Response of the Water Conservation Function to Vegetation Dynamics in the Qinghai–Tibetan Plateau Based on MODIS Products

Shuying Wu, Wei Zhou, Kai Yan, and Xunxun Zhang

***Abstract*—With the increasing demand for global water resources and general deterioration of the ecological environment of the Qinghai-Tibetan Plateau, changes to the water conservation functions of ecosystems and the impact mechanisms have attracted great attention. Currently, the research on water conservation has mainly focused on a single biome type, in particular, forests. Few studies explore the differences in water conservation functions of different biome types. Research on this topic mostly utilizes field investigations and sample plot settings to explore the differences in water conservation capacity of a small number of tree species, but these methods are limited in time and space. Therefore, this study uses MODIS products to evaluate the water conservation function of different biome types in the Qinghai-Tibetan Plateau. Dynamic monitoring of the vegetation and water conservation capacity in the study area and research on the responses of the water conservation functions of different biome types were conducted. The results indicate that the vegetation of the Qinghai-Tibetan Plateau increased slightly from 2000 to 2015; however, due to the dual influence of climate and topographic factors, the water conservation capacity showed a slight decline. The water conservation service function mainly comes from grassland ecosystems, which are closely related to vegetation density and biome types. Therefore, to greatly improve the water conservation service function of the Qinghai-Tibetan Plateau, the management and planting of vegetation should be conducted according to the optimal vegetation coverage area, vegetation quantities and biome types.**

***Index Terms*—Ecological environment, LAI, long time series, Qinghai–Tibetan plateau, water conservation.**

I. Introduction

With the increasing demand for water resources and the large-scale deterioration of water environments [1]–[2], more scholars have begun to study changes in ecosystem water conservation functions and their impact mechanisms [3]. Water conservation is an important function of ecosystems [4], and its main manifestations include blocking precipitation, mitigating surface runoff, inhibiting evaporation, affecting rainfall, enhancing soil infiltration, purifying water quality, etc. [5]. The water conservation capacity of ecosystems is closely related to the vegetation type, vegetation coverage, soil type, litter composition ,and litter quantity, and it is the result of the interactions between vegetation and soil [6]–[7]. Vegetation change will lead to significant changes in regional water conservation functions. Quantitative studies and mastering the response of the water conservation function to vegetation change is an important measure and effective way to restore and protect ecosystem structures.

Currently, research on the water conservation function in China has mainly focused on a single biome type [8]–[10], in particular, forest. He *et al.* [11] used the monitoring data of the Forest Ecosystem Positioning Research Station in eastern China to study the water conservation function of forest ecosystems under water and heat gradients. Therefore, early research areas mainly focused on the assessment of forest water conservation capacity in the southeast coastal areas, mainly due to the lack of understanding of water conservation function at that time. With the rapid development of research on water conservation function in China, the research area has gradually expanded to inland and northwest areas, showing a trend of development from point to surface. Yu *et al.* [12] evaluated the water conservation function of a forest ecosystem in a Beijing mountain area based on the water balance method and InVEST model, compared and analyzed the water conservation capacity of soil layers of different forest landscape types and further expanded the research content and field relative to the early stage. In other countries, there are few studies on water conservation capacity, and they mainly focus on forest biomes in the early stage. In the 1960s, water conservation mainly referred to the impact of forests on river flow [13]. Until 1997, Constanza [14] proposed that ecosystem services include 17 types such as water conservation. Since then, as an important function of ecosystems, water conservation has attracted widespread attention. With the continuous improvement and development of the theory, Tsiko *et al.* [15] found that vegetation interception is conducive to maintaining the balance of land rainfall by studying the interception of rainfall by canopy layers and deciduous layers, so the interception function of vegetation has

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been paid increasing attention. Research on the function of water conservation has not been limited to the hydrological process of forest ecosystems, but rather has further deepened, expanded and integrated the research content. This area of research mainly studies the response of the surrounding environment to forest change, including the impact of forests on precipitation, runoff, evapotranspiration and water quality, and pays more attention to the comprehensive effect of multiple hydrological processes [16], [17].

Previous studies have shown that forests are still the main subject of water conservation function research, but there is little research on the difference in water conservation capacity of ecosystems with different biome types. Therefore, Wang *et al.* [18] comprehensively evaluated the soil physical properties and water conservation function of six biome types in Nangan Nature Reserve in 2016 by using a comprehensive evaluation method. The research shows that there are significant differences in the water conservation capacity of different biome types. However, other researchers have used field survey methods to explore the differences in water source functions between different types of biome and obtained the best type of biome in terms of water conservation functions, providing important scientific evidence for the protection of regional water conservation functions [19]. Currently, the methods used to evaluate the water conservation functions of ecosystems mainly include the water balance method, precipitation storage method, comprehensive water storage capacity method, soil water storage method, canopy interception surplus method and multi-factor regression method. The water balance method is a simple and easily operated method, which uses the difference between the input water and the output water in the system as the water conservation amount of the system. It is also the most accurate and frequently among the current methods of estimating the water conservation amount [20]. The comprehensive water storage capacity method, soil water storage method and canopy interception surplus method ignore the influence of evapotranspiration on water conservation, which leads to a large error in the estimated water conservation [21]. The precipitation storage method ignores the influence of factors such as surface runoff [22], [23]. The application of multi-factor regression method needs a large amount of supporting observational data to fit the regression coefficient, which is difficult to obtain completely [24]. In the research and application of water conservation estimation methods, although there are many estimation methods, they all have advantages and disadvantages. Among them, the comprehensive water storage capacity method, the canopy interception surplus method and the precipitation storage method are only applicable to forest ecosystems. The water balance method is the basis of studying the mechanism of water conservation. Compared with other methods, it is a relatively mature and accurate method to evaluate the water conservation function of an ecosystem [25], [26].

