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Spatio-temporal Pattern of Net Primary Productivity in Hengduan Mountains area, China: Impacts of Climate Change and Human Activities

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Abstract: Net primary productivity (NPP), a metric used to define and identify changes in plant communities, is greatly affected by climate change, human activities and other factors. Here, we used the Carnegie-Ames-Stanford Approach (CASA) model to estimate the NPP of plant communities in Hengduan Mountains area of China, and to explore the relationship between NPP and altitude in this region. We examined the mechanisms underlying vegetation growth responses to climate change and quantitatively assessed the effects of ecological protection measures by partitioning the contributions of climate change and human activities to NPP changes. The results demonstrated that: 1) the average total and annual NPP values over the years were 209.15 Tg C and 468.06 g C/(m^2·yr), respectively. Their trend increasingly fluctuated, with spatial distribution strongly linked to altitude (i.e., lower and higher NPP in high altitude and low altitude areas, respectively) and 2400 m represented the marginal altitude for vegetation differentiation; 2) areas where climate was the main factor affecting NPP accounted for 18.2% of the total research area, whereas human activities were the primary factor influencing NPP in 81.8% of the total research area, which indicated that human activity was the main force driving changes in NPP. Areas where climatic factors (i.e., temperature and precipitation) were the main driving factors occupied 13.6% (temperature) and 6.0% (precipitation) of the total research area, respectively. Therefore, the effect of temperature on NPP changes was stronger than that of precipitation; and 3) the majority of NPP residuals from 2001 to 2014 were positive, with human activities playing an active role in determining regional vegetation growth, possibly due to the return of farmland back to forest and natural forest protection. However, this positive trend is decreasing. This clearly shows the periodical nature of ecological projects and a lack of long-term effectiveness.

Keywords: net primary productivity (NPP); Carnegie-Ames-Stanford Approach (CASA) model; climate change; human activities; Hengduan Mountains area

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1 Introduction

Net primary productivity (NPP) is central to research on carbon budgets and climate change because it reflects the production capacity of plant communities under natural environmental conditions and provides insights into the status of terrestrial ecosystems. It is also used to quantify carbon sources/sinks in ecosystems and can show how ecological processes are regulated (Lieth *et al*., 1975; He and Zhang, 2006). For these reasons, NPP has been adopted as a key indicator of vegetation cover status, and accurate estimations of NPP and its relationship with various driving factors have become fundamental research topics (Nemani *et al*., 2003; Grosso,

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2008).

Ecological process models, such as the terrestrial ecosystem model (TEM) (Raich *et al*., 1991), the carbon exchange between vegetation, soil, and atmosphere (CEVSA) model (Tao *et al*., 2003), an equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types (BIOME3) (Haxeltine and Prentice, 1996), and Process-based equilibrium terrestrial biosphere model – BioGeochemical Cycles (BIOME-BGC) model (White *et al*., 2000), are generally considered the most accurate NPP simulators; however, the complex parameter inputs that these models require and the fact that they are only suitable for small areas limit their usefulness (Plochl, 1995). Worldwide advances in '3S' technologies and research have led to the development of several large-scale NPP simulation models (Potter *et al*., 1993; McGuire *et al*., 1995; Semmartin *et al*., 2007). The Carnegie-Ames-Stanford Approach (CASA) model is a typical model for light-use efficiency and requires fewer input parameters than other models, which potentially reduces errors due to missing parameters. Furthermore, the model offers a wide range of remote-sensing data coverage and higher temporal resolution. These advantages mean that the CASA model has been applied by researchers to a number of ecosystem types worldwide (Christopher *et al.*, 1995; Bondeau *et al.*, 1999; Creamer *et al.*, 1999; Kicklighter *et al.*, 1999; Ruimy *et al.*, 1999; Jeffrey *et al.*, 2002; Tao *et al.*, 2005; Yang *et al.*, 2005; Joshi *et al.*, 2006; Piao *et al*., 2006; Yuan *et al.*, 2006; Nayak *et al.*, 2010). Zhu *et al*. (2006a; 2006b; 2007) made improvements to the CASA model based on the results from accuracy verification studies that better reflected real-life conditions in China (Zhang *et al.*, 2008; Li *et al*., 2012; Liu *et al.*, 2013; Zhang *et al.*, 2013; Mao *et al.*, 2014).

Drivers of changes in NPP can be divided into physical and anthropogenic factors. In terms of physical forces, vegetation zone boundaries, soil types, and climatic regions roughly coincide (Ahrens, 2012), which means that there is typically a strong correlation between NPP and these factors. In general, scientists now believe that global warming and subsequent changes in climate, especially with regard to drought and atmospheric CO_2 concentrations, also affect plant productivity (Ciais *et al*., 2005), and that alterations in regional temperature and precipitation regimes have become the most important climatic factors driving changes in NPP (Du *et al*., 2004). In terms of anthropogenic forces, quantifying the effect of human activities on NPP has supplanted the initial focus on qualitative approaches (Vitousek, 1997; Sanderson *et al*., 2002). At present, two methods are commonly used to measure relative changes in NPP caused by human activities: the first is to determine the relationship between the dynamic changes in NPP and human activity factors with a regression model, where changes in NPP are estimated using regression equations (Xin *et al*., 2008); and the second is the model simulation method, where NPP values under the influence of climatic conditions are estimated by constructing simulations of the relationship between climatic factors and real NPP. The effects of human activities on changes in NPP are represented by the residuals between actual NPP and simulated NPP (Evans and Geerken, 2004). Owing to the number of potential anthropogenic factors and the complexity of the relationships between these various factors, direct measurements of the relationship between human activities and NPP are difficult. However, by indirectly measuring the relationship between human activities and NPP via climatic factors, the model simulation method provides a reliable approach for estimating the proportion of NPP changes that are attributable to human factors.

Recently, the dynamic changes in NPP and its driving forces have attracted the attention of many researchers. However, most studies to date have focused on these issues in relation to national development, urbanization, and ecologically important areas (Sun *et al*., 2017), with only a few focusing on less-developed regions or ecologically fragile mountainous areas (Zhou *et al*., 2007). In China, mountainous areas account for 70% of the total land area and support approximately 40% of the country's population (Deng *et al*., 2013). This suggests that they are not only economically and demographically important but also extremely ecologically sensitive and susceptible to disturbance by human activities: once damaged, recovery is difficult. Therefore, maintaining ecosystem health and vitality in mountainous regions is crucial for sustainable regional development.

