Spatio-temporal Variation of Net Primary Productivity of Farmland Ecosystem in Central Yunnan Plateau

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Abstract. Based on MODIS data and CASA (Camegie Ames Stanford Approach) model to estimate the net primary productivity (NPP) of farmland ecosystem in the Central Yunnan Plateau from 1982 to 2019, the spatial autocorrelation method and Sen’s trend analysis were used to analyze the spatial-temporal variation characteristics of farmland NPP and the influence of climate factors for the last 38 years. The results indicated: The annual NPP of farmland varied from 772.43 to 993.72 g C/(m²·a) during 1982-2019, with the total mean value of 897.50 g C/(m²·a), which had the decrease trend during 1982-2000 but showed the increase fluctuation from 2001 to 2019. The total values of NPP tended to stabilize during 1982-2019. As for the spatial distribution, the farmland NPP in the southwest low-altitude areas were relatively high (>1500 g C/(m²·a)), whereas the farmland NPP in the northeast high-altitude regions had the lower values, especially in Kunming and urban in central Yunnan (<200 g C/(m²·a)). From the variation trend, the farmland NPP significantly increased in 31.7% of the agricultural area in the Central Yunnan Plateau, with no obvious change and significant decrease in 37.1% and 31.2%, which was observed for obvious increase tendency in the northeast area. The significant positive relationships were observed for 30.0%, 28.2% and 73.0% of mean pixel NPP with precipitation, temperature and SPEI drought index respectively, which indicated that the farmland ecosystem was largely influenced by drought to a certain extent.

1. Introduction
Net primary productivity (NPP) of vegetation refers to the amount of organic dry matter accumulated by green plants per unit time and area, which represents the production capacity of vegetation communities under natural environment conditions and is an important indicator of vegetation growth state and density distribution. The vegetation NPP not only reflects the quality of terrestrial ecosystem, but it is also a vital factor to regulate ecological process and estimate terrestrial carbon “source / sink” [1]. The NPP of agricultural vegetation represents the ability of farmland ecosystem to immobilize CO2 in the atmosphere through photosynthesis and determines the organic carbon content available in farmland soil, the most active part of global carbon pool [2]. Therefore, the size of farmland carbon pool and its role in global carbon balance have attracted more attention [3-4]. The precise monitoring of spatial and temporal changes in farmland ecosystem NPP in regional scale can provide basic information data for climate change and the assessment of land carbon balance as well as the research of the cultivated land productivity and food security [5].

The rapid development of remote sensing, geographic information science and the theory of plant physiological ecology provide the large scale data and methods with high spatial resolution for
monitoring spatial-temporal changes in long time series of ecosystem productivity at regional and even national scales. NPP estimation models can be divided into three categories [6-9]: climate production potential model, eco-physiological process model and light energy utilization model. Previous studies found that the Camegie Ames Stanford Approach (CASA) model needs less parameters than other remote sensing models and avoids the estimation error caused by artificial simplification due to the lack of parameters. CASA model can obtain the full coverage information of the land surface, and has advantages of the simulation process with easy operation and the high time resolution [10]. Meanwhile, as a representative of the model of light energy utilization, CASA model has been tested in different spatial scales (regional, global) [11] and different ecosystems (grassland, farmland and forest, etc.), which has been verified by field-measured data [12]. Zhu reported that based on CASA estimation of vegetation NPP in the Yellow River Basin from 1992 to 2019, vegetation NPP correlated well with precipitation in the upper and middle reaches of the Yellow River, while no relationship was observed for vegetation NPP with precipitation and temperature in lower reaches. Hou et al found the notable correlation for NPP multi-year variation with temperature and precipitation by simulating the spatial-temporal changes of vegetation NPP in in Hunshandake Sandy Land on the basis of CASA Model [13]. Shi et al reported that based on CASA model and the analysis of the correlation between NPP and drought, the vegetation NPP in 60.5% of Huaihe River Basin exhibited a downward trend according to drought intensity and drought range [14]. The estimation of farmland ecosystem NPP on the basis of CASA model has been studied extensively, but the spatial-temporal distribution characteristics of farmland NPP in the Central Yunnan plateau are still unclear. The Central Yunnan Plateau is the middle region of Yunnan Province and is the highest grain yield, which accounts for 1/3 of the province's annual grain production and is the core area of Yunnan's agricultural economy. Owing to the inland location, the society production and economic activities of the Central Yunnan Plateau depend heavily on the natural environment, leading to the weak ability to bear natural disasters. The Central Yunnan Plateau is a region with high frequency of drought occurrence in China [15-16], which belongs to the sensitive area of climate change and the ecological fragile area in plateau. Based on the long-time series of MODIS data and CASA model, our study investigated the spatial-temporal variation characteristics of farmland NPP in central Yunnan plateau from 1982 to 2019, and explored the influence of climatic factors on the spatial-temporal differences of farmland in this area. The results in this paper will help to understand the spatial-temporal variation characteristics of farmland NPP in the Central Yunnan Plateau, which is important to promote the regional agricultural planning and decision-making, and the rational utilization of agricultural nature resources.

