Application of a new productivity coupling hydrothermal factors (PCH) model for evaluating net primary productivity of grassland in Southern China

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ABSTRACT

Grassland ecosystems play important roles in the global carbon cycle. The net primary productivity (NPP) of grassland ecosystems has become the hot spot of terrestrial ecosystems. To simulate grassland NPP in Southern China, a new productivity coupling hydrothermal factors (PCH) model was built and validated based on data recorded from 2003 to 2014. The results show a logarithmic correlation between grassland NPP and mean annual temperature and a linear positive correlation between grassland NPP and mean annual precipitation in Southern China, both highly significant relationships. There was a highly significant correlation between simulated and measured NPP (R^2 = 0.8027). Both RMSE and RRMSE were relatively low, showing that the simulation results of the model were reliable. The NPP values in the study area had a decreasing trend from east to west and south to north. Mean NPP was 471.62 g C m^{-2} from 2003 to 2014. Additionally, the mean annual NPP of Southern grassland presented a rising trend increasing 3.49 g C m^{-2} yr^{-1} during the past 12 years. These results document performance and use of a new method to estimate the grassland NPP in Southern China.

KEY-WORDS: grassland NPP, PCH model, mean annual precipitation, mean annual temperature, Southern China

1 Introduction

Grassland is one of the major biological communities in the world. It covers more than 40% of the total land area on the planet, and plays an important role in the global biogeochemical cycle and energy transformation process (Chen and Zhang, 2000; Mosier et al., 1991). Meanwhile, grassland has also the functions of water and soil conservation, windbreak and sand-fixation, biodiversity maintenance, shaping soil from surface to depth, with close connection with human survival and development (Brevik et al., 2015). The roots system of grassland vegetation occurs in soil, so the direct link between soil and vegetation can be discovered. Most of soil functions have strong ties to vegetation, such as biomass production, biodiversity pool and Storing, filtering and transforming nutrient, substances and water (Keesstra et al., 2016). In soil – grassland vegetation – atmosphere continuum, grassland acts as the center of ecological functions on the ecosystem scale. The impacts of the climate on grasslands are quite complicated. On one hand, different types of grasslands have their own spatial distributions controlled by temperature and precipitation; on the other hand, a rise in temperature will alter some processes in the ecosystem (such as evapotranspiration, decomposition and photosynthesis). Therefore, temperature exerts a significant effect on biological community productivity (Douglas and Geoffrey, 1997). Net Primary Productivity (NPP) is an indicator that measures the production capacity and economically and socially significant products of the plant community under natural conditions (Sun et al., 2013). Changes in NPP directly reflect the response of ecosystems to climatic conditions, therefore it can be used as a research index in the relationship between ecosystem function and climate change (Zhou et al., 2014). It also has an important theoretical and practical significance for evaluating the environmental quality of terrestrial ecosystems, regulating ecological processes and estimating the terrestrial carbon sink to master the inter-annual variation rule of terrestrial NPP (Cao, 2013; Richardson et al., 2012; Picard et al., 2005; Zhang et al., 2011; Xu et al., 2012).

Estimation methods, most based on models, to calculate grassland NPP were discussed in previous research (Gill et al., 2002). Models demonstrate advantages over other methods in global, regional and other large scales studies, becoming an important tool in macro ecological research of grasslands. Grassland NPP estimation models have been used by some researchers for dynamic monitoring and forecasting (Raich et al., 1991; Matsushita and Tamura 2002) providing theoretical and technical support for ecological improvement and recovery of grasslands (Christenson et al., 2014). A large number of studies were conducted by domestic and foreign scholars to understand the influences brought by climate change to the ecosystem processes, including grassland productivity and grassland C circulation. Although many researchers have studied the influences on a national or regional scale (Parton et al., 1995; Hall et al., 1995; Braswell et al., 1997; Cao and Woodward, 1998; Fang et al., 2001; Ni, 2002; Mantgem and Stephenson, 2007; Wunder et al., 2013; Gang et al., 2015), there has been little research on relationships between grassland NPP and climate factors in Southern China. Grassland resources are abundant in China, with an area of nearly 400 million ha, nearly 1/6 of that in Southern China. As the grassland in northern areas are continues to deteriorate and desertize, the ecological system of grassy hills and slopes in Southern China are becoming increasingly important. Study of the relationship between NPP and climatic factors, together with their dynamic simulation will provide insights on the effective management and reasonable utilization of grasslands in Southern China, and the promotion of global change research. Our objectives were the following: (1) to build an ecological model (PCH) based on the statistical analysis of the relationship between measured NPP, precipitation and temperature; (2) to modify the adjustment coefficient and the parameter of the model based on the grassland types and their ecological characteristics; (3) to simulate NPP using the PCH model and analyze its changing trends on the spatial and temporal pattern from 2003 to 2014; (4) to verify the accuracy of the PCH model by comparing it with field observation data; (5) to explore the dominant hydrothermal factor for determining the NPP change of the study area.

