Estimation Terrestrial Net Primary Productivity Based on CASA Model: a Case Study in Minnan Urban Agglomeration, China

L Z Hua\(^1\)\(^*,\) H Liu\(^1\), X L Zhang\(^1\), Y Zheng\(^1\), W Man\(^1\), K Yin\(^2\)

\(^1\)College of Computer and Information Engineering, Xiamen University of Technology, Xiamen 361024, China

\(^2\)Institute of Remote Sensing Applications, Chinese Academy of Sciences, Beijing 100101, China

E-mail: lzhua@xmut.edu.cn

Abstract. Net Primary Productivity (NPP) is a key component of the terrestrial carbon cycle. The research of net primary productivity will help in understanding the amount of carbon fixed by terrestrial vegetation and its influencing factors. Model simulation is considered as a cost-effective and time-efficient method for the estimation of regional and global NPP. In the paper, a terrestrial biosphere model, CASA (Carnegie Ames Stanford Approach), was applied to estimate monthly NPP in Minnan urban agglomeration (i.e. Xiamen, Zhangzhou and Quanzhou cities) of Fujian province, China, in 2009 and 2010, by incorporating satellite observation of SPOT Vegetation NDVI data together with other climatic parameters and landuse map. The model estimates average annual terrestrial NPP of Minnan area as 16.3 million Mg C. NPP decreased from southwest to the northeast. The higher NPP values exceeding 720 gC·m\(^{-2}\)·a\(^{-1}\) showed in North Zhangzhou city and lower values under 500 gC·m\(^{-2}\)·a\(^{-1}\) showed in the some areas of northeast Quanzhou city. Seasonal variations of NPP were large. It was about 45% of the total annual NPP in the three months in summer, and the NPP values were very low in winter. From 2009 to 2010, the value of annual NPP showed a slightly decrease trend, approximately 7.8% because the annual temperature for 2010 decline 13.6% compared with 2009 in despite of an increase in rainfall of about 34.3%. The results indicate that temperature was a main limiting factor on vegetation growth, but water is not a limiting factor in the rainy area.

1. Introduction
Terrestrial vegetation has an important influence on the global carbon balance and the reduction of atmospheric concentrations of greenhouse gases, particularly carbon dioxide. Vegetation net primary productivity (NPP) is defined as the amount of photosynthetically fixed carbon available to the first heterotrophic level in an ecosystem, and the difference among autotrophic photosynthesis and its respiration\(^1\). As a key component of the terrestrial carbon cycle, the alteration of NPP greatly influences the global carbon cycle and global climate\(^2\). The study on NPP and its response to global change have been attracted attention in the scientific community. International Geographical and Biological Plan (IGBP), Global Change and Terrestrial Ecosystems (GCTE) and Kyoto Protocol have taken NPP as one of the key research areas\(^4\).
NPP models are considered as a cost-effective method for estimating vegetation NPP in the regional and global scales where NPP is difficult to measure directly. There are three kinds of NPP models including statistical model, parameter model and process-based model. The statistical models, e.g. Miami model and Montreal model, are lack of the vegetation eco-physiological basis because they calculate NPP by a simple relationship between vegetation and climate factors. The process-based model is driven by a multi-layer database of climate, soil and vegetation types[3]. With the increasing application of remote sensing data, process-based models based on remote sensing data provide a new and potentially promising method for the global and regional NPP estimation[4-5]. In the recent years, a number of process-based NPP models have been developed in the recent years to widely estimate the large scale vegetation NPP and explore effect of climate change on NPP[6-7]. CASA (Carnegie-Ames-Stanford Approach) model is an excellent process-based model to estimate the land plant NPP based on the plant growing mechanism[8].

The objectives of this paper aim to estimate the vegetation NPP in Minnan urban agglomeration of China using the satellite-based images combined with CASA model, evaluate its spatial-temporal distribution and assess the influence of climate factors on NPP in 2009 and 2010.

2. Materials and methods

2.1. Study area description
The study area is the Minnan urban agglomeration (116°89′ to 119°01′E, 23°58′ to 25°94′N), which is located in southeast Fujian province, China (Figure 1). The area consists of Xiamen, Zhangzhou and Quanzhou Cities and is also called with “South Fujian Golden Triangle” for its fast economic development. By 2012, the GDP of the area reaches RMB 0.95 trillion which accounts for 48.2% of the Fujian’s GDP. At the same time, the population of the area total 1.67 million which accounts for 44.8% of the Fujian’s population. It is expected to realize “Xia-Zhang-Quan” urban integration by 2020, according to the General Plan for Urban Integration Promotion among the cities. The entire area has an area of about 25,000 km². The terrain is undulating, ranging from 1 m to 1,856 m above sea-level. The area has a subtropical marine monsoon climate, with annual average temperatures of around 20°C. Annual rainfall ranges from 1,100 mm in the coastal areas to 2,000 mm in the high mountain areas. In summer the area is threatened by typhoons that bring rainstorm.

