5.** A heat map of the correlations among the variables. Colors indicate the strength of the correlation, where dark blue and dark red indicates a perfect correlation (ns, is not significant). The variables are the mean annual temperature (MAT), mean annual precipitation (MAP), tourist disturbance (TD), normalized difference vegetation index (NDVI), ratio vegetation index (RVI), modified soil-adjusted vegetation index (MSAVI), modified triangular vegetation index-improve (MTVI2), water retention (EF_WR), and carbon sequestration (EF_CS).

### *3.3. Multiple Controls of Water Retention and Carbon Sequestration*

The interpretations of water retention and carbon sequestration by climate factors and tourist disturbance were calculated by variance partitioning (Figure 6 and Table 4). Climate factors and tourist disturbance accounted for 43.51% of the ecosystem functions. Between them, the individual contribution of climate factors was 11.40%, and tourist disturbance was 7.03%. The combined contribution of climate factors and vegetation growth reached 23.19%, indicating that their interaction contributed significantly to changes in ecosystem functions (Figure 6a).

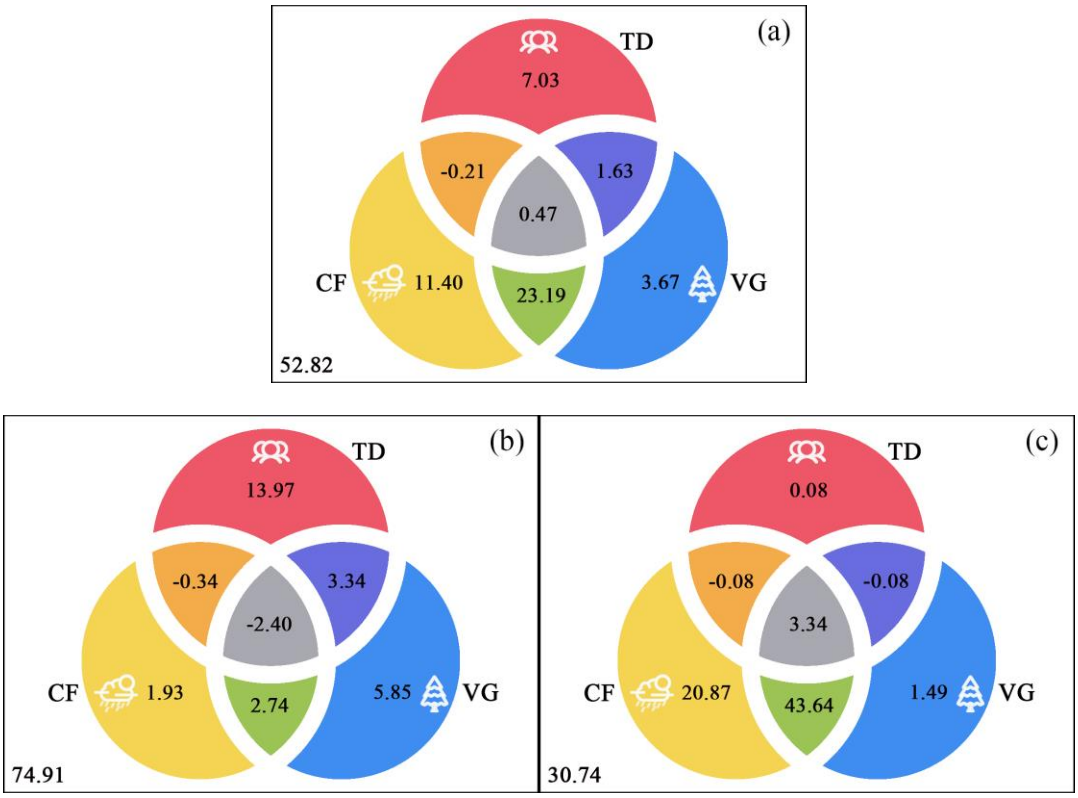


**Figure 6.** Variance partitioning (%) for two ecosystem functions (**a**), carbon sequestration alone (**b**), and water retention alone (**c**). The variables are tourist disturbance (TD), vegetation growth (VG), and climate factors (CF).