Since the beginning of the 21st century, a series of development strategies, including 'Western Development', have been implemented in the mountainous areas of China and have had significant effects on the ecosystems of these regions. Extensive tracts of forests have been destroyed and converted to farmland, which has caused large-scale soil erosion, desertification, and other issues that constrain the development of natural plant communities (Liu *et al*., 2002). Simultaneously, expanding urbanization and industrialization has intensified climate feedbacks, such as urban heat island effects. This has contributed to higher temperatures and modifications in prevailing precipitation regimes, which also threaten vegetation coverage (Peng *et al*., 2016). In an effort to alleviate these pressures, national projects designed to protect natural environment have been introduced that have had tremendous effect on regional plant communities. For example, the 'Grain for Green' policy and the Natural Forest Protection Project require that land be converted to forest if the land is deemed to be of high importance to ecological functioning. Therefore, there is a particularly urgent need to understand the changes that are occurring in plant communities and to determine the scale of the role that human activities play in driving these changes.

We used a CASA model based on normalized difference vegetation index (NDVI) data, as well as climate, vegetation, and elevation data, to estimate total and annual NPP in Hengduan Mountains area over the period 1998–2014. The spatial patterns of NPP changes were also analyzed. Furthermore, correlation analyses were performed to determine the relationships between NPP and various climatic factors. We also quantified the rate of variation in NPP residuals through residual and trend analyses so that the proportion of NPP changes due to human activities could be identified. These analyses will provide a basis for vegetation monitoring and ecological conservation efforts in Hengduan Mountains area.

2 Materials and Methods

2.1 Study area

Hengduan Mountains area located in the southeast corner of China's Qinghai-Tibet Plateau, and encompass 98 counties, including Sichuan Province, Yunnan Province, and the Tibet Autonomous Region (24°30′N–33°43′N, 97°20′E–104°25′E) (Fig. 1). Covering a total area of 376 000 km^2, Hengduan Mountains area is composed of a series of intersecting mountain chains and valleys that run both east-west and north-south (Yang, 1989). Moreover, owing to the influences of the southwest and southeast monsoons that originate from the Indian Ocean and Pacific Ocean, respectively, the climate is warm and wet in the southeastern part of the range, but cold and dry in the northwest, with significant regional differences in hydrothermal conditions (Yu *et al.*, 1989). The terrain is high in the northwest and low in the southeast, and deep river valleys are typical of the region; altitudes range from –219 to 7447 m. The stratified landscape provides a spatial environment that promotes the growth and differentiation of vegetation (Liu *et al.*, 1985), and consequently supports a diversity of vegetation types, of which shrubs, coniferous forests, and meadows account for the majority of areal coverage (76%). Forest coverage, at 48.3% of the total area, is relatively high, and as such, this region is an important ecological area in China. Formation of the natural vegetation in Hengduan Mountains area is primarily the result of long-term climatic factors, but in recent times, it has also become tightly linked to human activities, which have been increasing rapidly as the pace of industrialization and urbanization continues to accelerate. This has led to conflicts between conservation and economic development interests, especially in the valleys (Liu *et al.*, 2010), underlining the necessity of determining the impacts of human activities on plant communities.

2.2 Data and processing

NDVI is the index factor for the vegetation growth status and vegetation spatial distribution density. The present study utilized the SPOT VEGETATION products (with 1 km spatial resolution and 10 days temporal resolution) as the data source of the NDVI, and the pixel values used the universal maximum value composite (MVC) syntheses to reduce cloud impact. Data between April 1998 and July 2008 was obtained from the Environmental and Ecological Science Data Center of western China (http://westdc.westgis.ac.cn), while the data between August 2008 and December 2014 was from the Global SPOT VEGETATION product distribution website (http://www.vgt.vito.be/). The present study calculated the mean value of NDVI data from the last ten days of each month to obtain monthly NDVI values, and then used the MVC syntheses method for further processing to obtain the annual NDVI value, which further eliminated any interference from clouds, the atmosphere, solar elevation angle, and other factors.

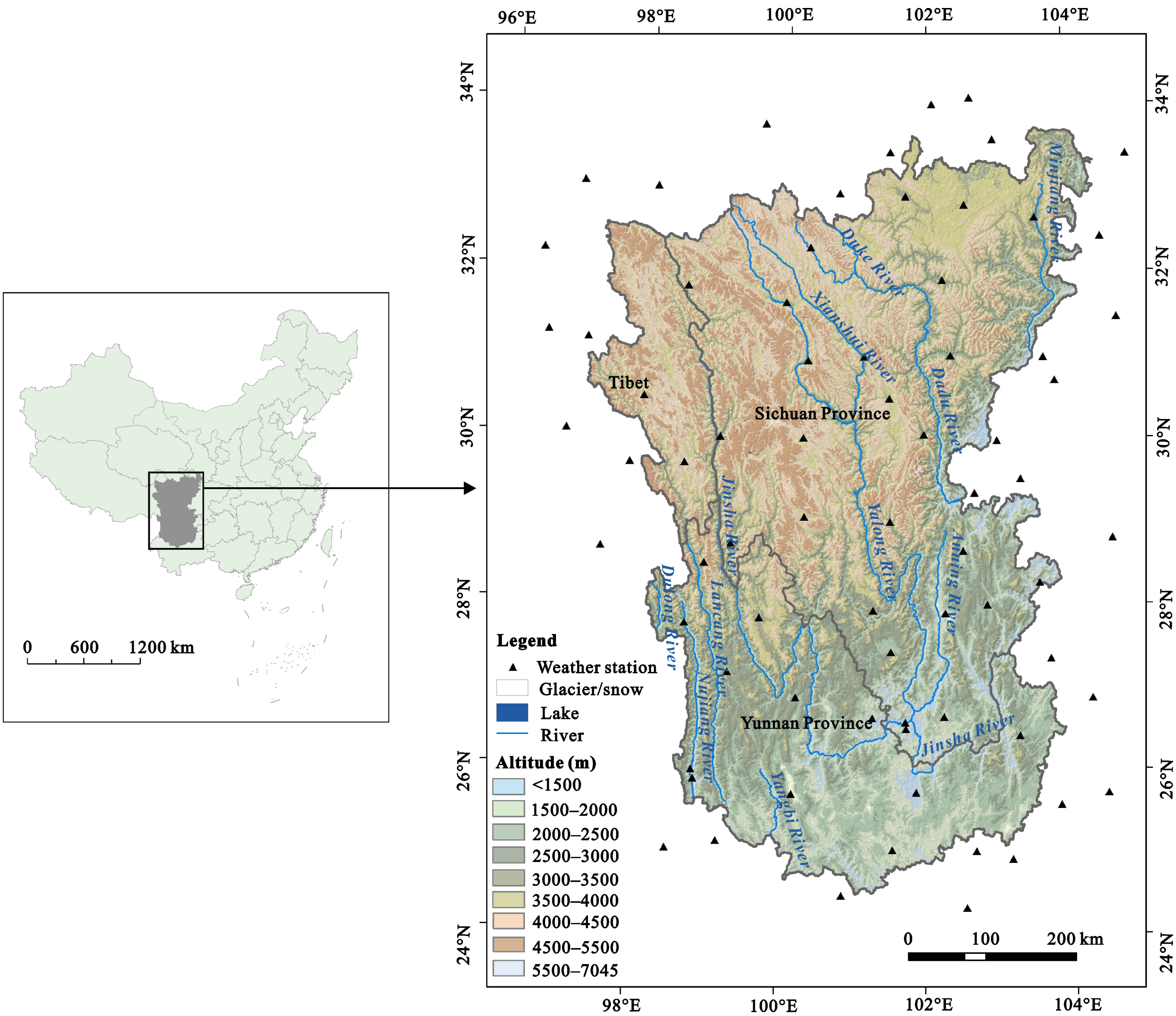

Fig. 1 Location map of Hengduan Mountains area, China

Terrain data adopted the Shuttle Radar Topography Mission digital elevation model (SRTMDEM) products, and applied other processes including projection transformation and resampling to the elevation data. Ultimately, the spatial resolutions were unified to 1 km.