The Qinghai-Tibetan Plateau is the roof of the world, the water tower of Asia, the third pole of the earth, and an important ecological security barrier for China [27], [28]. The Qinghai-Tibetan Plateau has a high degree of vulnerability and sensitivity to the impact of global environmental changes and human intervention [29]. This area serves as a natural laboratory on earth for conducting research on the evolution of the earth and life, sphere interactions, and human-earth relationships. This area plays an important role in the global climate system, the Asian monsoon system and the terrestrial carbon cycle [30]–[33], and it has received the same attention from the international scientific community as the Antarctic and Arctic [34]. In the process of global warming, warm and humid areas have become warmer and more humid while cold and dry areas have become colder and drier [35]–[38], resulting in endless extreme weather events. Some studies have shown a series of ecological environmental problems in the Qinghai-Tibetan Plateau, such as plant growth cycle changes, glacier retreat, permafrost degradation and desertification [39]–[42], and the water conservation capacity has changed accordingly. Therefore, studying the water conservation function of the Qinghai-Tibetan Plateau is very important to ensuring its ecological environment and water safety [43]. Currently, there are few studies on the water conservation function of the Qinghai-Tibetan Plateau, so, Yin *et al.* [43] based on the improved LPJ dynamic vegetation model, predicted and analyzed the response of the water conservation function of the Qinghai-Tibetan Plateau to climate change in the future. Nie *et al.* [44] evaluated the water conservation value of the Qinghai-Tibetan Plateau based on the principle of water balance and surface energy balance using RS and GIS technology. However, these studies mainly focused on analyzing the spatial and temporal changes of water resource conservation and the impact of climatic factors, and there is a lack of research on the effect of vegetation on the function of water conservation.

Although research on the function of water conservation has been abundant, there are still some aspects worth exploring. At present, most of the research on water conservation only focus on single biomes, mainly forests, and less research has focused on the water conservation function of entire regional ecosystems [45]. At the same time, studies on the water conservation of different biome types mostly adopt the method of field investigations and sample plot settings in a short period of time, with certain spatial and temporal limitations, and the degree of analysis and research is not sufficiently deep. The use of RS data to research the water conservation capacity of different biome types over a long time series using RS data is even more limited. The rapid development of RS technology can provide a wide range of surface characteristic parameters. MODIS products have a high time resolution and provide more than 40 types of data products, such as ocean, land, atmosphere, biology and ice and snow, and they have the advantage of free access [46]. It is widely used in large-scale, long-term and dynamic monitoring of vegetation and water conservation, which has obvious advantages for comprehensively understanding the change laws of vegetation and water conservation. However, limited research has been performed on the application of MODIS products in the water conservation function of the Qinghai-Tibetan Plateau.

The objectives of this study are 1) to explore the dynamic changes of vegetation and water conservation function of the

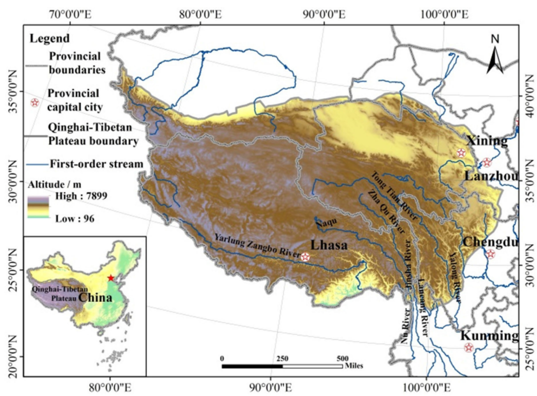

Fig. 1. Geographical location of the Qinghai–Tibetan Plateau (left); right Figure is the enlarged view of red rectangle.

Qinghai-Tibetan Plateau based on MODIS products and 2) to analyze the differences and impact factors of water conservation function in different biome types. This study solves the problem of unclear spatial and temporal change characteristics of water conservation in the Qinghai-Tibetan Plateau as well as the problems of the singularity of research on forest water conservation functions, incomplete coverage of biome types and the inconvenience of field investigation in existing studies for evaluating the function of water conservation in biomes. It is of great scientific significance to promote the management and protection of the ecosystems on the Qinghai-Tibetan Plateau, ensuring the safety of water resources and the sustainable development of the ecological environment.

II. Study Area and Dataset

A. Study Area

The Qinghai-Tibetan Plateau is in the southwestern part of China (see Fig. 1). The geographical location of this area is between 26°00′-39°47′N and 73°19′-104°47′E. The total area of the Qinghai-Tibetan Plateau is approximately 2.96×10^6 km^2, accounting for 26.8% of the mainland area of China. The Qinghai-Tibetan Plateau is the most widely distributed plateau in China and the plateau with the highest altitude in the world [47]. The Qinghai-Tibetan Plateau spans six provinces in China, namely, Tibet, Qinghai, Yunnan, Sichuan, Gansu, and Xinjiang, and has an average altitude of more than 4000 m [48]. The area can be divided into the Qaidam Basin, Qilian Mountain, Qinghai Plateau, Sichuan Tibet mountain canyon, Northern Tibetan Plateau and southern Tibet valley. The annual average temperature of the Qinghai-Tibetan Plateau, which has an alpine continental monsoon climate [49], is -5.8-3.7°C, and the annual average precipitation is 66-565 mm [50]. Under extremely cold climate conditions, the vegetation types of the Qinghai-Tibetan Plateau vary from southeast to northwest and include mountain forest, alpine meadow, alpine grassland and alpine desert, and they are widely distributed on the plateau [51]. The vegetation types in different regions are quite different, and the vegetation in the Qinghai-Tibetan Plateau is extremely sensitive to global climate change [52], [53]. The dominant alpine meadow species is Kobresia, and the associated species are Saussurea and Polygonum. The dominant alpine grassland species are Stipa and Carex, and the associated species are Artemisia and Oxytropis [54]. The Qinghai-Tibetan Plateau is also the birthplace of many important rivers, such as the Yangtze River, the Yellow River, the Yarlung Zangbo River, the Nu River, the Lancang River, the Ganges River and the Indus River. The plateau contains 36,800 glaciers covering an area of approximately 5.00×10^4 km^2, with a total glacier volume of approximately 4.56×10^{11} m^3 and an average annual melting water volume of 3.50×10^{10} m^3. These glaciers provide fresh water resources for more than 1 billion people in the region. Thus, this region is an important ecological barrier in China [55], [56].