**Table 4.** Total contribution of climate factors, tourist disturbance, and vegetation growth to ecosystem function variation; this result was statistically significant ($p < 0.05$).

| | Both Ecosystem Functions (%) | Carbon Sequestration (%) | Water Retention (%) |
|---|---|---|---|
| Climate factors | 34.85 | 1.93 | 67.77 |
| Tourist disturbance | 8.92 | 14.57 | 3.26 |
| Vegetation growth | 28.96 | 9.53 | 48.39 |

In addition, we separately analyzed variance partitioning results of water retention and carbon sequestration. For carbon sequestration, we found that tourist disturbance alone explained the most variance change at 13.97%, while climate factors contributed only 1.93%. (Figure 6b). For water retention, the individual contributions of climate factors were highest (20.87%), while tourist disturbance only explained 0.08%. The combined contribution of climate factors and vegetation growth had the greatest impact on water retention (43.64%) (Figure 6c).

As shown in Table 4, the total contribution of climate factors to both water retention and carbon sequestration (34.85%) was significantly higher than the total contribution of tourist disturbance (8.92%), indicating that climate factors were the dominant factors that changed these ecosystem functions. For carbon sequestration, the tourist disturbance had the highest total contribution (14.57%), which indicated that tourist disturbance was the dominant impact on carbon sequestration. Similarly, for water retention, the climate factors were dominant and explained 67.77%.

### 3.4. Analysis of the Fitted SEM

The final best-fit SEM describing the relationships among the latent variables and their observed variables is shown in Figure 7. Climate factors and vegetation growth had weak positive effects on carbon sequestration (0.14 and 0.11, respectively), with the tourist disturbance having a strong negative effect on the carbon sequestration (−0.44). The tourist disturbance had weak positive effects on vegetation growth (0.14), with climate factors having a strong positive effect on the vegetation growth (0.54) (Figure 7a).

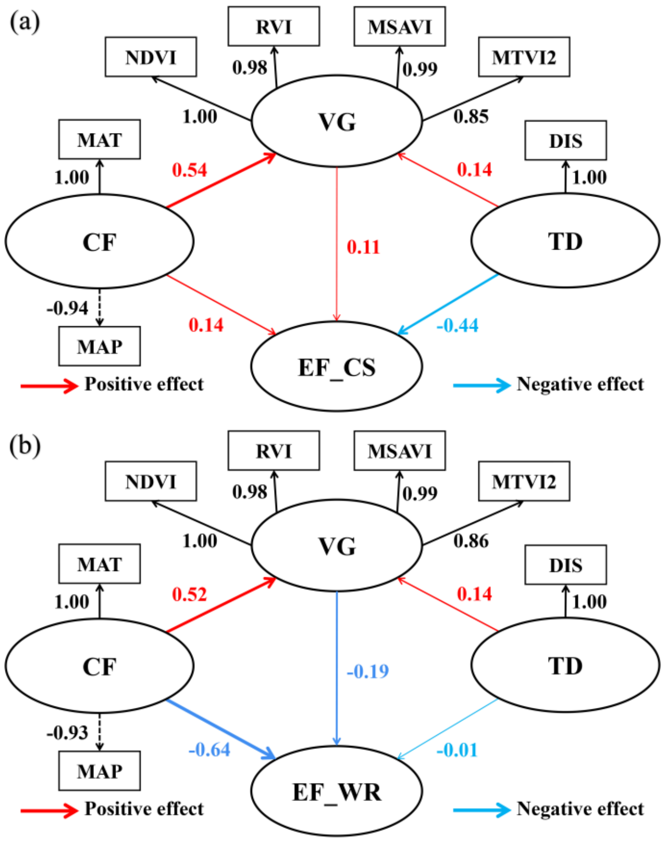


**Figure 7.** The final best-fit SEM model describing the relationships among the latent variables and their observed variables. Red paths represent positive effects, and blue paths represent negative effects. Numbers and thickness of paths indicate the size of the effect. Variables are tourist disturbance (TD), vegetation growth (VG), climate factors (CF), mean annual temperature (MAT), mean annual precipitation (MAP), tourist disturbance (TD), normalized difference vegetation index (NDVI), ratio vegetation index (RVI), modified soil-adjusted vegetation index (MSAVI), modified triangular vegetation index-improve (MTVI2), calculated disturbance (DIS), water retention (EF_WR), and carbon sequestration (EF_CS).

