

The analysis of net primary productivity in China based on GEOLUE model

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Abstract

GEOLUE model was designed with Light Use Efficiency (LUE) mechanism and was validated with observed data and models comparison (GLOPEM, CASA, and CEVSA). We found that: GEOLUE model correctly simulates monthly, quarterly and annual variation of Net Primary Product (NPP) in different vegetation communities under monsoon climate. The spatial distribution of NPP simulated by GEOLUE matched up to 96.67% with that of forest and shrub land. The GEOLUE model perfectly simulated the seasonal characteristics and spatial pattern of biomass in different types of vegetation. The total amount NPP of China simulated by GEOLUE is 0.667GtC in spring, 1.365GtC in summer, 0.587GtC in autumn and 0.221GtC in winter. The average total NPP of China for 5 years is 2.84GtC / year.

Keywords: China, model of Light Use Efficiency, Net Primary Product (NPP), Simulation

1. INTRODUCTION

The study of carbon cycle in terrestrial ecosystem is an important component in global change research, this study is the key scientific issues in predicting content of CO₂ and greenhouse gases in atmosphere, understanding the interaction between the atmosphere and the biosphere et al. And also this study is the basis to understand the water cycle, nutrient cycling and biodiversity changes in earth's ecosystem. Therefore, the function and evaluation of carbon sink / source in terrestrial ecosystem are the focus issues of negotiations in "United Nations Framework Convention on Climate Change," and the "Kyoto Protocol" for many years. The study of Net Primary Productivity (NPP) is an important component of the carbon cycle research in terrestrial ecosystem, especially this study has played an important role in the study of global biomass and the crop yield estimation, it is hot issue to study NPP in Global Change and in ecology from International Biological Programme (IBP) to International Geosphere-Biosphere Programme (IGBP)^[1].

The model of light use efficiency (LUE) with the energy balance mechanism estimates NPP using parameters of the Photosynthetic Active Radiation (PAR) absorbed by vegetation canopy, LUE (ϵ) and others environmental control factors. Monteith et al. first proposed to estimate NPP with PAR and LUE (ϵ) [2], whose expression is: $NPP = \epsilon \times PAR$, the LUE is the ratio between the chemical potential energy contained in dry matter per unit area and PAR in per unit area at same time. Ruimy et al. published paper about global NPP model based on PAR considered the variability of LUE(ϵ), the different ecosystems are allocated with different ϵ values [3]. The model of LUE to estimate NPP has concise principles and needs limited parameters and some parameters (such as PAR and FPAR : Fraction of PAR) can be retrieved by remote sensing, so this model is widely used in calculation of NPP and estimation of crop yield.

GLO-PEM (Global Production Efficiency Model) is light use efficiency model combined the

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ecological process of photosynthesis and autotrophic respiration mechanism mainly driven with the remote sensing data , this model has been used in estimation global NPP with long time and high-resolution[4 ~ 10]. CASA (The Carnegie Ames Stanford Approach) model is the first model to use concept of LUE to apply to global-scale studies of vegetation productivity [11]. Over the past 10 years, many Chinese researchers studied the change of NPP with LUE model. Sun et al. estimated the total NPP in 1992 as 2.645GtC / year for whole country with LUE model [12 ~ 13], and Piao et al. estimated the total NPP in 1997 as 1.95GtC / year for whole country with CASA model [14].

According to China's actual situation and parameters localized, GEOLUE model in this paper was designed based on LUE theory to estimate NPP with PAR and environmental control factors. Based on GEOLUE model validation with observational data and models compared, using the China NPP data simulated with GEOLUE in 4km of spatial resolution and 10-day of temporal resolution for 5 years, the spatial patterns of NPP for whole country are analyzed. This study will provide the supports and suggestions in data and principles to crop yield estimation by remote sensing and carbon cycle researches, and this work will provide references for calculation NPP of China and China's carbon negotiations on the Kyoto Protocol.