2 MATERIALS AND METHODS

2.1 Study area

The grassy hills and slopes of Southern China, centered on 110°0′E, 27°30′N, was the focus of research. The site encompassed 17 provinces and an area of about 60 million ha (Figure 1). The grasslands of Southern China are mainly composed of typical grassland, wetland grassland, lowland meadow and upland meadow. The Southern grasslands are scattered and distributed among areas of forest land and cultivated land, and mostly located on slopes. Most regions of Southern grasslands are managed with grazing and some regions with enclosure and cutting. The climate characteristics in this area include hot and rainy summer, and mild and rainy in winter, with the frost-free period being more than 300 days per year. The annual mean precipitation is between 800–1600 mm and the annual mean temperature is greater than 15 ℃. These climate conditions contribute to a suitable environment for grassland.

2.2 Data acquirement and processing

NPP data acquirement: in July of 2011, 2012 and 2013, 66 sample plots were investigated in several provinces of the study area. Large quadrats were set in each representative sample plot (10m×10m), and five small squares (1m×1m) were set on corners and in the center of large quadrats. Above-ground biomass and the latitude and longitude information were recorded in each small quadrat, with an average level calculated after sampling. Every 2.2 g dry matter was converted into 1g carbon, leading to the grass NPP in each sample area, represented in the form of carbon (g C m^{-2})(Fang et al., 2001).

Climate data acquirement: temperature and precipitation data from year 2003 to 2014 were acquired from the ground stations of China Meteorological data sharing service system (http://cdc.cma.gov.cn/) (Figure 1). Kriging interpolation from Geographic information system (GIS) interpolation tool was utilized to analyze meteorological data according to the latitude and longitude information of each station. Then the image projection transformation converted data into a raster image with a latitude and longitude network and 1000 m resolution. Finally, temperature and precipitation information was extracted according to latitude and longitude corresponding to the investigation points.

The distribution map of grassland in the study area (Figure 2): the 1980 Chinese grassland resource inventory and MOD12Q1 data acquired in 2004 were used to generate the land cover, land use map and the grassland distribution map. Open shrubs, woody savannas, savannas, grasslands and permanent wetlands were included as the grassland of Southern China based on the land use and land cover classification project proposed by the International Geosphere–Biosphere Programme (IGBP).

2.3 Model establishment and validation

Modeling methods: based on the statistical analysis of the relationship between measured NPP, precipitation and temperature, the preliminary structure of the model was developed. Then the nonlinear fitting algorithm was utilized to optimize and determine the parameters of the model.

Model validation: in order to verify the reliability of the simulation results, both Root Mean Square Errors (RMSE) and Relative Root-Mean-Square Errors (RRMSE) were applied to the model for testing and evaluating the simulation effects. RMSE and RRMSE were expressed as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2} \quad (1)$$

$$RRMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2} \,/\, O_a \quad (2)$$

where O_i was the real value, S_i was the simulated value, O_a was the average of real value, n was the total number of samples.

3 RESULTS

3.1 Relationship between grassland NPP and temperature

Grassland NPP is a joint result of the regional light, temperature, precipitation, soil and other natural conditions, which reflects the ability of using natural environmental resources (Gang et al., 2015). Under natural conditions, temperature and precipitation were the two dominate influential factors to grassland NPP in Southern China (Sun *et al*., 2014). The results of the analysis of the relationship between grassland NPP and temperature in Southern China showed that: (1) between 10 and 20 C there was a linear positive correlation between temperature and the

NPP, and (2) a para-curve relationship was found between from 20℃ to 30 ℃. Generally, the relationship between temperature and grassland NPP was logarithmic with correlation coefficient r being 0.4629, reaching a significant level ($P<0.01$). As a result, the relationship could be presented as a logarithmic equation.