Vegetation type data adopted the national vegetation types map of 1∶1 000 000 with statistics from the Resources and Environment Science Data Center of the Chinese Academy of Sciences of China. The major vegetation type code was regarded the benchmark to conduct the merging and processing, in order to obtain ten major vegetation types, which were coniferous forests, coniferous and broad-leaved mixed forests, broad-leaved forests, shrubs, grassland, brushwood, meadows, marshes, alpine vegetation, and planting vegetation. Moreover, after the corresponding processing and resampling had occurred, the data was converted into raster data with a spatial resolution of 1 km.

The present study selected the data of monthly average temperature and precipitation from 71 surface weather stations in and near the research area from 1998 to 2014. Based on terrain factors, the study adopted the local thin plate spline method to conduct the interpolation on temperature and precipitation, to obtain the time series raster images of monthly temperature and precipitation from 1998 to 2014.

2.3 Methods

2.3.1 Estimation and analysis of NPP

In this study, the NDVI data from SPOT-VGT and meteorological data were used by the Carnegie-Ames- Stanford Approach (CASA) model to estimate the NPP from 1998 to 2014. The algorithm of CASA model is as follows:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t) \quad (1)$$

$$APAR(x,t) = SOL(x,t) \times FPAR(x,t) \times 0.5 \quad (2)$$

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{max} \quad (3)$$

where, $APAR(x,t)$ represents the photosynthetic active radiation (MJ/m^2) absorbed by pixel x in t month; $\varepsilon(x,t)$ corresponds to the actual light energy utilization efficiency (g C/MJ) of pixel x in t month; $SOL(x,t)$ indicates the total solar radiation (MJ/m^2) of pixel x in t month; and $FPAR(x,t)$ denotes the absorption coefficient of the vegetation layer on incident photosynthetic active radiation. $T_{\varepsilon 1}(x,t)$ and $T_{\varepsilon 2}(x,t)$ means the stress function of low temperature and high temperature to light energy utilization, respectively. $W_{\varepsilon}(x,t)$ is water stress coefficient. ε_{max} is the biggest light energy utilization under ideal conditions.

The simulation of the largest light energy utilization ratio was determined with reference to the improvement method described by Zhu *et al.* (2006a; 2006b) and NPP was estimated using ENVI/IDL programming. The trend analysis method (Xu *et al.*, 2011) was used to describe the change in trend for NPP over time. We explored the relationship between NPP and climatic factors by calculating the partial correlation coefficient and the multiple correlation coefficient. The significance of their relationship was tested using t-tests and F-tests (Wang *et al.*, 2001).

2.3.2 Regression model for NPP and climatic factors

To establish the ideal regression equation between NPP and climatic factors, it was necessary to select vegetation data that, in theory, had not been affected by human activities; however, this is very difficult to achieve in practice. Therefore, this study undertook the following processing procedures, which incorporated some improvements:

(1) Regression models for NPP_{max} (the maximum NPP according to the maximum value composite, MVC) and climatic factors over two time intervals were constructed. In the present study, the whole time series was divided into two sections: 1998–2000 and 2001–2014. Human activities were considered weaker from 1998 to 2000, with a state of balance between NPP_{max} and climatic factors. A time-series regression model for NPP_{max} and climatic factors from 1998 to 2000 was established. Then, the residual analysis of the actual NPP_{max} and model values of the next period was conducted to identify NPP changes caused by human activities from 2001 to 2014.

(2) Based on similar studies (Liu *et al.*, 2013; Xu, 2004), we can know that cumulative precipitation and average temperature during the growing seasons are more related to NPP changes. Thus, this study selected cumulative precipitation and average temperature during growing seasons (May to October) as two independent variables in the regression model.

(3) In summary, we use pixel as the calculating unit to statistically analyze the images of annual NPP_{max}, average temperature, and cumulative precipitation during growing seasons between 1998 and 2000. Based on this, the present study further establishes the linear regression equation between climatic factors and NPP_{max}:

$$NPP'_{max} = a \times \overline{T} + b \times \sum P + c \quad (4)$$

where, NPP'_{max} represents the simulation value of NPP_{max} based on climatic factors; $\overline{T}$ means the average temperature of growing seasons; $\sum P$ is the cumulative precipitation in growing seasons; a and b are the regression coefficients; and c is the constant.

2.3.3 Residual analysis method

In this study, through the establishment of the regression model between climatic conditions and NPP_{max}, the influences of temperature and precipitation in long-time serial changes of NPP_{max} are eliminated to achieve the removal of natural and human factors. Without considering other non-decisive factors, the residual between the actual NPP_{max} and simulated NPP_{max} based on climatic conditions is the component influenced by human activities. When the residual is positive, human activities have a positive impact on vegetation growth and the ecological environment would be improved, whereas if the residual is negative, human activities have a negative impact on vegetation growth and the degradation of vegetation would be intensified.

2.3.4 Trend analysis method

Based on pixels, the absolute interannual change rate of NPP residual is calculated by the unitary linear regression analysis method, the computation formula is expressed as:

$$\theta_{slope} = \frac{n \times \sum_{i=1}^{n}(i \times \Delta NPP_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} \Delta NPP_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \quad (5)$$

where, n is for years (the time series is from 2001 to 2014, n = 14); ΔNPP_i is the residual NPP of one pixel in i year; θ_{slope} > 0 indicates an increasing trend, and the converse denotes a decreasing trend; and $|\theta_{slope}|\approx 0$ shows that there is almost no change in the regional NPP residuals.

2.3.5 Altitude classification

This study divided the altitude of Hengduan Mountains area into five grades in accordance with China's mountain classification standards, and they are called low altitude, middle altitude, middle-high altitude, high altitude and polar-high altitude.