2. METHODOLOGY

2.1 Data Description

In this study, the climate data derived from National Meteorological Bureau of China included: daily precipitation, daily temperature, daily pressure, daily sunshine, daily relative humidity and daily wind speed. The raster dataset of 10-day weather for five years in 4km spatial resolution was generated by interpolated with IDW command of GRID module in ARC/INFO calibrated by DEM with sites climate data.

The land use data derived from the remote sensing database in resources and environment, Chinese Academy of Sciences, the vector data of 1:100000 was processed into the fraction data of 1km spatial resolution and generated 1km grid database of land use / land cover(LULC). The elevation data derived from dataset in 1:250000 of National Mapping Bureau. The soil data derived from the dataset in 1:4000000.

In this paper, the MODIS data was ordered from EROS Data Center (EDC), the MODIS data covered China is the MOD15 (leaf area index & FPAR) product in 1km of spatial resolution and 16-day time resolution from 2000 to 2005.

2.2 Light use efficiency model

The Light use efficiency model estimates NPP with solar radiation absorbed by vegetation and environmental control factors based on the solar energy utilization efficiency mechanism, the calculation of NPP can be expressed as:

$$NPP = \sum_t [FPAR_t \times PAR_t \times \varepsilon_g \times (1 - R)] \quad (1)$$

Where: $FPAR_t$ (Fraction of PAR) is PAR proportion absorbed by vegetation; PAR_t is Photosynthetically Active Radiation in t time; ε_g is rate of PAR absorbed by vegetation conversion into organic matter, or the use efficiency of PAR, ε_g is affected by temperature, moisture, and the seasons of leaves growing. R is coefficient of autotrophic respiration. ε_g can be expressed as following:

$$\varepsilon_g = \varepsilon \times \varepsilon_0 = \varepsilon_T \times \varepsilon_V \times \varepsilon_W \times \varepsilon_0 \quad (2)$$

Where: ε is environmental stress factor; ε_0 is the maximum of LUE; ε_T is the factor of air temperature impact on plant growth; ε_V is the factor of the vapor pressure deficit (VPD) impact on plant growth; ε_W is the factor of water stress impact on plant growth.

3. MODEL SIMULATION

GEOLUE model is designed with C language running in line as spatial unit and in day as time unit, this model can simulate in different spatial scale for long time. This model includes of projection

module, energy transmission module, water evaporation module, photosynthetic efficiency module, moisture factor module, climatic factor module, soil factor module and data input and output module. The GEOLUE simulated in 4km of spatial resolution and in 10 days of time step length from 2000 to 2004, the input parameters included of land cover, elevation, slope, aspect, fraction of soil texture, the maximum temperature and minimum temperature in ten days, percentage of sunshine in ten days, precipitation in ten days, vapor pressure in ten days, the fraction of PAR in ten days (from MODIS data) and so on.

This paper made compare using simulation results of GLOPEM, CASA and CEVSA with GEOLUE. The CASA model is LUE model designed by Carnegie Institution of Washington Department of Global Ecology[11]. GLOPEM is LUE model driven by entirely remote sensing data, the GLOPEM simulation NPP data in this paper derived from Website of (<http://glcf.umiacs.umd.edu/data/GLOPEM/>) [8 ~ 14]. The CEVSA simulation NPP data covered China is in 10km of spatial resolution and 10day of time step length from 1980 to 2000^[15-21].

The Comparison of models (see below) shows that GEOLUE model correctly simulates monthly, quarterly and annual spatial and temporal variation of different vegetation communities under monsoon climate. The spatial distribution of NPP simulated by GEOLUE matched up to 96.67% with that of forest and shrub land. The GEOLUE model perfectly simulated the seasonal characteristics and spatial pattern of biomass in different types of vegetation.