3.2 Relationship between grassland NPP and precipitation

Precipitation is a key factor in many NPP estimation models (Huston, 2012; Yu et al., 2008). Mean monthly precipitation in the grassland ecological system of Southern China presented a large range throughout a year with min precipitation being 40 mm and max being over 200 mm. NPP also showed a regular distribution according to the precipitation, with a typical linear positive correlation. The correlation coefficient r was 0.7836, reaching a very significant level ($P<0.01$). Therefore, the influences of precipitation on grassland NPP could be expressed as a linear equation.

3.3 Estimation model of grassland NPP

3.3.1 Model establishment

According to the analysis results, a positive relationship existed between grassland NPP and mean annual temperature and annual precipitation in Southern China. Thus it is feasible to express the relationship with logarithmic and linear equations, respectively. However, the results varied greatly when temperature was directly used as the equation factor and any data below zero C would fail to be processed. Thus it was necessary to introduce a temperature adjustment coefficient, described here as:

$$T_a=Ln(T/t_1+a_1) \tag{3}$$

where T_a was the temperature adjustment coefficient, T was the mean annual temperature (℃), t_1 was the model parameter, a_1 was a constant, it was set to 2.5 in the paper.

Compared with the temperature, the precipitation has the same situation. Growth stopped when moisture was below a certain level. So another adjustment coefficient was introduced and expressed as following:

$$W_a=Sqrt(W/w_1+a_2) \tag{4}$$

where W_a was the adjustment coefficient, W was the mean annual precipitation (mm), w_1 was the model parameter, a_2 was a constant and being set to 0.5 in the paper.

According to the above information, the estimation model of grassland NPP in Southern China could be written as following:

$$NPP = T_a \times W_a \times (T + W/6) \quad (5)$$

The PCH model was built to simulate grassland NPP of Southern China based on the principle of grassland productivity coupling hydrothermic factors. In order to improve the applicability in the grassland of Southern China and accuracy of the simulation results, the adjustment coefficients related to temperatute and precipitation were introduced into the model. Thouth the PCH model has not been applied to simulate the NPP of different types of vegetation, the establishment and application of the model have been based on the specific spatial distribution of grassland and complicated hydrothermal condition in Southern China. Each model has its advantages and limitations depending on different study targets and scales. The limitations of the model is that fewer influential factors were introduced into the model comparing with other ecological model. The future analysis and explication about this will be made in the discussion part of this paper. The strenght of the PCH model lies in the origin of the model establishment and the focalization and directness of assessing the NPP of grassland in Southern China. The novelty of this model is mainly embodied in the process of hydrothermal assimilation in comparison to others models. Understanding controls over NPP will be crucial in developing models of these processes at larger spatial scale, so the PCH model combines the hydrothermal parameter and ecosystem process approach to quantify the carbon flow of grassland in Southern China (Gill et al., 2002).

3.3.2 Calculation of model parameters

The acquisition of model parameters was a quite complicated process, and would directly affect the accuracy of the final results. Based on the measured data from 2009 to 2010, by adopting the contraction expansion algorithm of the nonlinear fitting and MATLAB programs (Conway and Wilcox, 1970), those parameters were calculated as

t_1=5.8, w_1=560.4.

3.3.3 Model validation

The measured grassland NPP data from 2014 in Southern China were used to validate the simulation results. The results indicated that there was a strong and significant correlation between the simulated and measured NPP (R^2 = 0.802, P<0.01). The RMSE of the simulation was 58.351g C m^{-2}, the RRMSE was 0.326, and both were small. All those results indicated that the simulation of precipitation and temperature model for Southern grassland NPP was feasible. The trends of the simulated and measured grassland NPP were similar (Figure 3), which also indicated that the results were reliable.

3.4 Spatial-temporal variations of grassland NPP from the year 2003 to 2014

The spatial distribution map of grassland NPP produced by the estimation model was beneficial to monitor the grassland resource. This paper built the spatial distribution map of Southern grassland NPP using the estimation model of grassland NPP based on climatic conditions (Figure 4). It showed that the minimum of mean annual NPP of Southern grassland was 57.83g C m^{-2} and the maximum was 1328.06g C m^{-2} in recent 12 years. The NPP of Southern grassland had an obvious zonal distribution. The NPP value was lower in northwest regions and higher in southeast and south regions, especially in Jiangxi, Guangdong and Hainan province.