2.2. CASA model description
In CASA model, NPP (gC/ m²) is calculated as a function of photosynthetically active radiation absorbed by vegetation (APAR, MJ/m²) and actual light-use efficiency (ε).
\[ NPP(x,t) = \text{APAR}(x,t) \times \epsilon(x,t) \]  

(1)

where \( x \) is a pixel in a remote sensing image, and \( t \) is the time, such as a month. \( \text{APAR} \) and \( \epsilon \) can be obtained by the following formulas:

\[ \text{APAR}(x,t) = \text{FPAR}(x,t) \times \text{SOL}(x,t) \times 0.5 \]  

(2)

\[ \epsilon(x,t) = f_{\text{temp}}(x,t) \times f_{\text{water}}(x,t) \times \epsilon_{\text{max}} \]  

(3)

where the \( \text{SOL} \) is the total solar radiation (MJ/m\(^2\)) for each individual pix; \( \text{FPAR} \) is the fraction of absorbed photosynthetically active radiation, \( \epsilon_{\text{max}} \) is the maximum light-use efficiency variable (gC/MJ), and \( f_{\text{temp}} \) and \( f_{\text{water}} \) are the influences of temperature, moisture on light use efficiency of vegetation, respectively. The values of \( \epsilon_{\text{max}} \) were selected based on the literature \[5\]. Further details on the theoretical background of CASA model can be found in the literatures \[5-6\].

2.3. Data acquisition and processing

SPOT Vegetation Normalized Difference Vegetation Index (NDVI) data were obtained from Environmental & Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn) with 1-km spatial resolution and 10-day temporal resolution in 2009 and 2010. Monthly NDVI data were estimated by maximum value composite (MVC) method.

The meteorological data from 16 weather stations in 2009 and 2010 in the area were acquired from China Meteorological Administration (CMA), including monthly precipitation and the hours of sunlight, monthly mean temperature, and the percentage of sunshine. The monthly solar radiation data were calculated from the monthly hours of sunlight and the percentage of sunshine by the Angstrom-Prescott equation \[9\].

The climate data were interpolated at the same scale with remote sensing data using Kringing method based on DEM. The land cover map in 2000 with a spatial resolution of 1 km was provided by the Joint Research Centre (JRC), which was compiled by the Institute of Remote Sensing Application, Chinese Academy of Science.

All the above data were rectified to the UTM projection system (Zone N50), and were resampled to 1-km resolution.

3. Results and discussion

3.1. Spatial changes of NPP

With the data set and functions described above, NPP and its distribution in Minnan urban agglomeration was estimated (Figure 2). The mean NPP of the study area is 652.5 gC m\(^{-2}\) yr\(^{-1}\), which is consistent with the value (578.97 gC m\(^{-2}\) yr\(^{-1}\)) for Fujian province estimated by Jiang et al \[10\]. The total average annual NPP is 16.3 million Mg C. The NPP value in 2010 has a decline of 7.8% over 2009. Annual rainfall increases by 34.3% from 1,143 mm to 1,531.1 mm than that in 2009 and has the similar solar radiation while annual mean temperature decreases by 13.6% than that in 2009. It indicates that low temperature causes the NPP loss in 2010.

The gradient distribution of NPP in the area is distinct because of the different constraints from temperature and solar radiation. It shows a decreasing trend from the southwest to northeast of Minnan area, which was consistent with climate and vegetation distribution. The higher NPP values (above 720 gC m\(^{-2}\) yr\(^{-1}\)) occur in the north area of Zhangzhou city, e.g., Huan’an and Nanjing counties, which are covered by are a large number of broadleaved and needleleaved evergreen forests with optimum temperature and higher solar radiation. The lower NPP values (less than 500 gC m\(^{-2}\) yr\(^{-1}\)) occur in the northeast of Quanzhou city, e.g., Dehan and Yongcun counties, which are mainly covered by needleleaved evergreen forests with lower temperature, solar radiation and higher altitude.
3.2. Temporal change of NPP

Figure 3 shows seasonal variations of NPP of the area. The maximum value occurs in July and August when vegetation grows vigorously due to higher monthly solar radiation, optimum temperature and greater precipitation than other months. We can define June, July and August as summer, and December, January and February as winter. In summer, the total NPP value reaches 308.2 gC·m⁻²·month⁻¹ accounting for 45.4% of the NPP in 2009 while the value is 222.9 gC·m⁻²·month⁻¹ for 35.6% of that in 2010. In winter, the total NPP value are only 51.6 and 61.6 gC·m⁻²·month⁻¹ in 2009 and 2010 accounting 7.6% and 9.8% of the each yearly NPP, respectively. Because the temperature and solar radiation are the lowest in winter and vegetation growth is limited. It can also be found that the NPP value in June 2010 is much lower than that in June 2009. Compared with June, 2009, the temperature (23.5°C) for 2010 decreases by 14.9% (Figure 3), while the values of solar radiation and rainfall increase by 6.32% and decline 0.26%, respectively. This indicates low temperature greatly influences on vegetation growth.