4. RESULTS ANALYSIS

In this paper, using the NPP data by GEOLUE simulated in 4km of spatial resolution and 10-day time step length, combine the NPP data simulated with CASA, GLOPEM and CEVSA, the spatial and temporal variation and features of NPP in China are analyzed. And at same time, the simulation results of GEOLUE are validated by compared with the three models (CASA, GLOPEM and CEVSA) recognized by many scientists. Last, the seasonal and annual change and spatial pattern characteristics of NPP in China are analyzed.

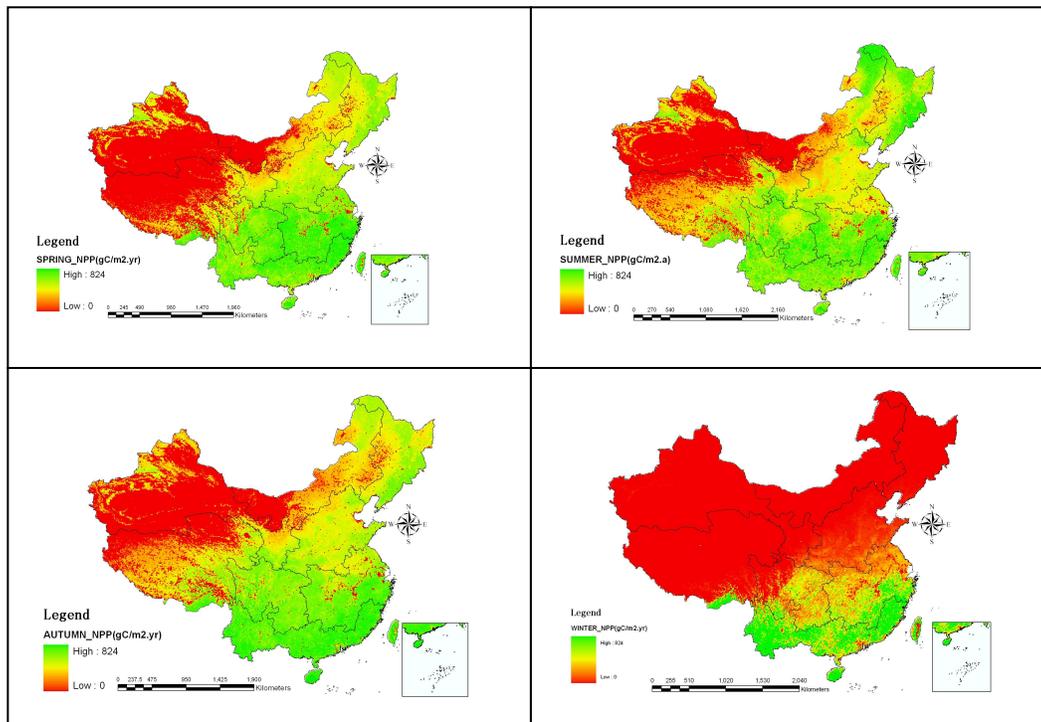


Figure 1. The spatial distribution maps of NPP simulated by GEOLUE in four seasons

4.1 The seasonal variation of NPP simulated by GEOLUE

The seasons NPP data was calculated based on the monthly NPP data simulated by GEOLUE for many years, the changes of NPP for four seasons (spring, summer, autumn and winter) were analyzed.

As Table 1 and Figure 1, the national average density of NPP and total amount of NPP simulated by GEOLUE are 29.2 gC/m² and 0.667GtC in Spring, 49.3 gC/m² and 1.365GtC in Summer, 24.0 gC/m² and 0.587GtC in Autumn and 9.4 gC/m² and 0.221GtC in Winter. The NPP seasonal changes are consistent with the seasonal variation of China's climate.