B. Dataset

MODIS Leaf Area Index (LAI) product. This study used the 2000–2015 Collection 6 (C6, also version 6) MODIS LAI product (MOD15A2H) provided by the National Aeronautics and Space Administration (NASA), and it represents one of the latest and highest quality LAI products available [57]–[60]. The temporal resolution and spatial resolution of the data are 8 days and 500 m $\times$ 500 m, respectively, and these data are mainly used to obtain vegetation information from the Qinghai-Tibetan Plateau. The data are processed by filling in missing values and eliminating abnormal and null values. In this study, the spatial resolution of data is unified to 1 $\times$ 1 km by resampling.

Division of biome types. The biomes in the Qinghai-Tibetan Plateau were classified using the MCD12Q1 products provided by NASA. The spatial resolution of the MCD12Q1 product is 500 $\times$ 500 m, and the product uses five different land cover classification schemes. In this study, the International Geosphere-Biosphere Programme (IGBP) classification provided by MCD12Q1 was used to classify the forests, other woody vegetation, grasslands and croplands into four major biome types. Forests include evergreen needleleaf forests, evergreen broadleaf forests, deciduous needleleaf forests, deciduous broadleaf forests and mixed forests. Other woody vegetation includes closed shrublands, open shrublands and woody savannahs. Grasslands include savannahs and grasslands. Croplands include croplands and mosaics of croplands and natural vegetation. A static land cover map (for 2007) was used to define the four aforementioned biome types [61].

Estimation of water conservation. The actual evapotranspiration data used in this study were MODIS global evapotranspiration products (MOD16) from 2001 to 2015, with a temporal resolution and spatial resolution of 8 days and 500 m $\times$ 500 m, respectively. The annual average was used to fill the missing actual evapotranspiration data in 2000. The ecosystem type map used in this study comes from the spatial distribution data of China's terrestrial ecosystem type provided by the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences.

Impact factor data. In this article, ten factors affecting the water conservation function were adopted [62]: climate factors, which include annual average evapotranspiration, annual average precipitation, annual average temperature, average wind speed, average relative humidity and accumulated sunshine hours; terrain factors, which include altitude and slope; and social and economic factors, which include GDP and total population. The number of samples is the number of pixels. The annual average evapotranspiration data were obtained from MOD16 data. The data on the annual average precipitation, annual average temperature, DEM, GDP and total population are from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. The slope data were extracted from the DEM in the GIS platform. The station data of average wind speed, average relative humidity and accumulated sunshine hours are from the China Meteorological Data Network, and the spatial information of these elements was obtained using the ANUSPLIN plug-in from Australia [63], [64].

III. Methods

A. Linear Regression Analysis Method

In this study, a linear regression analysis method was used to calculate the overall trend of LAI during the study period. The slope of the trend line was defined using formula (1):

$$\text{Slope} = \frac{n\sum_{i=1}^{n}(i \cdot P_{\text{LAI},i}) - (\sum_{i=1}^{n} i)(\sum_{i=1}^{n} P_{\text{LAI},i})}{n\sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}. \quad (1)$$

where *n* is the cumulative number of years in the study period; *i* is the value of the serial number of the year, *i* = 1,2,…,16; and $P_{\text{LAI},\,i}$ is the LAI value in the *i*th year. In general, this variable shows an increasing trend if slope > 0 and a decreasing trend if slope < 0 [65].The Mann-Kendall nonparametric test method does not require samples to follow a certain distribution and is not sensitive to outliers; therefore, it can reveal the trend of a time series. This method is widely used in trend and mutation analyses [66].

B. Water Balance Method

At present, the water balance method is an accurate method for calculating the water conservation quantity with a high frequency of use [20]. The water balance equation (2) is as follows:

$$TQ = \sum_{i=1}^{j}(P_i - R_i - ET_i) \cdot A_i. \quad (2)$$

where *TQ* is the total water conservation; P_i is precipitation; R_i is the surface runoff; ET_i is evapotranspiration; A_i is the area of ecosystem class *i*; *i* is the type of ecosystem class in the study area; and *j* is the number of types of ecosystems in the study area (this study includes farmland ecosystems, forest ecosystems, grassland ecosystems, water body and wetland ecosystems and desert ecosystems (see Table I)). The surface runoff coefficient was obtained by consulting articles [62], [67], and formula (3) is as follows:

$$R = P \cdot \alpha. \quad (3)$$

where *R* is the surface runoff; *P* is the annual precipitation; and α is the average surface runoff coefficient (see Table I).

