Estimating the Net Primary Productivity of Grassland in Poyang Lake Wetland with a Modified Atmosphere-Vegetation Interaction Model

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Abstract
This paper presents a modified land-atmosphere interaction process model to estimate the net primary productivity (NPP) of grassland in Poyang Lake wetland, China. The model is developed on the basis of an atmosphere-vegetation interaction model (AVIM), with two important improvements reflecting the impact of water level of wetlands on plant growth. Thus, a new module that estimates dynamic changes of the water level is proposed in the physical process model (LPM) component and another important controlling factor φ of plant physiological processes is introduced in the plant growth model (PLT) component. The daily NPP of grassland in 2006 was estimated using the modified AVIM and agreed well with the validation datasets of the observed biomass. According to the results, the NPP of grassland varies from 1250 to 2000 DM·m^{-2}·a^{-1}. The correlation analysis shows a significant relationship between NPP and the grassland elevation, and the NPP is highest in an elevation zone of 14.0~14.5 m. Another significant relationship between NPP and temperature or humidity was also found. In spring, the plant growth is affected by temperature, whereas in fall, it is mainly affected by humidity.

1. Introduction

Wetlands are one of the main ecosystems of the earth. They support high species diversity and serve as essential habitat for all kinds of organisms. Moreover, wetlands also provide ecological services as producers, stores, sinks, pathways and buffers of energy, water and nutrients from the local to the global scale (Jackson et al., 1991 and Muneepeerakul et al., 2008). The wetland ecosystem also plays a very important role in the global carbon cycle and in global climatic change. In this process, wetland vegetation plays a significant role, because it can fix atmospheric CO_2 with high efficiency. Research shows that the productivity of many wetland plants can be as high as almost any agricultural crop (Mitsch and Gosselink, 2000). The net primary productivity (NPP) is a good indicator of the accumulation of atmospheric CO_2 in a vegetation ecosystem, and can help us to study the global carbon cycle and the spatial and temporal distribution of CO_2. Since the 1960s, many methods have been developed to estimate the NPP of different ecosystems in the world (Kicklighter et al., 1999). In the 1970s, Lieth developed the first global model of terrestrial ecosystems to estimate the global distribution of potential vegetation productivity (Lieth, 1975). Subsequently, a number of models had been developed and used to study NPP, such as TEM (Melillo et al., 1993), Century (Parton et al., 1993), CASA (Potter et al., 1993), GTEC (Post et al., 1997), TsuBiMo (Alexandrov et al., 2002) and so on. Generally, these models can be classified into three types: (1) climate-relative models based on the relationship between NPP and climatic factors, e.g., the Miami model, the Thornthwaite Memorial model and the Chikugo model (Lieth, 1975 and Uchijima and Seino, 1985); (2) light-utilization efficiency models which are based on the view of resource balance (Monteith, 1972, Raymond et al., 1994 and Zhu et al., 2007); (3) models based on ecological processes such as plant photosynthesis, plant respiration, decomposition of soil organic matter and nutrient cycling (Melillo et al., 1993, Parton et al., 1993 and Potter et al., 1993). These ecological processes are controlled by a number of abiotic factors, e.g., water, light, temperature, soil texture and nutrients, so the process-based models are generally used to study the interactions among NPP, process parameters and the environment. In this paper, a process-based model is used to estimate the NPP of the grassland in Poyang Lake wetland.

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The model originates from an atmosphere-vegetation interaction model (AVIM) developed by Ji (Ji, 1995). To improve its applicability in the study area, the AVIM was modified so that its sub-modules such as the physical process model (LPM) and plant growth model (PLT) could appropriately reflect the characteristics of wetlands.

2. Study Area

Poyang Lake, the largest freshwater lake in China with an area of about 3000 km^2, is located in the northern part of eastern China's Jiangxi province. Water flows into the lake from the Gan, Fu, Xin, Rao and Xiushui rivers and pours out again into the Yangtze River. As the study area for this paper, we chose Poyang Lake Nature Reserve, which lies in the northwest corner of Poyang Lake and includes 9 lakes such as Big Lake Pool, Middle Lake Pool, Sha Lake, Band Lake, etc. The area is characterized by a subtropical warm and wet climate, sufficient sunshine, ample precipitation and a long frost-free period. The average annual temperature varies between 16.7 and 17.7 ℃. The average annual rainfall is 1426 mm, and the most intense precipitation occurs from April to June (47.4% of the annual rainfall). Affected by the five upstream rivers and the Yangtze River, the wetland is flooded regularly. In the flood season, the wetland is widely covered by the water of the lake, whereas in the dry season, the lake shrinks dramatically and the grassland emerges. As a result, the plants in the wetland grassland grow and die regularly with the rise and fall of the water level during the year. In the grassland of the wetland, the vegetation is dominated by mesohydrophytic plants such as *Carex*, which grow and die regularly within a year (Table 1). In early spring, *Carex* starts to germinate; it grows rapidly in March, and is called 'Spring Grass'. *Carex* is flooded when the water level of the lake rises; the aboveground parts die gradually and the underground parts enter a dormant state. When the flood recedes, *Carex* grows again over the grassland. Since its second growth peak occurs in October or November, it is called 'Autumn Grass'. In winter, the aboveground parts wither while the underground parts become dormant. The *Carex* population occupies the vast majority of the underground space through powerful and complex root systems so that other plants have difficulty in settling in the same place. Consequently, in this paper we assume that there is only a *Carex* population in the grassland.