3 Results and Analyses

3.1 Characteristics of NPP changes in Hengduan Mountains area

From the statistics on the total NPP (the sum of NPP in all pixels, its unit is Tg C) and annual NPP (the NPP per unit area, its unit is g C/(m^2·yr) in Hengduan Mountains area (Fig. 2), it was observed that the change trends of total NPP and annual NPP from 1998 to 2014 are similar, both presenting an increasing trend in fluctuation. The total NPP and annual NPP were from 175.22 to 225.22 Tg C, 392.25 to 503.77 g C/(m^2·yr), their average value is 205.30 Tg C and 459.46 g C/(m^2·yr), respectively, which is close to the study of Wang *et al.* (2016). Hengduan Mountains area accounts for approximately 4.7% of China's total land area, but the total NPP reached 5.5% of China's total NPP during the same period (Chen *et al*., 2011), implying that the vegetation per unit area was better developed, and the ecosystem was relatively stable.

To analyze the spatial distribution of NPP in Hengduan Mountains area further, the present study divided the annual NPP in Hengduan Mountains area into seven levels using the natural breakpoint method. From the spatial distribution map (Fig. 3), the annual NPP in Hengduan Mountains area in the south is higher than that in the north. Specifically, the majority of low NPP areas (0–400 g C/(m^2·yr)) are distributed in a banded shape in high altitude areas in the north of the study area. The median NPP areas (400–600 g C/(m^2·yr)) are situated in a centralized and scattered form throughout the whole Hengduan Mountains area, while the high NPP areas (> 600 g C/(m^2·yr)) are located in low-altitude areas in the northwest of Yunnan Province, as well as in the areas between the Jinsha River and Nujiang River. It appears that the NPP distribution is in contrast to altitude.

Hengduan Mountains area is typically located in middle-high altitude (2000–4000 m) areas (Table 1), which account for 54.08% of the entire study area. These are also the NPP concentration areas, with total NPP and annual NPP being the greatest here, reaching

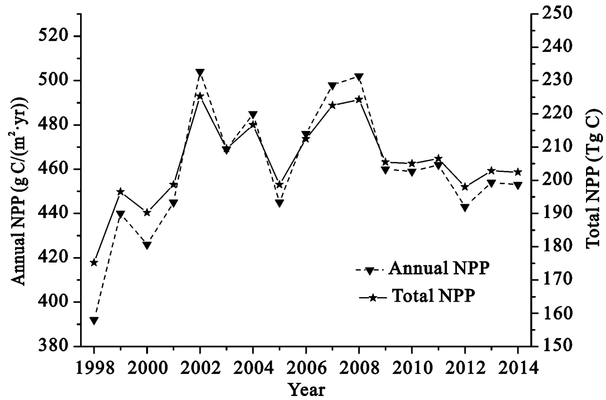

Fig. 2 Value of total NPP and annual NPP in Hengduan Mountains area during 1998–2014. 1 Tg C = 10^{12} g C, 1 Pg C =10^{15} g C

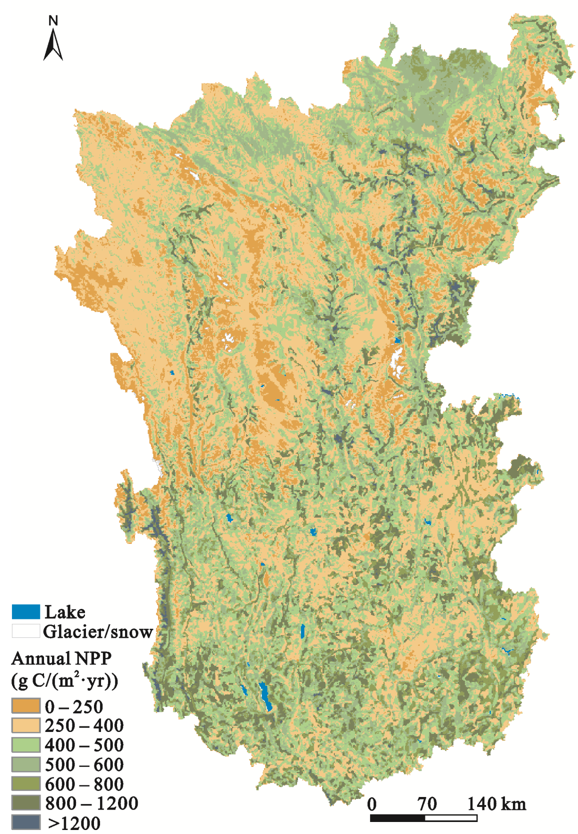

Fig. 3 Spatial distribution of annual NPP in Hengduan Mountains area during 1998–2014

Table 1 Classification comparison of NPP in different altitudes in Hengduan Mountains area

Statistics	Altitude (m)				
	Low altitude (<1000)	Middle altitude (1000–2000)	Middle-high altitude (2000–4000)	High altitude (4000–6000)	Polar-high altitude (>6000)
Area proportion (%)	0.45	12.69	54.08	32.77	0.01
Annual NPP (g C/(m^2·yr))	475.13	513.29	517.68	344.07	9.20
Total NPP (Tg C)	0.96	29.26	125.77	50.63	0.0003

125.77 Tg C and 517.68 g C/(m^2·yr), respectively. In addition, with an increase in altitude, NPP in Hengduan Mountains area shows a trend of declining after rising (Fig. 4). Below 700 m, annual NPP increases rapidly with an increase of altitude, with altitude increases of 100 m increments causing annual NPP to increase by 52.00 g C/(m^2·yr). Over 700 m in altitude, the growth of annual NPP starts to slow, and if the altitude increases by 100 m, then the annual NPP increases by only 5.80 g C/(m^2·yr).When the altitude reaches 2400 m, the annual NPP is highest (567.08 g C/(m^2·yr)), and over 2400 m, the annual NPP in Hengduan Mountains area decreases considerably (with an annual decline of 16.80 g C/(m^2·yr)). This implies that 2400 m is the critical altitude for NPP changes in Hengduan Mountains area.

3.2 Analysis of climatic factors in NPP changes

3.2.1 Spatial patterns of correlation between NPP and climate

Correlations between NPP and average temperature are stronger in the northern and southern sections than in the central part, thus forming a prominent concave pattern over the region (Fig. 5a). A majority of positive correlations occur in the Yi Autonomous Prefecture of Liangshan of Sichuan Province and the northeast corner of Yunnan Province, whereas negative correlations predominately occur in southeast Tibet, Muli County of Sichuan Povince, and the southern Hengduan Mountains area. Meantime, pixels representing significant (0.01 < P < 0.05) and highly significant (P < 0.01) correlations between NPP and average temperature account for 13.0% and 6.5% of the total pixels, respectively, and locate in the northwest, center, and southern portions of Hengduan Mountains area (Fig. 5b).