Figure 1 shows that the distribution of NPP by GEOLUE simulated in China gradually decreases from south to north in spring. The areas with NPP between 276-693gC/m² mainly distribute in humid subtropical and tropical regions where locate in south of the Qinling mountain and Haihe River. The areas with NPP between 50-275gC/m² mainly distribute in humid temperate and northern temperate regions covered with farmland and forest land where locate in north China plain, Changbai Mountains and Xing'an Mountains. The areas with NPP between 10-50gC/m² mainly distribute in semi-arid and semi-moist regions where located in the Loess Plateau and north-eastern plains. The areas with NPP less than 10gC/m² mainly distribute in semi-arid regions where located in central plateau of Inner Mongolia, eastern Qinghai-Tibet Plateau and Xinjiang Tarim Basin and Junggar basins. The areas with NPP equal 0 distribute in arid regions where locate in western Qinghai-Tibet Plateau, Xinjiang's Tarim and Junggar basins.

The distribution of NPP simulated by GEOLUE is bigger in north China and south China, smaller in Middle China, bigger in east China and smaller in west China in Summer. The areas with NPP between 236-824gC/m² mainly distribute in regions of south of Qinling Mountain and Haihe River (humid subtropical and tropical regions) and Xing'an mountains and the Changbai Mountain. The areas with NPP between 65-235gC/m² mainly distribute in North China Plain, Northeast China Plain, Sichuan Basin, the Loess Plateau, Inner Mongolia, and eastern part of Qinghai-Tibet Plateau and southern and northern of Tianshan Mountains. The areas with NPP less than 65gC/m² mainly distribute in the central Inner Mongolia Plateau, western part of Qinghai-Tibet Plateau, the around of Xinjiang's Tarim and Junggar basins. The areas with NPP equal 0 mainly distribute in the part of Inner Mongolia Plateau, part of Qinghai-Tibet Plateau, Xinjiang Tarim Basin, and Junggar basins.

Table 1. The average seasonal total amount (GtC/season) and density (gC/m²) of NPP in China.

Season	cevs		casa		glopem		geolue	
	Amount	Density	Amount	Density	Amount	Density	Amount	Density
Spring	0.698	34.7	0.525	20.7	0.457	18.0	0.667	29.2
Summer	1.914	95.2	1.557	61.2	1.652	64.9	1.365	49.3
Autumn	0.638	31.7	0.574	22.6	0.744	29.2	0.587	24.0
Winter	0.091	4.5	0.090	3.6	0.120	4.7	0.221	9.4
Total	3.341	166.2	2.746	108.2	2.973	116.8	2.840	111.9

The distribution of NPP simulated by GEOLUE decrease from south to north, it is bigger in east China and smaller in west China in Autumn. The areas with NPP between 215-682gC/m² mainly distribute in subtropical and tropical regions where located in south of Nanling mountains. The areas with NPP between 85-214gC/m² mainly distribute in regions between North of Nanling mountain and south of Qinling Mountain and Changbaishan Mountains, The areas with NPP between 23-84gC/m² mainly distribute in plains of east China, Huangtu Plateau and Daxing and Xiaoxing'anling Mountains and Tianshan Mountain. The areas with NPP less than 22gC/m² mainly distribute in the eastern part of Inner Mongolia Plateau, western part of Qinghai-Tibet Plateau and northeastern plains. The areas with NPP equal 0 mainly distribute in the part of Inner Mongolia Plateau, part of Qinghai-Tibet Plateau, Xinjiang Tarim Basin, and Junggar basins where are arid regions covered with the Gobi and desert vegetation.

The distribution of NPP simulated by GEOLUE located in south of Qinling Mountains and Huaihe River in winter. Since the temperature is lower in winter to limit the biomass distributed in North China

Plain and the Loess Plateau. The areas with NPP between 107-554gC/m² mainly distribute in subtropical and tropical regions where locate in south of Nanling mountains. The areas with NPP between 35-106gC/m² mainly distribute in regions between the north of Qinling Mountains and south of Nanling mountains, The areas with NPP less than 35gC/m² is mainly distributed in North China Plain and the Loess Plateau.

Can be seen from the above analysis, the seasonal distribution of NPP simulated by GEOLUE in China is coincident with spatial distribution pattern of vegetation and seasons growth pattern and rhythm of vegetation under monsoon climate.