TABLE I
Details of Ecosystem Types. The Type of Ecosystem Includes Level 1 and Level 2; the Average Runoff Coefficient is the Mean Surface Runoff Coefficient of Each Ecosystem

Ecosystem type (Level 1)	Ecosystem type (Level 2)	Average runoff coefficient
Farmland ecosystem	Paddy field	0.500
	Dryland	
Forest ecosystem	Closed forestland	0.425
	Shrub land	
	Sparse woodland	
	Other woodlands	
Grassland ecosystem	High coverage grassland	0.500
	Medium coverage grassland	
	Low coverage grassland	
Water body and wetland ecosystem	Channel	0.000
	Lake	
	Reservoirs and ponds	
	Permanent glacial snow	
	Flooded land and tidal flats	
	Beach land	
	Marshes and swamps	
Desert ecosystem	Sandy land	0.001
	Gobi	
	Saline-alkali land	
	Other	

C. Partial Correlation Analysis Method

In order to eliminate the interference of various factors, partial correlation analysis was used to explore the correlation between the water conservation function of different biome types and influencing factors. The formula (4) of partial correlation analysis is as follows [68]:

$$R_{xy,z} = \frac{R_{xy} - R_{xz} \cdot R_{yz}}{\sqrt{(1 - R_{xz}{}^2)(1 - R_{yz}{}^2)}} \quad (4)$$

Where $R_{xy,z}$ is the partial correlation coefficient between variables *x* and *y* after the interference of variable *z* is removed, and R_{xy}, R_{xz} and R_{yz} are the correlation coefficients between variables *x* and *y*, *x* and *z*, *y* and *z*, respectively.

IV. Results

A. Measuring the Trend of Vegetation Variation

The vegetation of the Qinghai-Tibetan Plateau shows a slight improvement trend from 2000 to 2015. There were no significant changes in most areas of the Qinghai-Tibetan Plateau. The areas with significant vegetation improvements were mainly

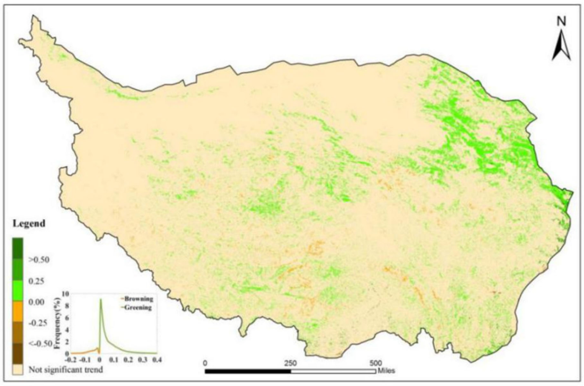

Fig. 2. Annual average MODIS LAI trend from 2000 to 2015. The picture in the lower left corner is the frequency statistic of the LAI slope value. The calculation of slope was tested by Mann Kendall, $P \leq 0.05$.

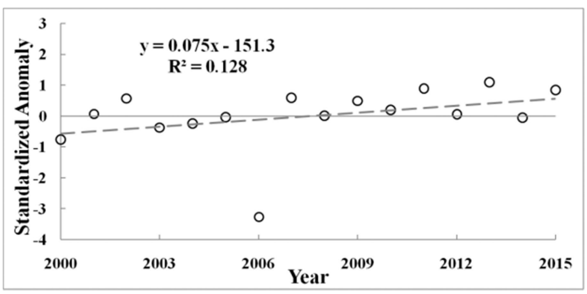

Fig. 3. Inter-annual change trend of MODIS LAI from 2000 to 2015. The value of LAI was calculated by standardized anomaly, and the ordinate represents the standardized anomaly value of LAI. The dotted line in the figure shows the fitting line of LAI value change trend in 2000–2015.

distributed in the northeast while the areas with significant degradation were distributed in the southwest (see Fig. 2). From 2000 to 2015, the slope value of the vegetation change trend in the Qinghai Tibetan Plateau was mainly in the range of 0–0.2, and a small part was in the range of −0.2–0, indicating that the overall vegetation showed a slight improvement trend. According to the inter-annual changes trend of MODIS LAI from 2000 to 2015 (see Fig. 3), the vegetation showed a slow improvement trend from 2000–2002 and increased again after falling in 2003. In 2006, the annual average LAI value reached the lowest value in 16 years at only 0.34. From 2007–2015, the annual average LAI value fluctuated slightly between 0.47 and 0.52, reaching the highest value of 0.52 in 16 years in 2013. According to the frequency of the annual LAI standardized anomalies (see Fig. 4), the vegetation presented an obvious normal distribution, and the slope value was mainly concentrated at −1.00–1.00 and decreased near both ends, indicating that the range of vegetation changes was small. With the passage of time, the peak LAI value showed a gradual downward trend. At the same time, as shown in Fig. 4, the curve of LAI moved to the right each year, the area with a slope greater than 0 gradually expanded, the curve became more moderate, and the dispersion also increased, indicating that the vegetation of the Qinghai-Tibetan Plateau showed a slight improvement trend each year, and the changes became increasingly discrete.

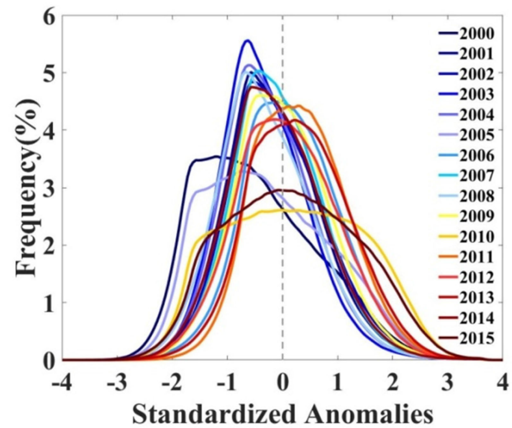

Fig. 4. Standardized anomalies of MODIS LAI from 2000 to 2015. The standard anomaly was calculated for the LAI value from 2000 to 2015, and the standard anomaly value was subjected to frequency statistics.