Vegetation growth and tourist disturbance had weak and negative effects on water retention (−0.19 and −0.01, respectively). However, climate factors had a strong negative effect on the water retention, reaching −0.64. Additionally, climate factors had a strong positive effect on the vegetation growth (0.52), while tourist disturbance had a weak positive effect on vegetation growth (0.14) (Figure 7b).

The direct impact of climate factors on carbon sequestration was a positive effect (0.14), whereas the direct impact of tourist disturbance on carbon sequestration was a negative effect (−0.44). The indirect impact value of climate factors on carbon sequestration was 0.06, and the total impact value was 0.20. The indirect impact of tourist disturbance on carbon sequestration was 0.02, and the total impact on carbon sequestration was −0.42. Thus, the total impact of the climate factors on carbon sequestration was smaller than that of tourist disturbance (Figure 7a). However, the total impact of the climate factors on water retention was much larger than that of tourist disturbance (−0.74 and −0.04, respectively).

## 4. Discussion

### 4.1. Changes in Water Retention and Carbon Sequestration in the HUGG

The carbon sequestration and water retention calculated for the study changed significantly during the 15-year period (2000–2015) in the HUGG. The water retention in the HUGG increased slowly from 2000 to 2010 (0.15 $m^3$ $ha^{-1}$ $year^{-1}$ on average) and remained almost unchanged from 2010 to 2015 (0.01 $m^3$ $ha^{-1}$ $year^{-1}$ on average). he carbon sequestration increased greatly during the first ten years (16.29 g C $m^{-2}$ $year^{-1}$ on average) and slowed from 2010 to 2015 (9.28 g C $m^{-2}$ $year^{-1}$ on average). The results from our assessment indicated that both ecosystem functions of the HUGG were gradually changing with the rapid growth of tourism programs and ongoing climate change, which was consistent with results found by other researchers in nearby areas [38]. In addition, from 2000 to 2015, the water retention increased the most in Region III, followed by Region II, Region IV, and Region I. Similar to water retention, the greatest increase in carbon sequestration was also observed in Region III. The results suggested that excessive development of tourism resources could slow down water retention and carbon sequestration and even lead to habitat degradation.

### 4.2. Factors Affecting the HUGG Ecosystem Functions

Our multivariate analysis showed that climate factors played a more important role in water retention than in tourist disturbance. The mean annual temperature had a strong negative effect on water retention, while the mean annual precipitation had a strong positive effect. However, tourist disturbance had a weak negative effect. Previous studies found that, as temperature rises, soil respiration increases due to enhanced biological activity, increasing the release of $CO_2$ and accelerate organic matter decomposition and reducing water retention [77,78]. Additionally, the surface runoff and groundwater brought by precipitation will significantly increase soil moisture content [79].

In contrast, tourist disturbance had a stronger negative effect on carbon sequestration than climate factors. With an increase in temperature, the carbon sequestration function gradually increased, which was consistent with results from previous studies [29,80]. However, precipitation was negatively correlated with carbon sequestration, which may be due to the low photosynthetic activity in plants on rainy days [20,21]. The current study proved that vegetation restoration played an important role in ecosystem functions [9]. Tourist disturbance had a negative effect on carbon sequestration, and our study suggests that trampling by tourists increases soil compaction, reducing soil voids and soil moisture [81].

### 4.3. Implications and Uncertainties

This study clarified the relationships between influential factors (climate factors and tourist disturbance) and two ecosystem functions (water retention and carbon sequestration) in the HUGG. The HUGG Administrative Committee could properly develop tourism resources, control the number of visiting tourists in the peak season, and regulate tourist behavior to protect the HUGG ecosystem. A previous study indicated that the development of tourism resources is a double-edged sword [82]. If the HUGG Administrative Committee adopts the appropriate management measures, natural resource conservation and sustainable development can be achieved. If not, the development of tourism resources will have a negative impact on ecosystem functions [9,81]. Our research on water retention and carbon sequestration in the HUGG can provide a reference for other Chinese national geoparks to carry out related research and provide a basis for the scientific planning and management of other geoparks.