Compared with the other three models (CASA, GLOPEM and CEVSA), the average NPP density and total amount simulated by GEOLUE in Spring are 29.2gC/m² and 0.667GtC / spring, they are similar to that simulated with CEVSA (34.4gC/m², 0.698GtC / Spring); the average NPP total amount simulated by CASA and GLOPEM in Spring are 0.525GtC/spring and 0.457GtC/ spring. The NPP total amount simulated by GEOLUE is between that simulated by CASA and GLOPEM. The average NPP density and total amount simulated by GEOLUE in summer are 49.3gC/m² and 1.365GtC / summer, they are closer that simulated with CASA. The average NPP density and total amount simulated by GEOLUE in Autumn are 24 gC/m² and 0.587GtC / autumn, they are near with that simulated with CASA. The average NPP density and total amount simulated by GEOLUE in Autumn are 9.4 gC/m² and 0.221GtC / winter, they are large than that simulated with others three models.

Can be seen from above analysis, the NPP simulated with GEOLUE is too big in winter than that simulated by others three models, and too small in summer than that simulated by others three models, and are similar in spring and autumn to that simulated by others three models.

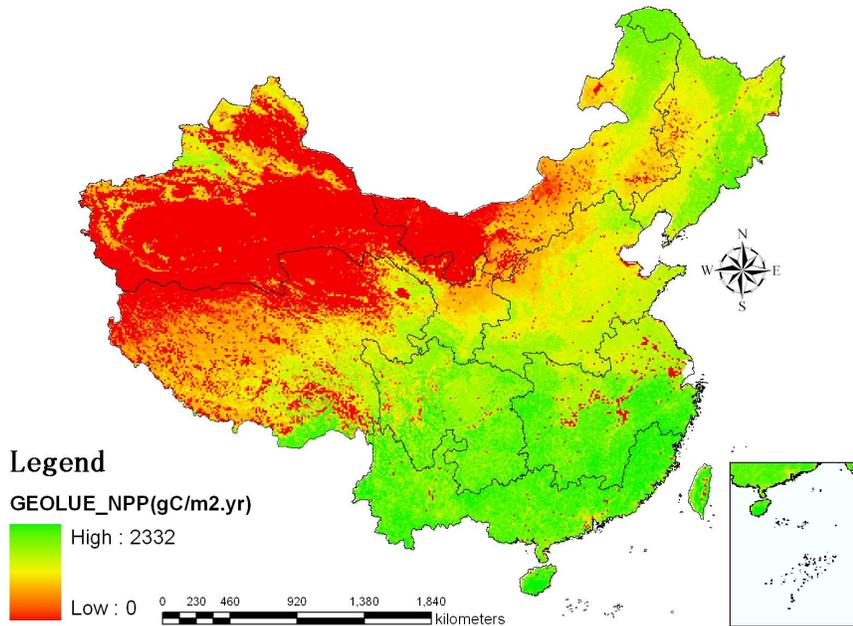


Figure 2. The spatial distribution map of NPP simulated by GEOLUE in 2000

4.2 Annual variation of NPP simulated by GEOLUE

From Table 1 shows that average national density and total amount of NPP in China for many years are 111.9gC/m² and 2.84GtC / year, the minimum total amount of NPP is 2.72GtC/year which appeared in 2003, the maximum total amount of NPP is 3.04GtC /year which occurred in 2003.