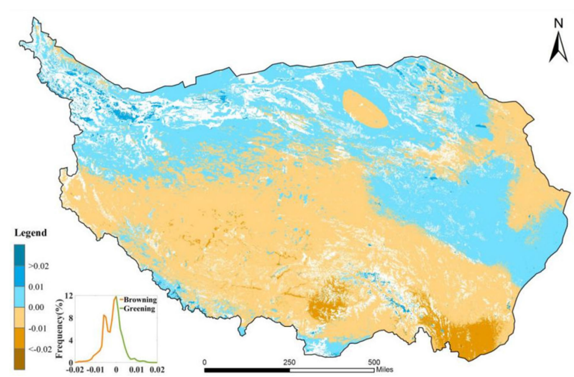

Fig. 5. Water conservation trend in 2000–2015. The figure in the lower left corner is the frequency statistical of the slope value of water conservation from 2000 to 2015.

B. *Estimation of Water Conservation and Its Changing Trend*

The water conservation of the Qinghai-Tibetan Plateau showed a small declining trend, and the slope remained basically stable at −0.02–0.02. From 2000 to 2015, the water conservation of the Qinghai-Tibetan Plateau showed a small declining trend (see Fig. 5), mainly in the southwest and a small part of the northeast region, while the southeast region showed a large declining trend. The areas where the water conservation of the Qinghai-Tibetan Plateau improved were mainly located in the north, northwest, and east. According to the frequency diagram of the slope, the area with a slope value less than 0 was slightly larger than that with a slope value greater than 0, indicating that the water conservation function of the Qinghai-Tibetan Plateau showed a small declining trend from 2000 to 2015.

The water conservation of the Qinghai-Tibetan Plateau showed significant spatial heterogeneity and gradually decreased from southeast to northwest. In this study, the spatial distribution map of water conservation from 2000–2015 was standardized; according to the quantile classification in ArcGIS, the water conservation function was divided into five levels: low (0–0.1), relatively low (0.1–0.3), medium (0.3–0.5), relatively

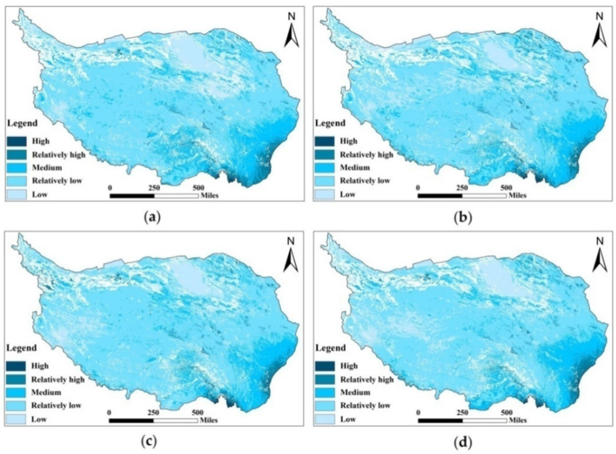

Fig. 6. Functional level of water conservation: (a) 2000–2003a functional level of water conservation; (b) 2004–2007a functional level of water conservation; (c) 2008–2011a functional level of water conservation; (d) 2012–2015a functional level of water conservation.

TABLE II
PROPORTIONS OF WATER CONSERVATION FUNCTION GRADE AREAS. THE PROPORTION OF WATER CONSERVATION FUNCTION AREA OF EACH LEVEL IN THE TOTAL AREA OF QINGHAI–TIBETAN PLATEAU IN FOUR TIME PERIODS, UNIT:%

Year	Low	Relatively low	Medium	Relatively high	High
2000-2003	11.119	66.030	18.817	3.713	0.321
2004-2007	10.708	66.730	18.543	3.610	0.410
2008-2011	10.059	68.306	17.892	3.430	0.313
2012-2015	12.537	65.640	17.838	3.682	0.303

high (0.5–0.7) and high (0.7 1) (see Fig. 6). During 2000–2003, 2004–2007, 2008–2011 and 2012–2015, the regions with high water conservation functions were mainly distributed in the southeast of the Qinghai-Tibetan Plateau and gradually declined to the northwest. The regions with low water conservation function were mainly located in the Qaidam Basin. According to the statistics of the distribution area of water conservation function grades in the four- time periods (see Table II), the relatively low water conservation function areas were most widely distributed in the four- time periods, followed by the areas with medium, low, relatively high and high water conservation functions, and the proportions of each function grade area remained basically stable.

Grassland is the main ecosystem for water conservation on the Qinghai-Tibetan Plateau. According to the water balance principle, the amount of water conservation in the Qinghai-Tibetan Plateau of China was estimated scientifically (see Fig. 7). The total amount of water conservation showed a slowly increasing trend from 2000–2005. In 2005, the amount of water conservation reached the maximum value in nearly 16 years, increasing by 64.64% compared with that in 2000. In 2006, there was a large decrease to 1.02×10^{11} m³, which corresponds to the sharp decline in the LAI value in 2006. The total amount of water

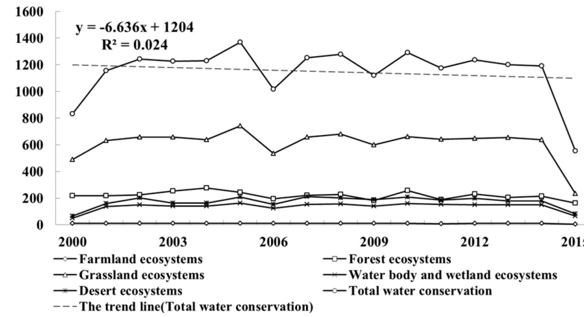

Fig. 7. Trends of water conservation in the Qinghai–Tibetan Plateau and its ecosystems from 2000 to 2015. The dotted line represents the fitting line of the change trend of the total amount of water conservation in the Qinghai–Tibetan Plateau from 2000 to 2015, unit: $\times 10^8$m³.