3.3. Effect of climate factors on NPP

To some extent, the vegetation yield in some region mainly depends on light, heat and water.
Therefore, the quantitative correlations between climate factors and NPP are a continual focus of scientific research\cite{11}. Figure 4 shows that the correlation ($R^2$ of 0.84 and 0.86 for 2009 and 2010) between the NPP and the temperature is the strongest within all the seasonal variations. The correlation between the NPP and the solar radiation is also strong, but less than that between the NPP and the temperature. The correlation between the NPP and the rainfall is very low, indicating rainfall has a weaker impact on vegetative growth.

![Figure 4](image-url)  
*Figure 4. Comparison of monthly NPP and climate factors: (a) monthly rainfall in 2009; (b) monthly rainfall in 2010; (c) monthly solar radiation in 2009; (d) monthly solar radiation in 2010; (e) monthly mean temperature in 2009; (f) monthly mean temperature in 2010.*

### 4. Summary and conclusion

In this study, integrated with SPOT Vegetation NDVI, temperature, rainfall and solar radiation data, CASA model was used to estimate the NPP in Minnan urban agglomeration in Fujian province of China, in 2009 and 2010.

The mean annual NPP value in the area is 652.5 gC m$^{-2}$ yr$^{-1}$. Regions with higher NPP values were found in the north of Zhangzhou city, whereas smaller NPP values were found in the northeast of Quanzhou city. The seasonal vegetation NPP shows that the area with the largest NPP increase is in summer, accounting for 45% of total study area, while the lowest NPP increase is in winter, only accounting for less than 10%. The NPP remarkably declined in June, 2010 when the NPP is very high.
under usual conditions. The main reason may be that the temperature in June, 2010 is much lower than that in other years. The analysis between the relationship NPP and climate factors demonstrates that temperature is highly correlated with vegetation NPP, and solar radiation follows, but rainfall is an exception, which indicates temperature is a main factor limiting growth of vegetation in the area. The results also imply that water is not a main limiting factor on vegetation growth in this region with enough rainfall.

5. Acknowledgement
This work was financed jointly by the Natural Science Foundation of Fujian Province (2013J01165) and Education Department of Fujian Province (JA10253, JA09219) and National Undergraduate Training Programs for Innovation and Entrepreneurship (201311062014), China. We thank Dr. Lihui for language correction and improvement. We are also grateful to the Environmental & Ecological Science Data Center for West China for the remote sensing data, the China Meteorological Administration for meteorological data and Joint Research Centre (JRC) for the Chinese land cover map in this study.

References
[1] Field C B, Behrenfeld M J, Randerson J T and Falkowski P 1998 Primary production of the biosphere: integrating terrestrial and oceanic components Science 281 237-240
[2] Fang J, Piao S, Tang Z, Peng C and Ji W 2001 Interannual variability in net primary productivity and precipitation Science 293 1723
[3] Churkina G, Tenhunen J, Thornton P, Falge E, Elbers J A, Erhard M, Grunwald T, Kowalski A, Rannik U and Sprinz D 2003 Analyzing the ecosystem carbon dynamics of four European coniferous forest using a biogeochemistry model Ecosystems 6 168-184
[4] Arindam S, Marcos H C, Edson L N, Simone A V, Liang X and Ranga B M 2011 Comment on “Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009” Science 333 (6046) 1093
[5] Zhu W Q, Pan Y Z, He H, Yu D Y and Hu H B 2006 Simulation of maximum light use efficiency for some typical vegetation types in China Chin. Sci. Bull. 51(4) 457-463
[6] Nemani R R, Keeling C D, Hashimoto H, Jolly M, Running S W., Piper S C, Tucker C J and Myneni R 2003. Climate driven increases in terrestrial net primary production from 1982 to 1999. Science 300 1560-1563.
[7] Zhaor M. and Running S W 2010 Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science. 329 940-943.
[8] Potter C S, Randerson J T, and Field C B 1993 Terrestrial ecosystem production: a process model based on global satellite and surface data Global Biochem. Cy. 7 811-841
[9] Prescott J A 1940 Evaporation for a water surface in relation to solar radiation Trans. Roy. Soc. Aust. 64 125-134
[10] Jiang H, Wang X Q, Sun W J 2010 Simulation by Remote Sensing and Temporal-spatial Analysis of Forest Ecosystem Net Primary Productivity in Fujian Province China Environ. Earth Sci. 59 1337-1347