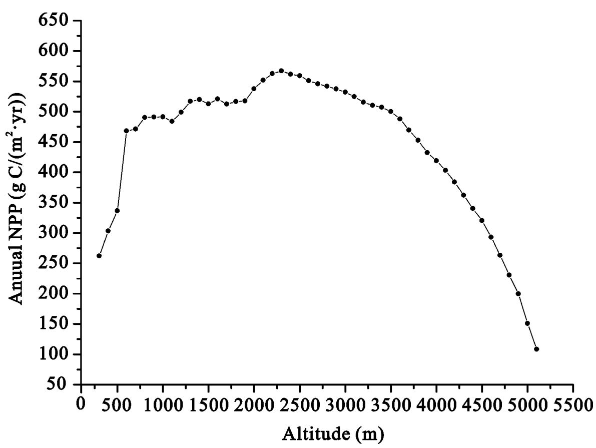

Fig. 4 Relationship of annual NPP and altitude in Hengduan Mountains area during 1998–2014

Correlations between NPP and cumulative precipitation are stronger in the central section than in the northern section, and stronger in the northern section than in the southern section, thus presenting a distinct convex pattern (Fig. 6a). Areas of positive correlations between NPP and cumulative precipitation are mainly concentrated in northwest Yunnan Province and along the Jinsha River, whereas areas of negative correlations are primarily located in the transition zone of the Yunnan-Guizhou Plateau and the Qinghai-Tibet Plateau, as well as adjacent to the Dadu River valley. At the same time, pixels where correlations between NPP and cumulative precipitation are significant (0.01 < P < 0.05) and highly significant (P < 0.01) account for 7.7% and 2.0% of total pixels, and occur primarily in the central part of Hengduan Mountains area (Fig. 6b).

3.2.2 Partition of climate factors for NPP change

This study obtained references from the principles and standards of the drive partitions of vegetation coverage changes (Piao *et al*. 2006b), and applied proper modifications to differentiate the climatic factors of NPP changes in Hengduan Mountains area (Table 2).

Fig. 7 shows that even though areas with NPPs that are heavily affected by climate are extensively distributed, they only account for 18.2 % of the entire research area, whereas areas with NPPs that are primarily affected by non-climatic factors account for 81.8 % of the research area. This means that NPP changes are mainly caused by non-climatic factors (i.e., human activities) in most regions of Hengduan Mountains area. Those areas

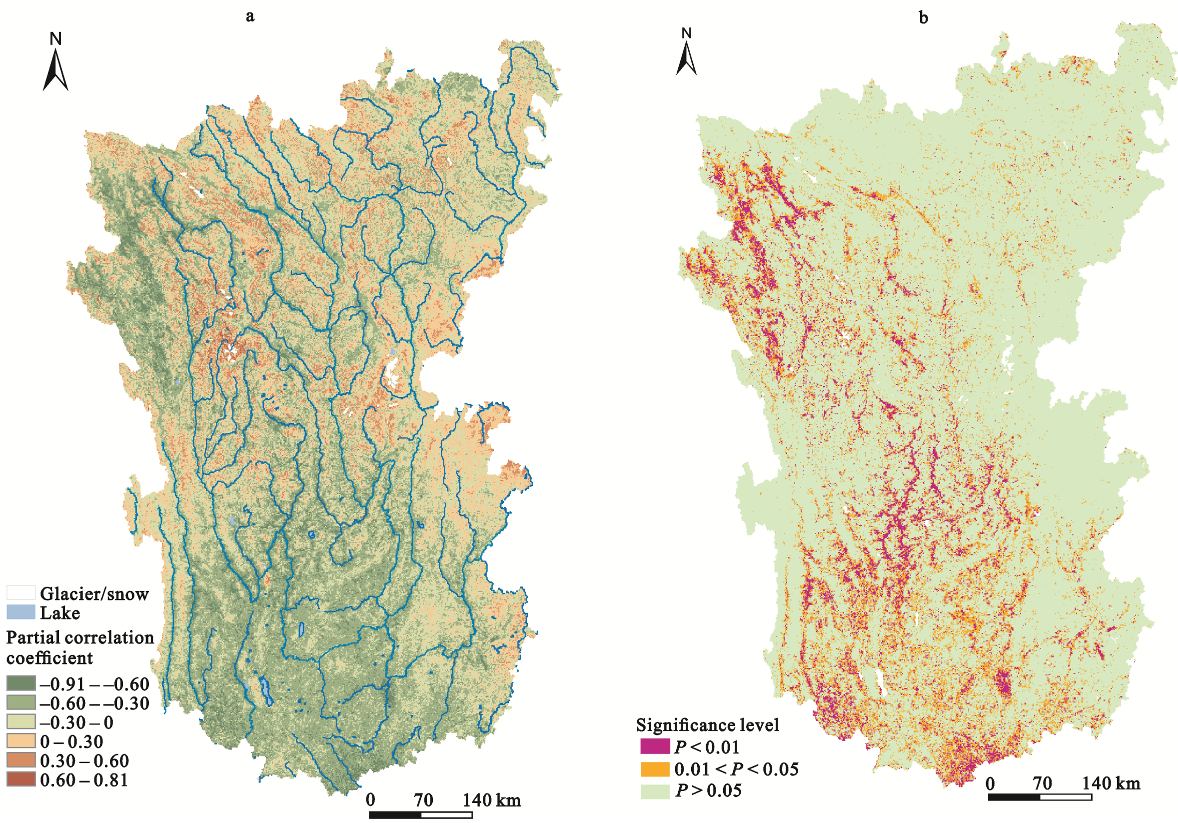

Fig. 5 Spatial distribution of correlation (a) and significance (b) between NPP and average temperature during 1998–2014