There are some uncertainties in this study. We found that tourist disturbance had a weak positive effect on vegetation growth, possibly “artificial fertilization”. During the field survey in July-August

2018, our team noticed that cleaners in the HUGG only transported hard-degradable plastic products, and ignored organic residues, such as melon peels or cores. These organics may have promoted the growth of vegetation. Additionally, vegetation growth had a weak negative effect on water retention, possibly due to the high evapotranspiration rates in the Huangshan forest. In follow-up research, we will proceed from the above endpoints and continue to improve the research.

## 5. Conclusions

Our study suggests that the water retention and carbon sequestration in the HUGG changed significantly from 2000 to 2015. Tourist disturbance reduced these two ecosystem functions in the HUGG. The changes in water retention were mainly due to climate variability, while the reduced carbon sequestration was linked to increased tourist disturbance during the study period. This phenomenon should be considered to preserve natural ecosystems and protect water retention and carbon sequestration in the HUGG, as well as other Chinese national geoparks.

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## Appendix A

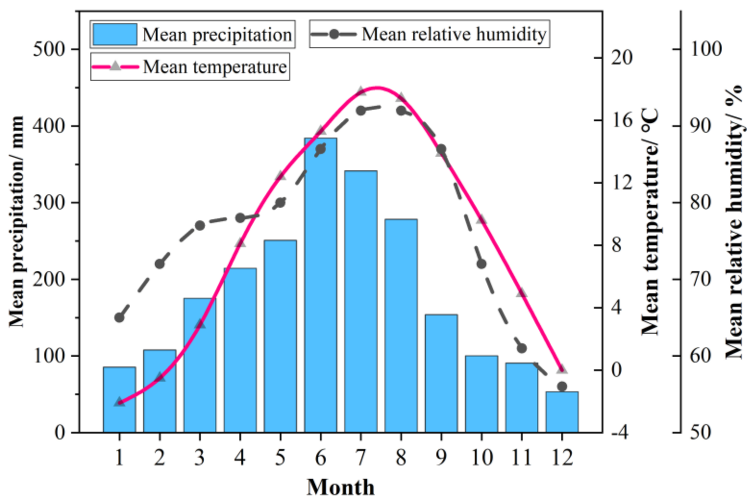


**Figure A1.** Mean temperature, precipitation and relative humidity for the Huangshan UNESCO Global Geopark.

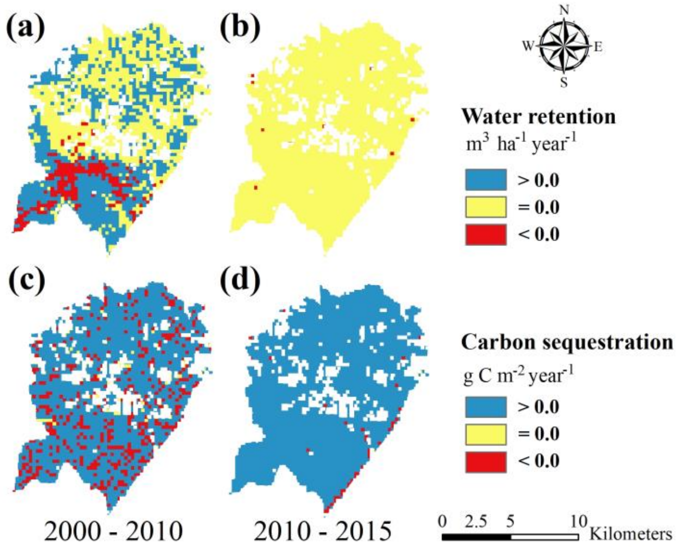


**Figure A2.** Changes in water retention between 2000 and 2010 (**a**) and between 2010 and 2015 (**b**) and the changes in carbon sequestration between 2000 and 2010 (**c**) and between 2010 and 2015 (**d**) in the Huangshan UNESCO Global Geopark.