2. Study Area
The Central Yunnan Plateau is the middle region of Yunnan determined by the Central Yunnan Urban Agglomeration Plan (2009 - 2030): Kunming is the core area with a radius of 150 ~ 200 kilometers, including Yuxi, Chuxiong and Qujing. The Central Yunnan Plateau (99° 30′ ~ 104° 14′ E, 23° 12′ ~ 26° 41′ N) belongs to the plateau basin, which is dominated by mountainous land and intermountain basins with gentle topography. The climate of the Central Yunnan Plateau is like spring in the whole year, which has a short winter in northern area and a short summer in southern region. Meanwhile, it’s worth noting that the distinction of dry and wet seasons is also an important feature. The precipitation in the Central Yunnan Plateau is largely concentrated in the rainy season from May to October, especially in the main flood season (June ~ August), which accounts for 40% ~ 60% of the annual total rainfall.

3. Materials and Methods
3.1. Data Sources and Processing
The MOD17A3 NPP datasets at 1 km × 1 km spatial resolution during 2000 - 2009 were downloaded from the NASA website (https://ladsweb.nascom.nasa.gov/data/search. html) Modis Reprojection Tool
(MRT) software was applied to projecting and splicing the NPP data to ensure the matching accuracy with other data. All the data were projected into Albers equal area conic projection.

Monthly meteorological data from 1982 to 2019 were downloaded from the National Meteorological Information Center (http://www.nmic.gov.cn/), including all observation stations (involving national reference stations, basic stations and general climate stations) in central Yunnan. After excluding the stations with discontinuous observation data, the meteorological stations with little change in observation position were chosen to carry out the quality inspection. Finally, the data of 37 stations were selected in this study. According to the data of adjacent stations, multiple regression interpolation was carried out to complement the missing observation data of individual months.

The land-use/land-cover data were obtained from Key Research and Development Program "Formation and Evolution Mechanisms of Southwest Ecological Security Pattern" of the technical research group in Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. The farmland spatial distribution map was extracted from the land use map, then spliced into the vector format of the farmland distribution map, and the vector data was converted into the grid data of the 250 m × 250 m farmland distribution map. Finally, the farmland distribution map is superimposed with the MODIS17A3NPP data and the distribution map of meteorological element to extract the farmland NPP and meteorological data.

3.2. Analysis Methods

3.2.1. Mechanism of CASA Model. The CASA model multiplies the photosynthetically Fraction of Photosynthetically Active Radiation (FPAR) from solar radiation and the Normalized Difference Vegetation Index (NDVI) with the maximum light energy utilization ratio $\varepsilon_{\text{max}}$ from temperature and precipitation to simulate the NPP calculation by using the following equations [17-18]:

\[ NPP(x,t) = \text{APAR}(x,t) \times \varepsilon(x,t) \]  
\[ \text{APAR}(x,t) = \text{SOL}(x,t) \times \text{FPAR}(x,t) \times 0.5 \]  
\[ \text{FPAR}_i = \min\left[ \frac{SR - SR_{\text{min}}}{SR - SR_{\text{max}}} , 0.95 \right] \]  
\[ \text{FPAR}_s = \min\left[ \frac{\text{NDVI} - \text{NDVI}_{\text{min}}}{\text{NDVI} - \text{NDVI}_{\text{max}}} , 0.95 \right] \]  
\[ \text{FPAR} = \frac{\text{FPAR}_i + \text{FPAR}_s}{2} \]  
\[ \text{SR}(x,t) = \frac{1 + \text{NDVI}(x,t)}{1 - \text{NDVI}(x,t)} \]  
\[ \varepsilon(x,t) = T_{\varepsilon_1}(x,t) \times T_{\varepsilon_2}(x,t) \times \omega_2(x,t) \times \varepsilon_{\text{max}} \]
3.2.2. Analysis of Sen trend. The analysis method of Sen trend was used to calculate the variation trend of farmland NPP. The Mann-Kendall statistical test method was applied to testing the significance of farmland NPP variation trend. The calculation equations were as follows [19-20]:

\[
Sen_{slope} = \text{median} \left( \frac{NPP_j - NPP_i}{j - i} \right)
\]

Equation (8)

\(Sen_{slope}\) was the variation trend of NPP. \(i\) and \(j\) were the number of time series. \(NPP_i\) and \(NPP_j\) were NPP at time \(i\) and \(j\). \(Sen_{slope} > 0\) meant that NPP showed an upward trend, whereas \(Sen_{slope} < 0\) indicated a downward trend of NPP.

4. Results and Analysis

4.1. Validation of NPP

The comparative analysis was applied for NPP estimated by CASA model with the MODIS statistics NPP from 2000 – 2019 in the Central Yunnan Plateau (Figure 1), which showed that the farmland NPP obtained from the MODIS statistics was slightly higher than NPP value estimated by the CASA model. Moreover, both have strong positive relationships \((R^2 = 0.71, \ P < 0.01)\). This phenomenon indicated that the farmland NPP estimated by CASA model can accurately reflect the actual situation of farmland ecosystem productivity in the Central Yunnan Plateau. Thus, the NPP data estimated by CASA model was feasible to analyze the spatial-temporal characteristics of farmland productivity in the Central Yunnan Plateau.