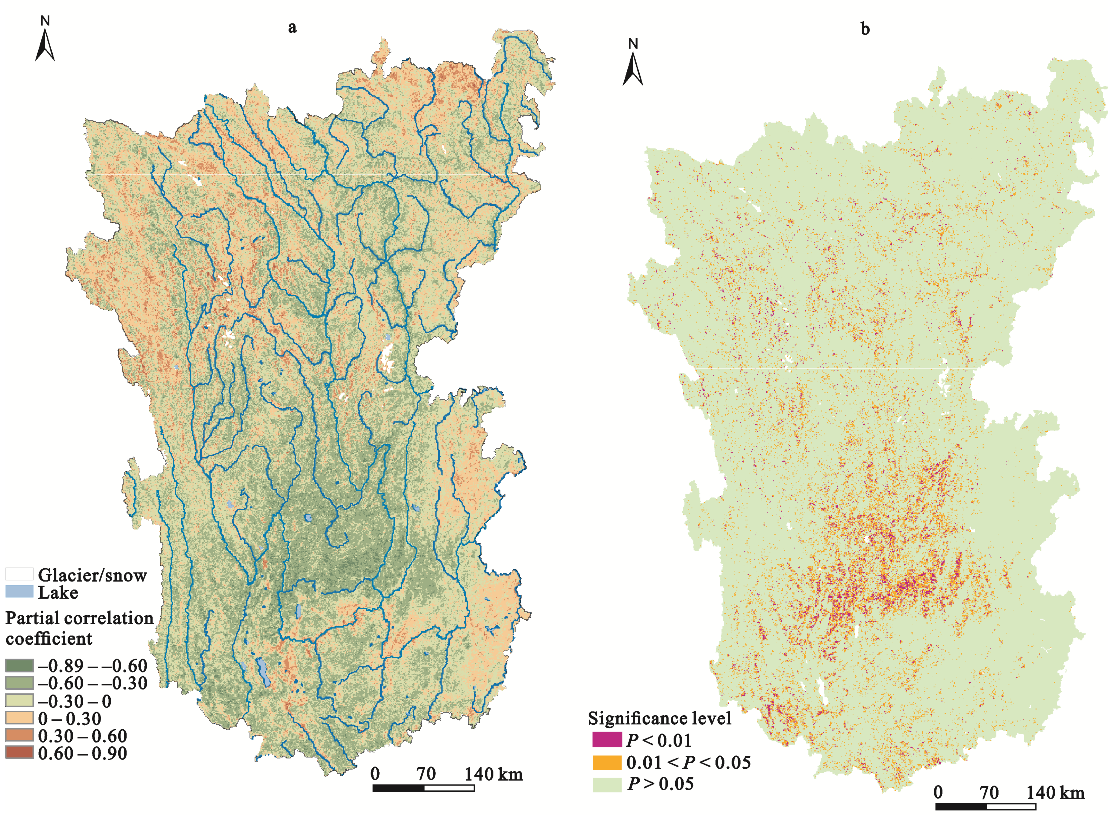

Fig. 6 Spatial distribution of correlation (a) and significance (b) between NPP and cumulative precipitation during 1998–2014

Table 2 Partition rules of driving factors for NPP change

Driving factors of NPP change		Partition rules		
		$R_{npp,tmp\cdot pre}$	$R_{npp,pre\cdot tmp}$	$R_{npp\cdot pre,tmp}$
Climate	Strong driving of temperature and precipitation, [T+P]+	$\|t\|>t_{0.05}$	$\|t\|>t_{0.05}$	$F>F_{0.1}$
	Temperature is main factor, T	$\|t\|>t_{0.05}$		$F>F_{0.1}$
	Precipitation is main factor, P		$\|t\|>t_{0.05}$	$F>F_{0.1}$
	Weak driving of temperature and precipitation, [T+P]-	$\|t\|\le t_{0.05}$	$\|t\|\le t_{0.05}$	$F>F_{0.1}$
Non-climate	Human activity, NC			$F\le F_{0.1}$

Notes: $R_{npp,tmp\cdot pre}$ is the partial correlation coefficient of NPP and temperature under the condition of precipitation is constant; $R_{npp,pre\cdot tmp}$ is the partial correlation coefficient of NPP and precipitation under the condition of temperature is constant; $R_{npp\cdot pre,tmp}$ is the multiple correlation coefficient of NPP and precipitation, precipitation. $|t|> t_{0.05}$ means it passes significant t test ($P < 0.05$); $|t|\le t_{0.05}$ means it does not pass significant t test ($P < 0.05$); $F>F_{0.1}$ means it passes significant F test ($P < 0.1$); $F\le F_{0.1}$ means it does not pass significant F test ($P < 0.1$)

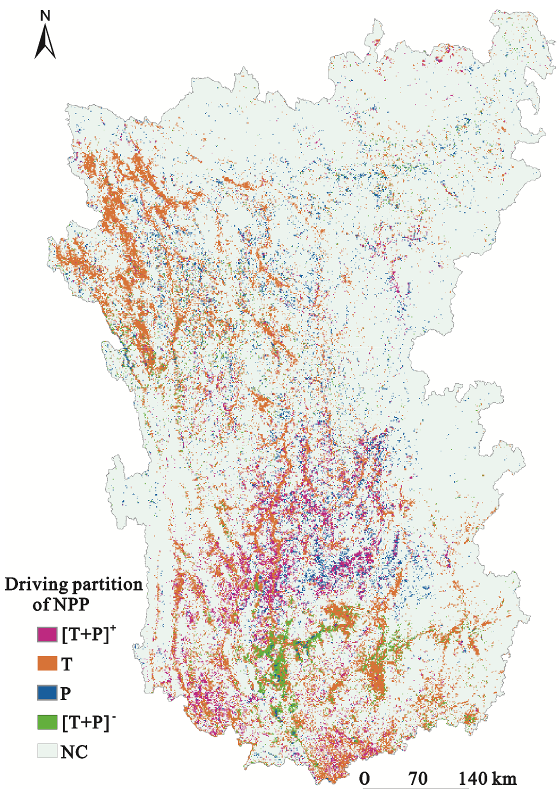

Fig. 7 Driving partition of NPP changes in Hengduan Mountains area during 1998–2014. Meanings of T, P and their combinations see Table 2

driven strongly by precipitation and temperature are located along the southwest edge of Sichuan Province and account for 3.2% of the total Hengduan Mountains area. However, those areas where NPP is weakly driven by precipitation and temperature account for 1.8% of the total study area and are scattered along the Lancang River. Areas with temperature as the main driving factor are located in the northwest corner of Sichuan Province and the northeast corner of Yunnan Province, and account for 13.6% of the total research area. However, the intersections of the Yalong River and Anning River, and the areas near the Xueshan Mountain are mainly affected by precipitation. They account for 6.0% of the total research area.

3.3 Analysis of human activities on NPP changes

The statistics for NPP residuals from 2001 to 2014 in Hengduan Mountains area (Fig. 8) show that the average NPP residual is greater than 0 for each year. This means that human activities play a positive role in promoting regional vegetation growth, which may be related to the implementation of regional policy to return farmland to forests and to natural forest protection projects. Average NPP residuals show a fluctuating downward trend from 51.00 g C/(m^2·yr) in 2001 to 21.20 g C/(m^2·yr) in 2014, which indicates that the positive effect of human activities is mainly weakened by the periodical characteristics of the artificial forestation measures. This study used 0 as the critical value, which divided the average NPP residuals from 2001 to 2014 into eight classes (Fig. 9). Overall, the average NPP residual was between –324.56 g C/(m^2·yr) and 243.52 g C/(m^2·yr). The effect of human activities on the ecological environment was positive in 76.3% of the whole area, and was distributed across the whole Hengduan Mountains area, especially in the southern part. The effect of human activities on the ecological environment was negative in 23.7% of the whole area for various reasons, and the ecological environment parameter had a decreasing trend. The areas that were ecologically deteriorating were concentrated in southeast Tibet, Muli County of Sichuan Province, Panzhihua City of Sichuan Province, and northwest Yunnan Province.