The variation of mean annual NPP and the relevant statistical indices of Southern grassland in the recent 12 years were shown in Figure 5. The trend of mean annual NPP presented an increasing tendency of the whole Southern grassland from 2003 to 2014. The variation range of the mean annual NPP was from 430.31 to 519.82 g C m^{-2}, and the mean was 471.62 g C m^{-2}. The minimum of the mean annual NPP appeared in 2006, and the maximum value appeared in 2013. The tilt rate of the mean annual NPP of Southern grassland in recent 12 years was 3.49 g C m^{-2} yr^{-1}, which indicated that the NPP increased about 3.49 g C m^{-2} every year ($P < 0.05$).

4 Discussion

Research on the relationships between the NPP and climate factors in global or regional ecological systems started in mid-1800s (Nemani et al., 2003; Zhou et al., 2014). As revealed in these studies, the vegetation index showed periodic variations with corresponding climate indices including temperature and precipitation, during the growth process of most plants. Temporal and spatial variations were quite distinct in grassland NPP, since climatic factors, especially precipitation and temperature, were factors directly linked to periodic variations (Ronnenberg and Wesche, 2010). This study showed that a temperature rise would cause a certain level rise in the grassland NPP in Southern China, especially in the high temperature zones. However, these results differed from some previous reports (Mcguire et al., 1993). In addition, there was a significant positive correlation between precipitation and NPP. When mean annual precipitation increased, grassland NPP would also increase significantly. This conclusion is consistent with previous studies (Sala et al., 2000; Knapp and Smith, 2001; Mohamed et al., 2004).

The ultimate goal of those studies on the relationship between climate and terrestrial ecosystem NPP is to predict the possible impacts on climate change and to take scientific countermeasures (Pablo et al., 2007), and establishing a model is an efficient means to make these predictions. Through modeling and simulation, one could reveal the quantitative change and trend of NPP caused by climate change. That was why the research of NPP model had attracted a vast amount of attention (Ren et al., 2011). This study establishes an estimation model for the grassland NPP of Southern China by using the statistical analysis of the relationship between the Southern grassland NPP and precipitation and temperature combined with biological process. The relationship between simulated and observed values reached a highly significant level. This and the low RMSE validated the reliability of the model. Therefore, it was feasible to estimate the grassland NPP in Southern China by using the PCH model described in this paper.

The estimation of grassland NPP is a complex process. It is not only affected by climatic factors such as precipitation and temperature, but also by the grassland vegetation's own inner physiological process, fire severity, slope position and aspect, grazing, human activities, cutting frequency and grassland ecotypes (Pereira et al., 2016; Shaw et al., 2016; Lu et al., 2015; Lin et al., 2015; Poeplau et al., 2016; Roosendaal et al., 2016).

Grassy hills and slopes in Southern China had a wide distribution with various vegetation types, therefore the NPP distribution was uneven. Although the model estimation worked well, some imperfection exists. Firstly, a classification for grass hills and slopes is needed, without of which the NPP estimation fell into a single type (Hu et al., 2016). Secondly, the NPP estimation results were representative of the entire year, while arbitrary NPP estimation for a single month has not been verified yet. Thirdly, as an important ecological parameter, MODIS normalized difference vegetation index (NDVI) needs to be added into the model (Gong et al., 2015). Then, precision of the model could be improved in the process of evaluating the changes of grassland in Southern China. Fourth, grassland soil coarseness needs to be taken into account as a result of nutrient cycling and respiration in grassland (Lü et al., 2016). The last is a sensitivity issue. The study indicated that the simulation results by the PCH Model were slightly large in a small fraction of areas with relatively low NPP, while small in a part of area with high NPP. It may be caused by the limited time span, and other factors including the influences from different types of grasslands. Hence, there might be some uncertainty to estimate the lower or higher grassland NPP using the estimation model. Further study is required to solve these problems.

5 Conclusion

In this study, a new productivity coupling hydrothermal factors (PCH) model was built to simulate the NPP in Southern China's grasslands. The PCH model is a productivity coupling hydrothermal factors model that can be expressed by the transformation of the model parameters, mean annual temperature and mean annual precipitation, which are the most critical two factors affecting the NPP of Southern China's grasslands. The results show that there is a logarithmic correlation between grassland NPP and mean annual temperature, and a linear positive correlation between grassland NPP and mean annual precipitation in Southern China. There was a very significant correlation between simulated and the measured NPP (R^2 = 0.8027). Meanwhile, both RMSE and RRMSE stayed at a relatively low level, showing that the simulation results of the model were reliable. The NPP values in the study area had a decreasing trend from east to west and south to north respectively. The mean NPP was 471.62 g

C m^{-2} from 2003 to 2014. Additionally, the mean annual NPP of Southern grassland presented a rising trend and the rate of change was 3.49 g C m^{-2} yr^{-1} in recent 12 years.