conservation in 2007–2008 steadily increased and fluctuated in the range of 1.12×10^{11}m³ and 1.29×10^{11}m³ from 2009–2011. However, from 2012 to 2014, the total amount of water conservation showed a small declining trend, with a decrease of 4.55×10^9 m^3. In 2015, the total amount of water conservation decreased significantly, reaching a minimum value in the past 16 years of only 5.53×10^{10} m³.In the five ecosystems, the water conservation service function of the Qinghai-Tibetan Plateau mainly originated from grassland ecosystems, followed by forest ecosystems, desert ecosystems, water body and wetland ecosystems, and farmland ecosystems. The trend of water conservation in grassland ecosystems from 2000 to 2015 was similar to the trend of the total water conservation in the Qinghai-Tibetan Plateau. The water conservation function of forest ecosystems and farmland ecosystems remained stable. The total amount of water conservation in desert, water body and wetland ecosystems tended to remain the same and showed decreasing trends in 2000, 2006 and 2015. The main reason for the change in the water conservation function of the Qinghai-Tibetan Plateau over the past 16 years was the change in the water conservation function of grassland ecosystems, desert ecosystems and water body and wetland ecosystems.

C. Measuring the Trend of Different Biome Water Conservation Variations

The water conservation function is closely related to vegetation density. Within the range of LAI value changes, the water conservation function showed an obvious tendency to weaken after strengthening. The mean values of water conservation from 2000–2003, 2004–2007, 2008–2011, and 2012–2015 were standardized, and the relation curve of water conservation in the range of LAI value changes was established (see Fig. 8). The figure shows that the relationship between the LAI and water conservation in the four time periods clearly remained consistent. When the LAI was between 0.00 and 2.00, the amount of water conservation increased with the increase in LAI. When the LAI reached the peak, the amount of water conservation showed a significant downward trend. When the LAI value reached above 4.00, the amount of water conservation slightly increased. This finding shows that when the LAI value

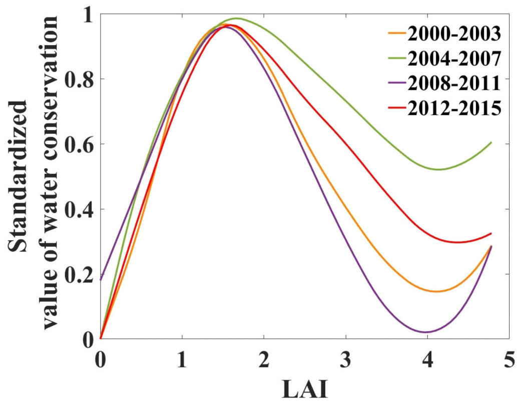

Fig. 8. Relationship between LAI and water conservation. The abscissa value represents the LAI, and the ordinate value represents the standardized value of water conservation quantity over four time periods

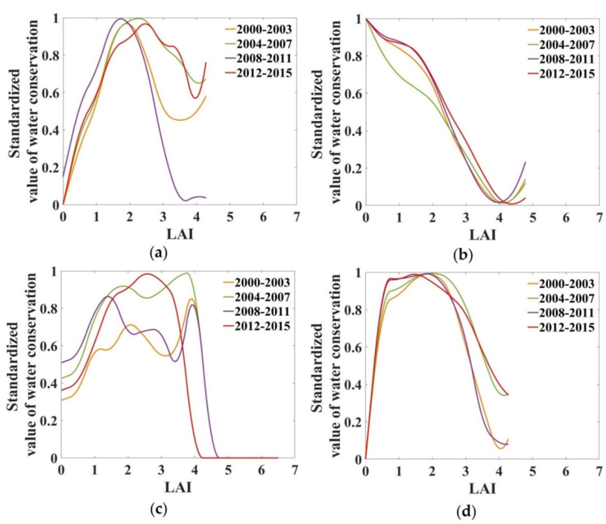

Fig. 9. Water conservation curves of four biome types: (a) grasslands water conservation curve; (b) forests water conservation curve; (c) croplands water conservation curve; (d) other woody vegetation water conservation curve.

is small (LAI $\leq$ 1.70), the water conservation capacity will increase. When the LAI value reaches a certain level (LAI $>$ 1.70), the water conservation function will show a downward trend.

The water conservation function is closely related to the biome type. Relationship curves of water conservation in the four biome types within the range of the variation in LAI values were established (see Fig. 9). The water conservation capacities of the four biome types showed obvious change trends. When the LAI was small (LAI $<$ 2.50), the water conservation of grasslands increased with increasing LAI, and when the LAI was large, the water conservation of grasslands decreased slowly with the increase in LAI. For forests, when the LAI value gradually increased, the water conservation of forests presented a monotonous decreasing trend, and when the LAI value was greater than 4.00, the water conservation amount slightly increased. When the LAI value was small (LAI $<$ 1.50), the water conservation of croplands increased with increasing LAI. When the LAI value was between 1.50 and 4.00, the water conservation of croplands presented a fierce fluctuation, but basically remained at a high level (0.50–1.00). When the LAI value was greater than 4.00, the water conservation of croplands decreased sharply and finally tended to remain at the lowest value. For other woody vegetation, when the LAI value was small (LAI $<$ 0.80), the water conservation amount showed a rapid upward trend and tended to remain at the highest level when the LAI value was between 0.80 and 2.00. When the LAI value was greater than 2.00, the water conservation of other woody vegetation showed a slow downward trend with increasing LAI. These results showed that with the change in the LAI, the water conservation functions of different biome types showed their own unique trends; therefore, the water conservation function is closely related to the biome type.