Fig. 10 shows that NPP residual slope in Hengduan Mountains area is between –45.90 and 42.71 g C/(m^2·yr),

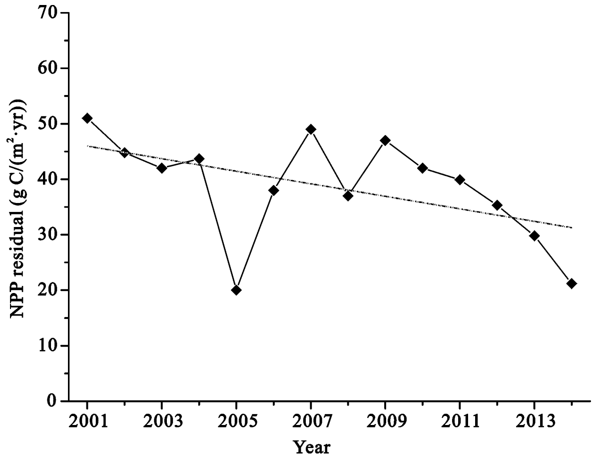

Fig. 8 NPP changes caused by human activities (NPP residual) from 2001 to 2014

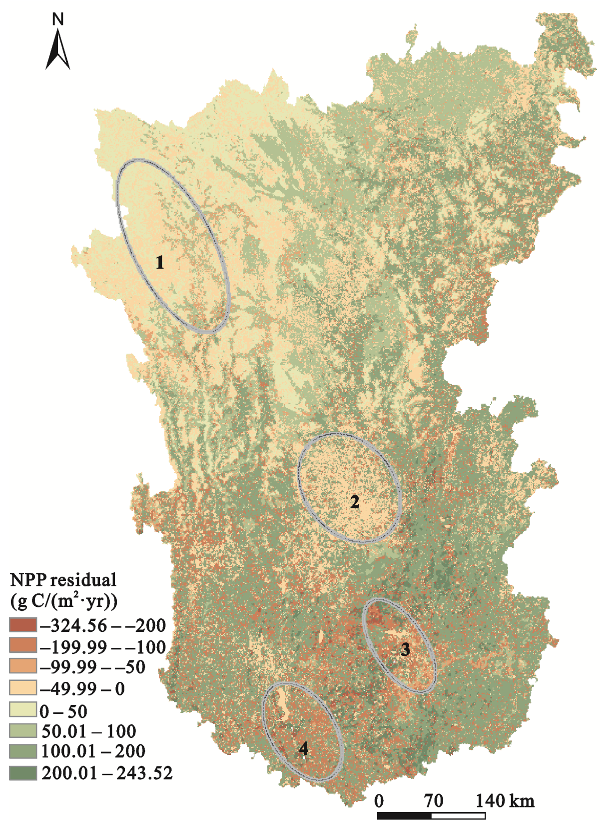

Fig. 9 Spatial distribution of average NPP changes caused by human activities from 2001 to 2014. 1. Southeast Tibet; 2. Muli County of Sichuan Province; 3. Panzhihua City of Sichuan Province; 4. Northwest Yunnan Province

but is concentrated mainly between –15 to 15 g C/(m^2·yr), which accounts for 90.2% of the total Hengduan Mountains area. Areas where the NPP residual slope is greater than zero account for 37.3% of the total Hengduan Mountains area, but these are irregularly scattered across the whole area. The 62.7% of the total study area where the NPP residual slope is less than zero is distributed in a belt along the river in the north of Hengduan Mountains area, and in a patch in the south of Hengduan Mountains area. This is because the altitudes and relief amplitudes are higher in the northern region of Hengduan Mountains area. The population is also concentrated in the valley, which takes the river as the axis to expand and form zonal residential areas. However, in the southern region, which has lower altitudes and a gentler terrain, it is easier for human production activities to take place. When a few population points are found at the center, and then the points radiate gradually outward to form strip areas.

4 Discussion

According to Wang *et al*. (2006), total and annual NPP in Hengduan Mountains area amounts to 208.498 Tg C and 463 g C/(m^2·yr), respectively, which are similar to our results (209.15 Tg C and 468.06 g C/(m^2·yr)). However, there are slight differences in the spatial NPP distribution between the results of our study and those

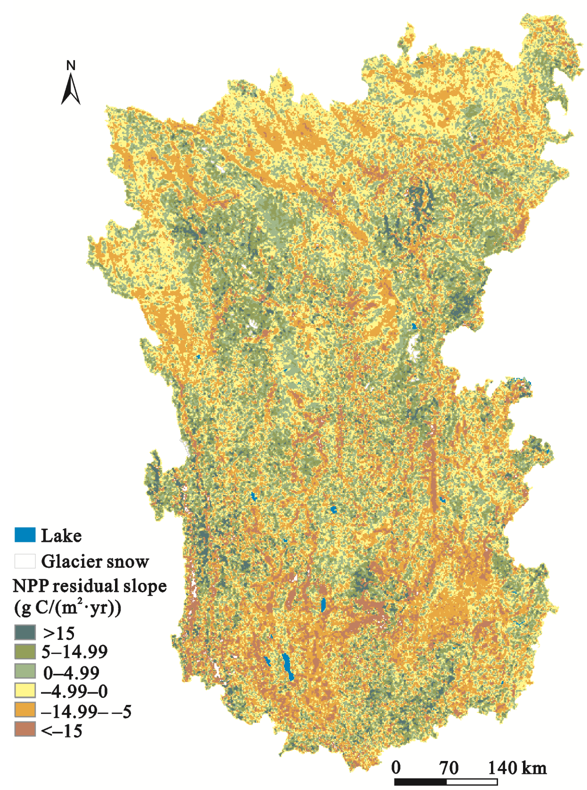

Fig. 10 Distribution pattern of NPP residual slope in Hengduan Mountains area from 2001 to 2014

of Wang *et al*. (2006) due to 1) differences in data sources: our study takes NDVI products provided by SPOT-VGT as the data source, and our NPP estimates are generated by the CASA model, which uses a 1000 m spatial resolution. However, Wang *et al*. (2006) rely on the NPP products provided by MODIS17A3, and use a spatial resolution of 500 m; 2) differences in time periods: we used the period of 1998–2014, whereas Wang *et al*. (2006) only covered 2004–2014 due to the unreliability of MODIS data prior to 2004 (Heinsch *et al*., 2003); and 3) differences in basic data used for model calculations: the meteorological data used in our study was derived from data measured directly at monitoring sites and interpolated by the specialized meteorological software Anuspline, which takes into account the effect of terrain and coastlines on temperature and precipitation. Therefore, reliability is relatively high in our study (Hijmans *et al*., 2005). NPP products generated by MODIS17A3 rely on temperature and precipitation estimates that are derived from MODIS meteorological data (Hutchinson, 2004). This means that their accuracy is lower than the estimates derived from directly measured data. Therefore, we conclude that our NPP estimations are credible and can provide a reliable basis for further study.