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Fig. 1 Study area and meteorological stations in Southern China (the black boundary-lines indicate the provincial boundary; the red dots represent the locations of the meteorological stations).

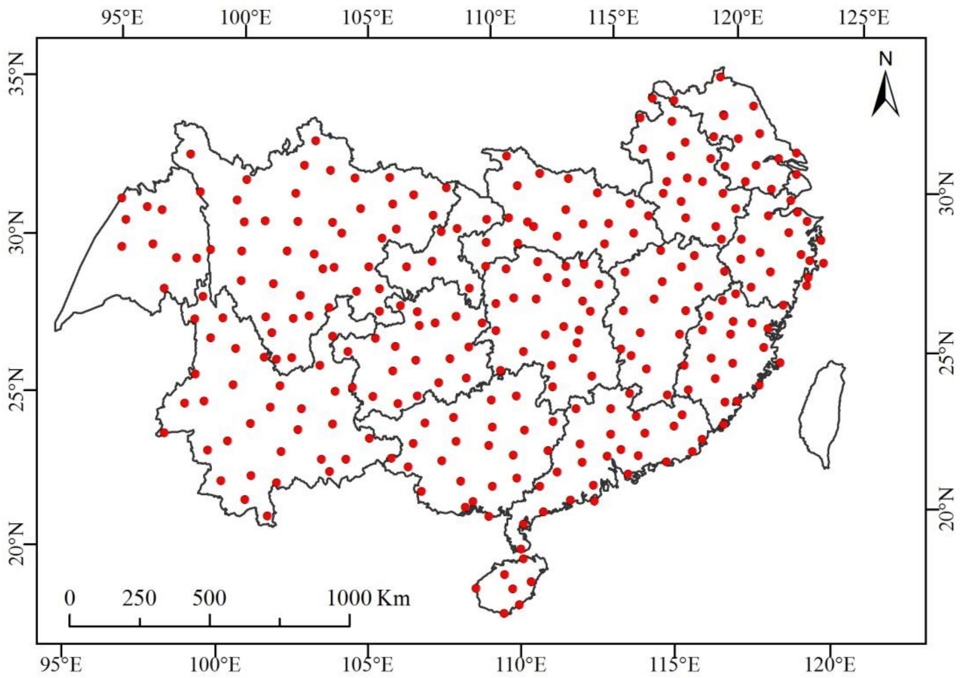

Fig. 2 The distribution map of grasslands of Southern China (the black boundary-lines indicate the provincial boundary; the green zone represents the grassland area, and the colorless region represents the non-grassland of the study area).

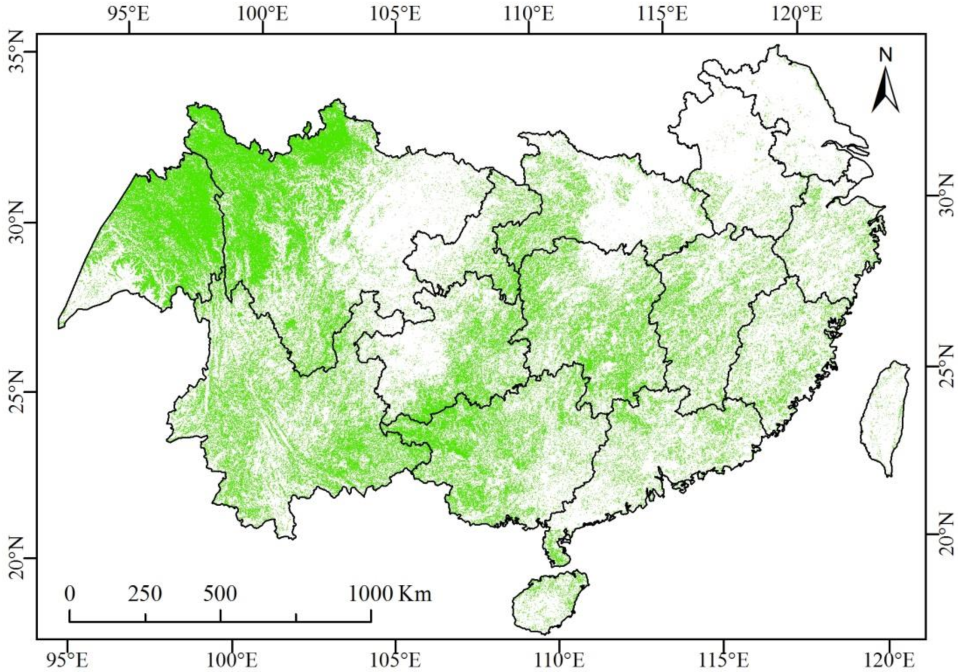

Fig. 3 Comparison between simulated and observed grassland NPP (net primary productivity) of Southern China.