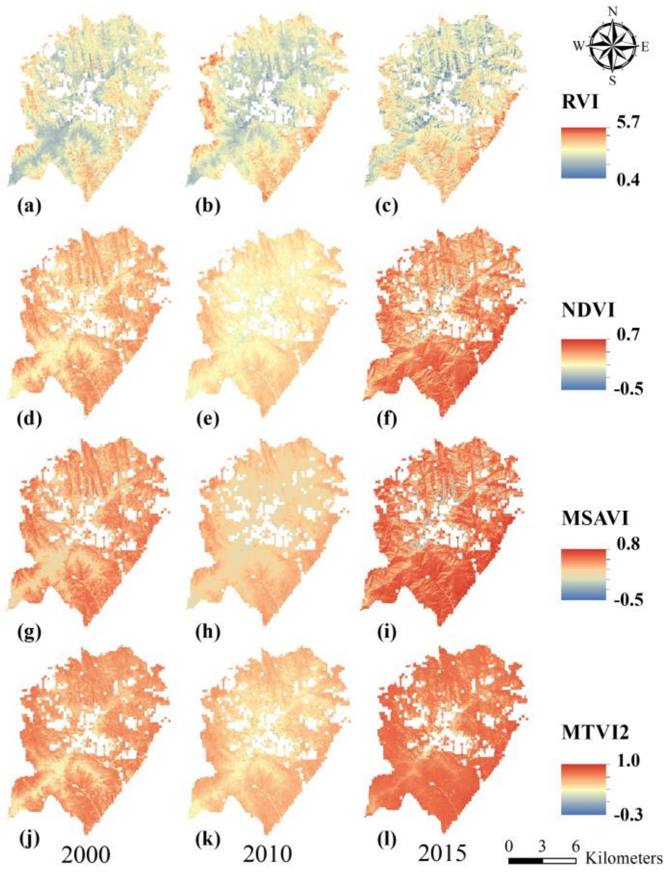


**Figure A3.** The vegetation indices in the Huangshan UNESCO Global Geopark: RVI in 2000 (**a**), 2010 (**b**) and 2015 (**c**); NDVI in 2000 (**d**), 2010 (**e**), and 2015 (**f**); MSAVI in 2000 (**g**), 2010 (**h**), and 2015 (**i**); and MTVI2 in 2000 (**j**), 2010 (k), and 2015 (**l**).

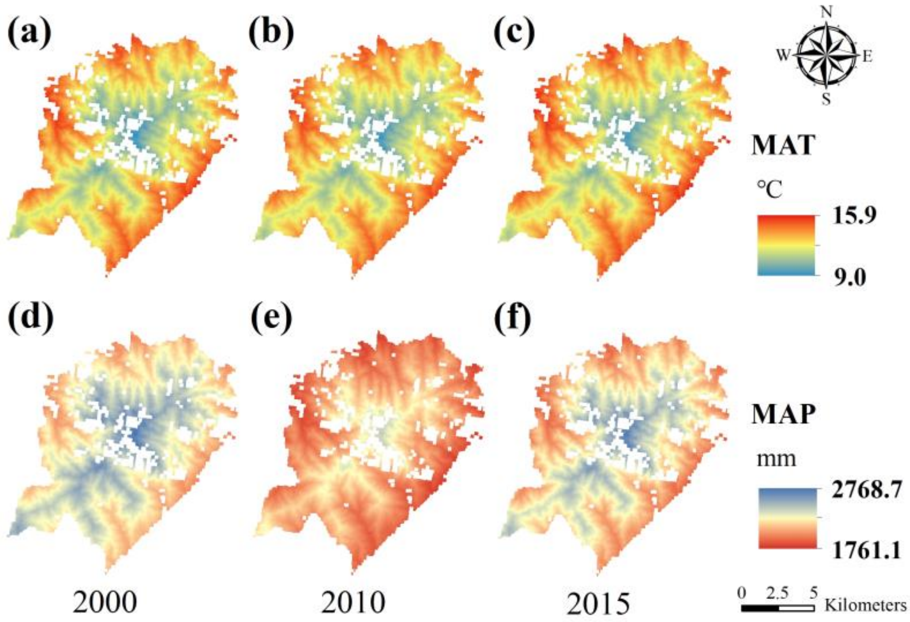


**Figure A4.** Mean annual temperature (MAT) (°C) in 2000 (**a**), 2010 (**b**), and 2015 (**c**) and mean annual precipitation (MAP) (mm) in 2000 (**d**), 2010 (**e**), and 2015 (**f**) for the Huangshan UNESCO Global Geopark.

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