V. Discussion

A. Analysis of the Factors Influencing the Water Conservation Functions of Different Biome Types

In this study, a partial correlation analysis was used to analyze the factors influencing the water conservation function of different biome types (see Table III).The water conservation capacity of the ecosystem in the Qinghai-Tibetan Plateau is mainly affected by climate and topography factors, and the impact of human activities is relatively weak. Climate change will cause severe turbulence in the Qinghai-Tibetan Plateau ecosystem, and the water conservation function will be affected to some extent. Due to the special geographical environment of the Qinghai-Tibetan Plateau, it is difficult to develop at a large scale, so there is less large-scale human activity in the region, and the human disturbance to the water conservation function of the ecosystem is lower. As an important function of an ecosystem, the change of vegetation will also cause a significant change in water conservation, and the change degree of water conservation will be different with different biome types. In different biome types, the degree of influence of each influencing factor on water conservation function is different. In grasslands, precipitation is the determinant of water conservation function, and other factors have little influence on water conservation function; in forests, water conservation has a high correlation with precipitation, evapotranspiration and altitude; in croplands, in addition to the significant impact of precipitation on water conservation, evapotranspiration, wind speed and altitude have important effects; and in other woody vegetation, water conservation is mainly affected by precipitation and evapotranspiration. The effect of evapotranspiration on the water conservation function of grasslands was lower than that of other biomes; The degree of influence of wind speed on the water conservation functions of different biomes is, in order; croplands, other woody vegetation, grasslands and forests; at different altitudes, the water conservation function of croplands changed significantly, followed by forests, grasslands and other woody vegetation, The effects of GDP and population on the water conservation functions of different biomes are different and may be inhibited or promoted, indicating that the impact

TABLE III
CORRELATION BETWEEN THE WATER CONSERVATION FUNCTION OF DIFFERENT BIOME TYPES AND VARIOUS INFLUENCING FACTORS IN 2015: $P < 0.01$

	Climate factors						Terrain factors		Social and economic factors	
	Evapotrans piration	Average precipitation	Average temperature	Average wind speed	Average relative humidity	Total sunshin e hours	Slope	Altitude	GDP	Total population
Grasslands	-0.399	0.843	-0.060	-0.314	-0.178	-0.109	0.319	-0.378	-0.003	0.034
Forests	-0.668	0.973	0.139	-0.135	0.179	-0.251	-0.087	-0.420	0.108	-0.193
Croplands	-0.559	0.892	0.063	-0.547	0.266	0.252	0.065	-0.543	0.065	-0.198
Other woody vegetation	-0.609	0.958	0.092	-0.367	-0.264	-0.365	0.271	-0.273	0.034	0.059

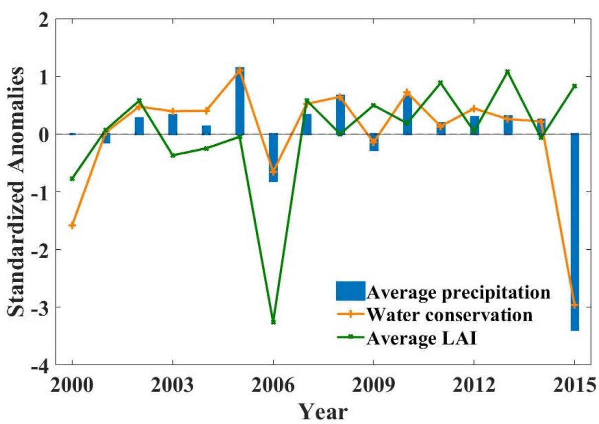

Fig. 10. Annual change trend of LAI, water conservation and precipitation from 2000 to 2015. The annual LAI, annual water conservation and annual precipitation are all calculated by standardized anomaly, and the ordinate represents their standardized anomaly value.

of human activities on water conservation ability cannot be determined.

B. *Analysis of the Effect of Precipitation on Water Conservation Function and Vegetation Growth*

In the research process of the response of the water conservation function to vegetation dynamics, in order to analyze the interference of precipitation on the relationship between vegetation growth and water conservation, the annual mean data of precipitation, LAI and water conservation from 2000 to 2015 are selected for research (see Fig. 10). From 2000 to 2014, the change range of precipitation was relatively small, while in 2015, there was a large underground drop. It can be seen that the annual change trend of water conservation is basically consistent with the changing trend of annual precipitation. However, there are some differences between the annual average LAI and the annual average precipitation. The correlation coefficient between water conservation and precipitation is 0.903, and the correlation coefficient between LAI and precipitation is 0.028. The results show that there is a weak correlation between vegetation change and precipitation in the Qinghai-Tibetan Plateau, and precipitation has a little direct impact on vegetation change. Therefore, the effect of precipitation on the relationship between water conservation and vegetation growth is weak, and the interference on the results of this study can be ignored. There is a high correlation between precipitation and water conservation. Precipitation has a great influence on water conservation, which indicates that precipitation indirectly affects vegetation growth through the change of water conservation. Therefore, when researching the dynamic changes of vegetation on the Qinghai-Tibetan Plateau, it is necessary to comprehensively consider the direct and indirect effects of precipitation on vegetation changes in order to accurately evaluate the impact of precipitation on the dynamic changes of vegetation.