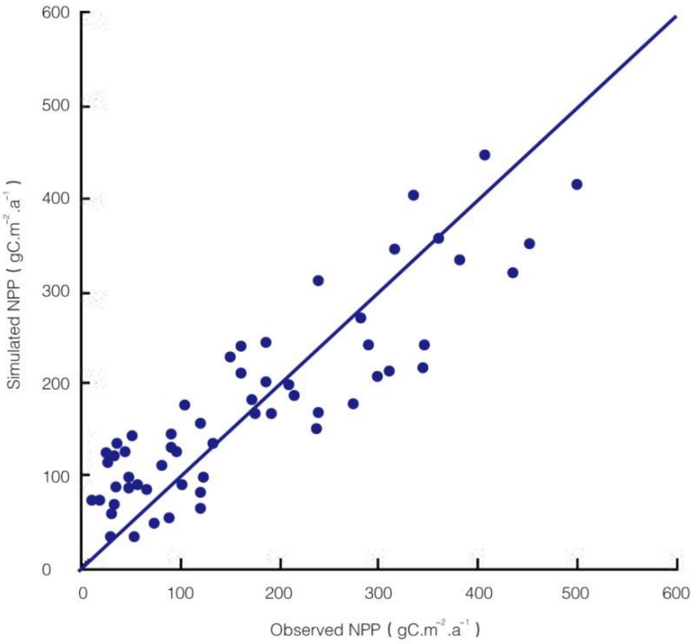

Fig. 4 Spatial characteristics of grassland NPP of Southern China from 2003 to 2014.

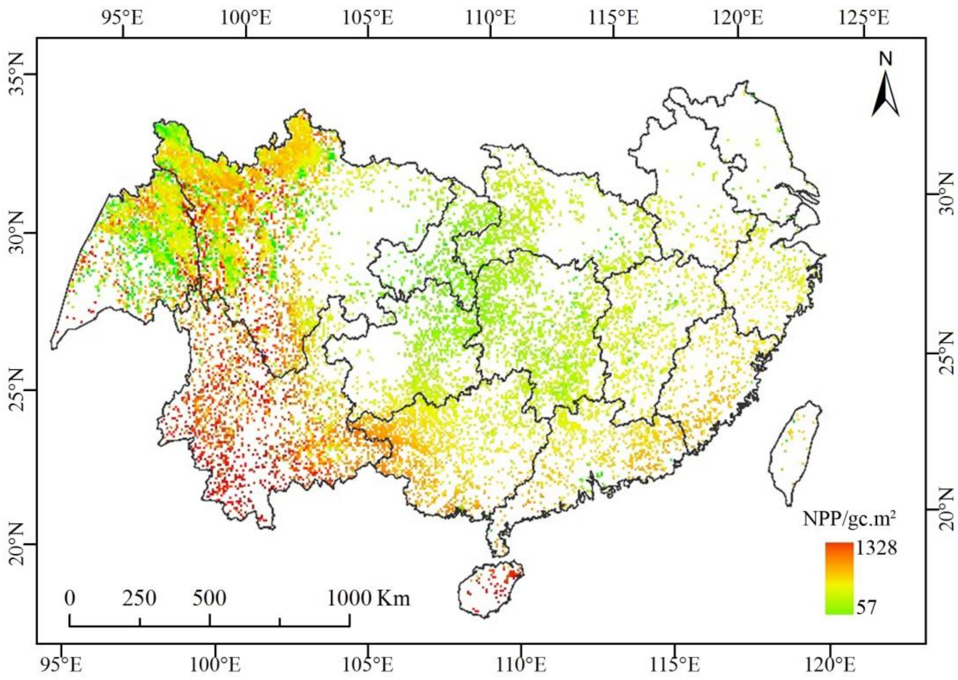

Fig. 5 The inter-annual variation of grassland NPP of Southern China from 2003 to 2014.