![Figure 1. The accuracy comparison of MODIS-NPP and CASA-NPP.](image)

4.2. Temporal Variation Characteristics of Farmland NPP

The total annual NPP of farmland in Central Yunnan Plateau tended to be stable from 1982 to 2019. The annual mean NPP had a downward trend during 1982 – 2000, but fluctuatingly increased from 2001 to 2019 (Figure 2). The annual mean NPP of farmland ranged from 772.43 to 993.72 g C/(m²a), with a total mean value of 897.50 g C/(m²a), which had the maximum value in 1994 and the minimum value in 2001.

4.3. Spatial Distribution Characteristics of Farmland NPP

The spatial distribution of mean farmland NPP in Central Yunnan Plateau from 1982 to 2019 was shown in figure 3. The farmland NPP in most regions in the Central Yunnan Plateau varied from 700 to 900 g C/(m²a), which showed that the NPP value was relatively high in the southwest high-altitude farmland (> 1500 g C/(m²a)). However, the lower farmland NPP was observed in the northeast low-
altitude region, especially in Kunming (< 200 g C/(m²-a)) in the Central Yunnan Urban Agglomeration Area.

The Sen trend of farmland NPP from 1982 to 2019 was calculated and also tested by M-K test method in this study. The results were classified into significant increase ($p < 0.05$), significant decrease ($p < 0.05$) and no significant change (Figure 4), which demonstrated that 31.7% of farmland in Central Yunnan Plateau had a significant increase in NPP, while 37.1% and 31.2% showed no significant change and a significant decrease in NPP. The areas with the significant increase in NPP were concentrated in northern Kunming, northern and northeastern Qujing, whereas the areas with NPP significant decrease were mainly scattered around the cities in central Yunnan.

![Figure 2. Temporal variation trend of farmland NPP during 1982 - 2019.](image_url)

![Figure 3. Spatial distribution characteristics of farmland NPP.](image_url)
4.4. Influence of Climate Factors on Farmland NPP

Nemani reported that due to the large annual precipitation in the south of the Yangtze River, farmland NPP was mainly restricted by solar radiation. But in the north of the Yangtze River and northwest region [21-22], farmland NPP was largely restricted by water conditions [23-24]. To illustrate the effect of climate factors on farmland ecosystems in the Central Yunnan Plateau, the spatial distribution of coefficient map was generated by analyzing the pixel-by-pixel relationships for the mean farmland NPP from 1982 to 2019 with the annual precipitation, temperature and Standardized Precipitation Evapotranspiration Index (SPEI) (Figure 5). The results showed that there was no significant correlation between 49.1% of farmland NPP and the annual mean temperature. 28.2% of farmland NPP had significant positive relationship with annual mean temperature, while 22.7% of farmland NPP negatively correlated with annual temperature. For precipitation, 70.20% of farmland NPP had no significant correlation with annual precipitation, 30.0% showed significant positive correlation and 1.0% showed significant negative correlation. For SPEI, 27.0% of farmland NPP had no significant correlation with SPEI, but the remaining 73.0% of farmland NPP showed significant positive correlation with SPEI. Therefore, the area with significantly positive correlation between the farmland NPP and precipitation was slightly larger than that for the farmland NPP with temperature. But it’s worth noting that farmland NPP positively correlated well with SPEI in most areas. The SPEI reflected the dry and wet condition of the study area by two factors: water deficit (difference between precipitation and potential evapotranspiration) and duration time. Although there was a certain correlation between the NPP value of farmland ecosystem and temperature and precipitation in the Central Yunnan Plateau, most regions are not significant, but the farmland NPP was related to drought strength in most regions. With the increase of drought strength, the NPP decreased.
5. Conclusions
The mean value of farmland NPP in Central Yunnan Plateau from 1982 to 2019 was 897.50 g C/(m²·a). The interannual variation of NPP exhibited a trend of first decrease and then increase. The spatial distribution of farmland NPP is higher in the lower altitude area of southwest, while lower in the higher altitude area of northeast, especially the lowest characteristic in the urban area of central Yunnan. During 1982-2019, the farmland NPP obviously increased in the northeastern mountain agriculture area but significantly decreased near the edge of cities in central Yunnan. The average value of 50% pixel farmland NPP significantly correlated with temperature, and 31.0% pixel farmland NPP significantly correlated with precipitation. 70.0% pixel farmland NPP significantly correlated with drought, which was mainly distributed in the northeastern mountain agriculture area with high altitude. This study found that farmland ecosystem was less affected by temperature and precipitation, and was influenced by drought to a certain extent. Furthermore, the quantification of human factors should be strengthened in the study of influencing factors on farmland ecosystem in the future.

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Figure 5. The correlation analyses for farmland NPP with temperature, precipitation and SPEI.
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