C. *Reasons for the Decline of Water Conservation*

The evaluation of the water conservation function of an ecosystem is a popular and difficult issue in ecosystem service research [4]. Currently, most research on the water conservation function of vegetation has used field investigation and sample plot setting methods to prove that there is a certain relationship between vegetation types and water conservation functions [19], and the results of this article are consistent with the results of these previous studies. In this study, long time series RS data are used to determine that the LAI of vegetation and water conservation is not a simple linear relationship. Water conservation will change to different degrees with different vegetation densities and biome types, which indicates that in future studies of water conservation evaluation, in addition to using RS technology instead of field investigation methods to expand the research area and research period, it is also necessary to consider the actual situation of the local ecosystem and perform differential analyses of each biome type rather than just a single biome to eliminate the uncertainty of the evaluation results. Although the growth of vegetation affects the water conservation function of the Qinghai-Tibetan Plateau, according to the above study, it was found that the growth of vegetation in the Qinghai-Tibetan Plateau slightly improved, but the water conservation capacity showed a slight downward trend. In terms of the Qinghai-Tibetan Plateau, its water conservation function is not only closely related to the growth of vegetation but is also determined by climate and terrain factors, which is consistent with the relevant research results of Hua and Wang on the Qinghai-Tibetan Plateau [69]. Due to the fragile ecosystem and unique geographical environment in the Qinghai-Tibetan Plateau, the response of water conservation to climate change in this region is obvious. The emergence of extreme climate events has led to a series of ecological and environmental problems on the Qinghai-Tibetan Plateau, which also has a huge impact on the water conservation function of the plateau. Different biome types and growth conditions have long-lasting and long-term effects on the water conservation capacity of the Qinghai-Tibetan Plateau, while severe climate change will cause severe responses to the water conservation function. Therefore, even if the vegetation growth of the Qinghai-Tibetan Plateau is improved, its water conservation capacity cannot be improved well due to the interference of climate and terrain factors. In the prediction of future water conservation changes in the Qinghai-Tibet Plateau, it is necessary to consider the comprehensive influence of various factors, so as to lay a theoretical foundation and technical support for more accurate assessment of water conservation changes in the future.

D. Limitations of This Study

First, limited by the availability of data, the selection of factors influencing the water conservation function in this study did not consider the differences in soil physical characteristics of different biome types, such as soil depth and capillary porosity of forests and croplands. Second, although the glacier meltwater is a part of the total runoff of the Qinghai-Tibetan Plateau, it is difficult to fully consider the impact of the glacier meltwater on the water conservation amount in the existing estimation methods of water conservation. Therefore, it is an important future research direction to improve the estimation accuracy of water conservation amount in the Qinghai-Tibetan Plateau to fully consider the impact of glacier meltwater in the study of water conservation estimation.

VI. Conclusion

At present, the vegetation on the Qinghai-Tibetan Plateau has slightly improved while the water conservation capacity shows a weak decreasing trend, indicating that China's Qinghai-Tibetan Plateau has relatively adequate vegetation protection measures. However, due to its unique geographical environment and fragile ecological environment, the Qinghai-Tibetan Plateau is highly sensitive to global environmental changes. At the same time, the altitude of the region is quite different, and the water source in the high altitude region is difficult to be conserved. Therefore, the water conservation function of the Qinghai-Tibetan Plateau is easily affected by climate and terrain factors, and it is difficult to significantly improve the water conservation capacity. Grassland ecosystems are the main ecosystems for water conservation in the Qinghai-Tibetan Plateau. One of the priorities for improving ecological security measures is to manage and protect grassland ecosystems. Grassland, desert, water body and wetland ecosystems have a trend that is consistent with the overall changes in water conservation in the Qinghai-Tibetan Plateau. The water conservation function of forest ecosystems and farmland ecosystems remained stable. The water conservation function is closely related to vegetation density and biome type. The degrees of the response of the water conservation capacities of different biome types are different. With the change of vegetation growth, the water conservation functions of different biome types showed their own unique trends. To protect the water conservation service function, vegetation should be managed and planted according to the best vegetation coverage area, vegetation quantity and biome type. Although it is still a complex task for humans to improve the water conservation service function, the dynamic monitoring of water conservation by RS can play a large role in promoting and providing a scientific basis and technical support for the sustainable development of ecological environments.

Appendix

The data used in this study mainly include MODIS LAI C6 products (MOD15A2H), MCD12Q1 and MODIS global evapotranspiration product (MOD16), annual average precipitation, annual average temperature, DEM, GDP and population data provided by Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, and station data of average wind speed, average relative humidity and total sunshine hours provided by the China Meteorological Data Network.

1) The MODIS-LAI C6 product used in this article performed considerably better than C5 in comparisons to true LAI measurements. The RMSE decreased from 0.80 down to 0.66, which is close to the target accuracy (± 0.5) as required by the GCOS [58].
2) For the division of biome types, this study adopts the global vegetation classification scheme of land cover classification 1: IGBP in the MCD12Q1 product. Among the five schemes of MCD12Q1, some studies show that the R value of IGBP is 98.22% - 99.61% according to the correlation coefficient R, and the IGBP has the best compatibility and robustness, which shows that the consistency of IGBP is the best on a regional scale [70].
3) Through the comparison of MODIS global evapotranspiration product (MOD16) and measured evapotranspiration data, some research found that there is a good correlation between MOD16 data and measured evapotranspiration data, and the overall correlation coefficient of a monthly sequence is 0.918 [71].
4) The meteorological data provided by the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences is based on the daily observation data of more than 2400 meteorological stations across the country, and is generated through calculation and spatial interpolation. The interpolation application is ANUSPLIN interpolation software from Australia. Compared with the encrypted station data, the temperature interpolation result of ANUSPLIN interpolation software has a 92% error within 2°C, and the error of the 75% precipitation interpolation result is less than 5 mm [72]. DEM data is obtained by the Institute of Remote Sensing and Digital Earth, Chinese Academy

of Sciences through processing the Shuttle Radar Topography Mission (SRTM) data of the U.S. space shuttle Endeavour. After data processing, the final global digital elevation model (DEM) obtained can improve the existing global DEM accuracy of the U.S. by about 30 times. GDP and population data are obtained by the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences through processing the statistics data of GDP and the population of each county in China.

5) The data of average wind speed, average relative humidity and total sunshine hours are provided by China Meteorological Data Network. The real rate of each elemental data type is generally over 99%, and the accuracy of the data is close to 100%.

In summary, the accuracy of the products used in this study has been fully verified, and the data errors are within the controllable range, so the impact on the analysis and results of this research can be ignored.

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