Can be seen from Figure 2, the distribution patterns of annual NPP value simulated by GEOLUE are too big in south China and north China, too small in middle China, too big in east China and too small in west China. The areas with annual NPP value more than 900gC/m² are mainly distributed subtropical and tropical regions where locate in south of Nanling mountains. The areas with annual NPP value between

the 470-900gC/m² are mainly distributed regions between the north of Nanling mountains and south of Qinling Mountains and Da Xiaoxing Anling Mountains and Changbai Mountains. The areas with annual NPP value between the 100-470gC/m² are mainly distributed in regions of the North China Plain, Loess Plateau, Northeast China Plain covered farmland and regions of semi-arid and sub-humid covered grassland where locate east part of Inner Mongolia Plateau and east part of Qinghai-Tibet Plateau. The areas with annual NPP value less than 100gC/m² are mainly distributed in regions of central part of Inner Mongolia Plateau, central and western part of Qinghai-Tibet Plateau, peripheral part of Xinjiang Tarim and Junggar basins. The areas with annual NPP value is zero are mainly distributed in the Gobi and desert regions. The spatial distribution pattern of annual NPP in China is consistent with that of vegetation cover.

The annual NPP value in China simulated by GEOLUE compared with that simulated by others three models (CASA, GLOPEM and CEVSA), the density and total amount of annual NPP value simulated with CEVSA are 166.2gC/m² and 3.341GtC/year, the density and total amount of annual NPP value simulated with GLOPEM are 116.8gC/m² and 2.973GtC/year, the density and total amount of annual NPP value simulated with CASA are 108.2gC/m² and 2.746GtC/year, the annual NPP value simulated with GEOLUE (density: 111.9gC/m², total amount: 2.84GtC/year) is between that simulated by CASA and that simulated by CEVSA, and is closer to that simulated by GLOPEM. Based on the annual total amount NPP simulated by each model, the annual average total amount NPP (four models) in China is 2.97GtC/year.

4.3 The spatial variation of NPP simulated GEOLUE

Also refer to the boundaries of natural comprehensive zoning, China is divided into eight major regions in accordance with provincial boundaries: Inner Mongolia (Inner Mongolia), Northeast China (Heilongjiang, Jilin, Liaoning), North China (Beijing, Tianjin, Shandong, Shanxi, Shaanxi, Henan), Central China (Shanghai, Jiangsu, Anhui, Hubei, Hunan, Jiangxi, Zhejiang), South China (Fujian, Guangdong, Guangxi, Hainan, Taiwan, Yunnan), Southwest China (Sichuan, Chongqing, Guizhou), Qinghai-Tibet (Qinghai, Tibet), Northwest China (Xinjiang, Gansu, Ningxia). Because the spatial distribution of NPP is directly related to that of China's land cover (woodland, grassland and farmland), the spatial distribution of Land cover is also basically consistent with that of NPP in China. We analyzed the relationship between NPP spatial distribution of NPP simulated by four models and that of land cover with the resources and environmental database, Chinese Academy of Sciences in 2000. The woodland with high NPP values is mainly distributed in south China, southwest China and northeast China, The farmland with lower NPP is mainly distributed in the north China, northeast China and southwest China, the grassland with relatively lower NPP is mainly distribute in arid and semi-arid regions where locate in Inner Mongolia, Qinghai-Tibet Plateau and northwestern China. The unused land with small or even 0 value of NPP is mainly distributed in the Northwest China and the Qinghai-Tibet Plateau;