Our results indicated that NPP initially rises, but then decreases with increasing altitude. Furthermore, 2400 m represents the critical point for NPP changes, which is the same altitude at which local human populations are concentrated (Guo, 2012). The results showed that NPP was higher in densely populated areas in Hengduan Mountains area, which differed from other areas (Zeng *et al*., 2013). We attribute this to two primary factors: firstly, on the whole, a majority of the areas at altitudes lower than 2400 m are located on the plateau in the southern Hengduan Mountains area where the relief amplitude is smaller and the hydrothermal conditions are well matched. This area is dominated by subtropical evergreen broad-leaved forests, and thus, the NPP is higher than in the high altitude plateaus (Li, 1988). Secondly, although human populations are concentrated in the areas with altitudes around or lower than 2400 m, these communities are largely rural and not heavily industrialized (Chen *et al*., 2016). Therefore, NPP in these areas is generally enhanced due to the contributions made by agricultural cultivation.

Our study has also highlighted several important issues concerning the effects of climate and human activities on NPP changes. The changes in temperature (~0.5℃) and precipitation (~100 mm) in Hengduan Mountains area (Figs. 11 and 12) were minor between 1998 and 2014, which suggested that climate change has yet to have a significant effect on the plant communities in this region. We found that climate is the main factor driving NPP changes in only 18.2% of the study area, an area much smaller than that dominated by human activities, a result that was consistent with Wu *et al*. (2011). Human activities clearly play an active role in driving changes in NPP, which indicates that ecological protection measures have achieved their initial results and aims. However, the positive effect had a downward trend between 1998 and 2014 and the NPP fluctuated, which indicates that ecological project implementation has only had short-term benefits and that ecological construction has had few long-term effects. Therefore, for ecologically

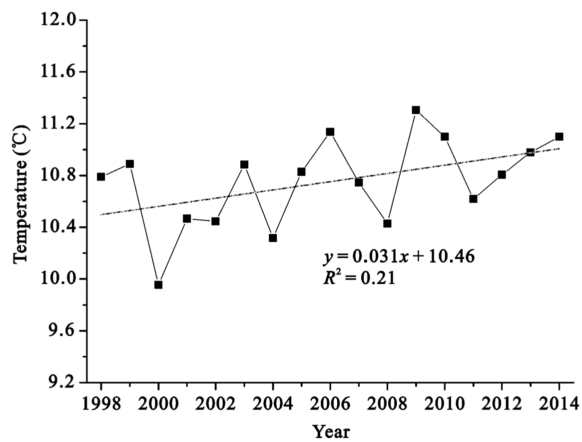

Fig. 11 Temperature changes in Hengduan Mountains area from 1998 to 2014

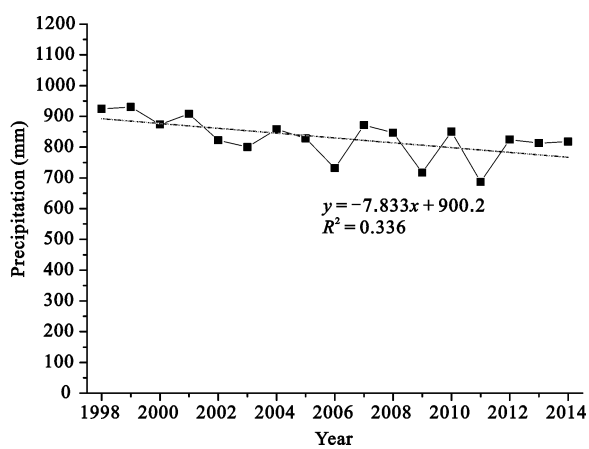

Fig. 12 Precipitation changes in Hengduan Mountains area from 1998 to 2014

vulnerable and important areas, such as Hengduan Mountains area, government control and supervision of ecological construction projects must be strengthened to ensure successful project implementation.

Although changes in NPP were generally positive in most parts of Hengduan Mountains area, 23.7% of the region was determined to have experienced at least some degree of ecological degradation, mainly in southeast Tibet, Muli County of Sichuan Province, Panzhihua City of Sichuan Province, and northwest Yunnan Province. The underlying causes differed slightly. For example, population increase, intensive urbanization, and overgrazing due to the expansion of regional animal husbandry and pastoral areas are largely responsible for the vegetation destruction and environmental deterioration in southeast Tibet (Zhou *et al*., 2010). In the grasslands of Muli County, in addition to livestock overgrazing, rodent damage and weed encroachment have also disrupted and damaged the ecosystem balance (He *et al*., 2015). Panzhihua City is a city that depends largely on a resource-based (particularly mineral resources) economy. During the industrialization and urbanization process, extensive exploitation and utilization of resource products and the failure to comprehensively manage the environment has led to the deterioration in regional ecology (Liu *et al*., 2012). Finally, ecological damage in northwest Yunnan Province can be largely attributed to tourism and other high-intensity development activities (Jin *et al*., 2016).

In this study, the analysis of residuals was used to distinguish between the effects of climate and human activities on NPP changes. However, detailed exploration of the relative roles of the specific human activity driving factors on NPP was beyond the scope of this study, because such work would require improvements in research methods, and extensive field research and data collection. Therefore, it must remain a subject for future research. In this study, we attempted to establish a baseline for the relationship between NPP and altitude in Hengduan Mountains area. This baseline can be used as a foundation for future research on the zonal relationships between regional NPP and altitude, slope, aspect, *etc*.

5 Conclusions

The NDVI dataset and meteorological data enabled the NPP in Hengduan Mountains area to be estimated using the CASA model. Then, relationships and spatial patterns for NPP and climatic factors were identified by the correlation analysis method. Finally, the effect of human activities on NPP changes was separated out by the residual analysis method and the effect of ecological construction projects was verified in Hengduan Mountains area. We determined that fluctuations in average values for total and annual NPP in Hengduan Mountains area increased between 1998 and 2014, with average values of 209.15 Tg C and 468.06 g C/(m^2·yr), respectively. Areas with non-climatic factors (i.e., human activities) as the main driving force accounted for 81.8% of the total research area, whereas areas where climatic factors were dominant only accounted for 18.2%, which confirmed the outsized effect of human activities on changes to the plant communities in this area. The effect of temperature on NPP changes is larger than that of precipitation, which indicates that temperature is the main climatic factor affecting vegetation growth. Furthermore, human activities play an active role in NPP changes, which indicates that ecological construction projects have achieved their preliminary results. However, this positive effect shows a downward trend, suggesting that ecological protection measures have few long-term effects and we should pay much more attention to ecological construction.

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