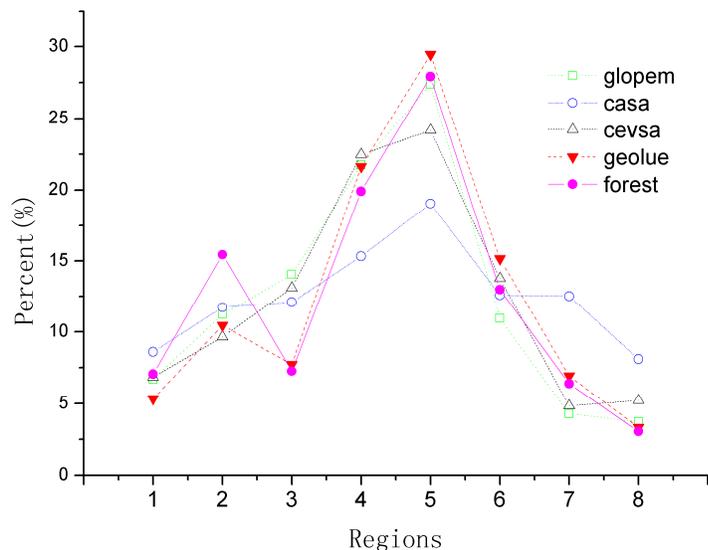


Figure 3 Scatter Plot of regional percent of NPP simulated by models and woodland in China (1 : Inner Mongolia , 2 : Northeast China , 3 : North China , 4 : Central China , 5 : South China , 6 : Southwest China , 7 : Qinghai-Tibet , 8 : Northwest China)

Because there is close relation between NPP value and distribution of woodland, in order to study the degree of agreement between NPP simulated by models and distribution of vegetation cover. The correlation is analyzed between the proportion of NPP in the eight regions accounted for the country's total NPP and the proportion of woodland area in eight regions accounted for the country's total woodland area.

Except the CEVSA model and CASA model, there is good agreement between distribution of NPP simulated by GEOLUE and GLOPEM and distribution of woodland. The correlation coefficients between proportion of NPP simulated by models in the eight regions and proportion of woodland in eight regions were calculated as follows: the degree of agreement of spatial distribution of NPP simulated by GEOLUE and spatial distribution of woodland is up to 96.67%, The degree of agreement of spatial distribution of NPP simulated by GLOPEM and spatial distribution of woodland is up to 92.18%, The degree of agreement of spatial distribution of NPP simulated by CASA and spatial distribution of woodland is up to 90.22%, The degree of agreement of spatial distribution of NPP simulated by CEVSA and spatial distribution of woodland is up to 89.57%.

Can be seen from the above analysis, the degree of agreement between distribution of NPP simulated LUE models (GEOLUE , GLOPEM and CASA) and distribution of woodland is better than that between NPP simulated by ecological process model (CEVSA) and distribution of woodland in China. The average degree of agreement (correlation coefficients) between distribution of NPP simulated by models (GEOLUE, GLOPEM, CASA and CEVSA) and distribution of woodland is 94.54%. The distribution of NPP simulated by models (GEOLUE,GLOPEM, CASA and CEVSA) in China is consistent with spatial distribution of woodland (Forestland and shrub land).

5. CONCLUSION

The GEOLUE model was designed with Light Use Efficiency mechanism and was validated with observed data and models comparison (GLOPEM, CASA, and CEVSA). We simulated NPP in China for

5 years and the NPP is agreement with the temporal and spatial characteristics of vegetation communities and regional variation. The conclusions are following:

GEOLUE model correctly simulates monthly, quarterly and annual spatial and temporal variation of different vegetation communities under monsoon climate. The GEOLUE model perfectly simulated the seasonal characteristics and spatial pattern of biomass in different types of vegetation.

Compare the NPP simulated by GLOPEM, CASA and CEVSA, the NPP simulated by GEOLUE is bigger in winter, smaller in summer and is close in spring and autumn. The national average density and total amount of NPP for 5 years simulated by GEOLUE are 111.9gC/m² and 2.84GtC/year.

The degree of agreement (Correlation coefficient) between spatial distribution of NPP simulated by GEOLUE and distribution of woodland (forest and shrub land) is up to 96.67%, the spatial distribution of NPP simulated by GEOLUE is consistent with the law of the spatial distribution of vegetation. The GEOLUE simulated better the season characteristics and spatial pattern of China's biomass in different types of ecological communities.

In short, GEOLUE model correctly simulates monthly, quarterly and annual spatial and temporal variation of different vegetation communities under monsoon climate and also simulated better the season characteristics and spatial pattern of China's biomass in different types of ecological communities.

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REFERENCE

1. VEMAP Members. VEMAP: a comparison of biogeography and biogeochemistry models in the context of global climate change [J]. *Global Biogeochemical Cycle*, 1995, 9: 407-437.
2. Monteith J L. Solar radiation and productivity in tropical ecosystems. *Journal of Applied Ecology*, 1972, 9:747-766.
3. Ruimy A., and Saugier B., 1994, Methodology for the estimation of terrestrial net primary production from remotely sensed data. *J. Geophysical research*, 97: 18515-18521
4. Prince S. D., Goward S.N., GoetzS., Czajkowski. Interannual atmosphere-biosphere variation: implications for observation and modeling. *Journal of geophysical research*, 2000, **105**(D15): 20,055-20,063.
5. Prince, S.D., J. Haskett, M. Steininger, H. Strand and R. Wright. Net primary production of U.S. Midwest croplands from agricultural harvest yield data. *Ecological Applications*, 2001, 11: 1194-1205.
6. Prince, S.D., S.N. Goward, S. Goetz, K. Czajkowski. Inter-annual atmosphere-biosphere variation: implications for observation and modeling. *J. Geophys. Res.* 2000, **105**: 20,055-20,063.
7. Prince, S. D., Goward, S. N., Global primary production: a remote sensing approach, *Journal of Biogeography*, 1995, 22: 815_835.
8. Prince, S. D. A model of regional primary production for use with coarse-resolution satellite data, *International Journal of Remot Sensing*, 1991.12 (6): 1313-1330.
9. Prince, S. D. Satellite remote sensing of primary production: comparison of results for Sahelian grasslands 1981-1988, *International Journal of Remote Sensing*, 1991.12 : 1301-1330.
10. Prince, S. D., S. J. Goetz and S. N. Goward. Monitoring primary production from Earth observing satellites, *Water, Air, and Soil Pollution*, 1995, 82 : 509-522.
11. Potter, C. S. , J. T. Randerson, C. B. Field, P. A. M atson, H. A. Mooney & S. A. Klooster. Terrestrial eco system p roduction: a p rocessmodel based on global satellite and surface data, *Global Biogeochem ical Cycle*, 1993,7: 811 ~ 841.
12. Sun,R., and Zhu,Q.J. The study of Terrestrial Net Primary Productivity. *Journal of Applied Ecology*, 1999,10 (6): 757-760.(In Chinese)
13. Sun,R., and Zhu,Q.J. the researches of terrestrial Net Primary Productivity and seasonal change in China. *Geographic Sinica*, 2000,55 (1): 36-45.
14. Pu, S.L., Fang,J.Y., and Guo, Q.H. the estimation of net primary productivity in China with CASA model. *Acta Botanica Sinica*, 2001,25 (5) 603-608.
15. Melillo J M, McGuire A D, Kicklighter D W, et al. Global climate change and terrestrial net primary

- production [J]. *Nature*, 1993, 363: 234-340.
16. Cao, M. K., Woodward, F. I. Dynamics responses of terrestrial ecosystem carbon cycling to global climate change, *Nature*, 1998, 393: 249_252.
 17. Cao, M. K., Woodward, F. I. Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change, *Global Change Biology*, 1998, 4: 185_198.
 18. Cao, M. K., Prince, S., Li, K. R. et al., Response of terrestrial carbon uptake to climate interannual variability in China, *Global Change Biology*, 2003, 9: 536_546.
 19. Woodward, F. I., Smith, T. M., Emanuel, W. R., A global land primary productivity and phytogeography model, *Global Biogeochemical Cycles*, 1995, 9: 471_490.
 20. Woodward, F. I., A global land primary productivity and phytogeography model, *Global Biogeochemical Cycles*, 1995, 9(4): 471_490.
 21. GAO Zhiqiang, LIU Jiyuan, CAO Mingkui, LI Kerang & TAO Bo, Impacts of land-use and climate changes on ecosystem productivity and carbon cycle in the cropping-grazing transitional zone in China, *Science in China Ser. D Earth Sciences* 2005 , 48(9): 1479_1491.