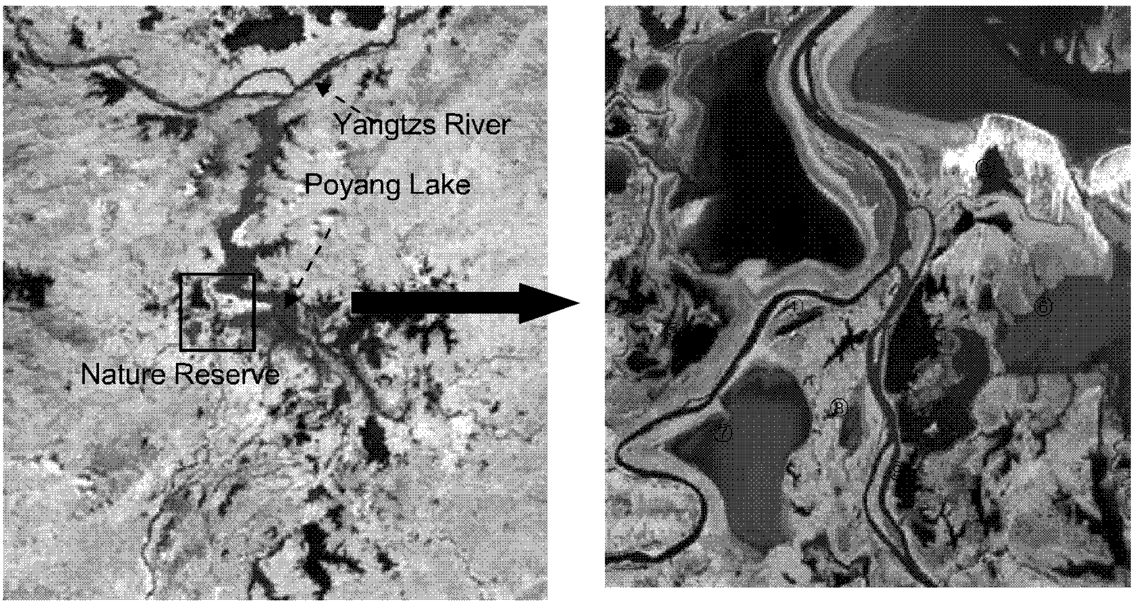

Figure 1: The remote sensing images of study area (Left: MODIS image; Right: Landsat/TM image)
①Bang Lake;②Meixi Lake;③Sha Lake;④Zhushi Lake;⑤Middle Lake Pool;
⑥Big Cha Lake;⑦Big Lake Pool;⑧Chang Lake Pool;⑨Xiang Lake

Table 1: Growth cycle of *Carex* (Cui, 1999)

Time	Growth phase	Month	Growth phase
January	Winter buds	July	Summer buds
February	Budding and growing slowly	August	Summer buds
March	Growing rapidly	September	Budding
April	Growing rapidly	October	Growing rapidly
May	Submerged, the aboveground is dead	November	Growing slowly
June	Submerged	December	Growing slowly

3. Methods

3.1 About AVIM

The theoretical basis of AVIM is that the exchange of material (water and CO_2) and energy (radiation, latent flux and sensible flux) between the atmosphere and the surface affects the physiological processes of the plants, which then causes obvious morphological changes in the vegetation. As the plants grow, the changing leaf area index (LAI) and leaf biomass determine the dynamic parameters of the vegetation, which in turn influence the intensity of energy and water exchange processes. AVIM consists of three sub-models: the LPM, the PLT and the vegetation dynamical parameter model (DYN) (Ji, 1995 and Ji and Hu, 1989). The basic structure of AVIM is shown in Figure 2.

In Figure 2 the solid lines show the flows of energy and materials while the dashed lines indicate the interactive directions. The atmospheric variables V, T, q, CO_2, P_r, R_s and R_L are the wind speed, temperature, specific humidity, carbon dioxide concentration, precipitation, short-wave and long-wave radiations, respectively.

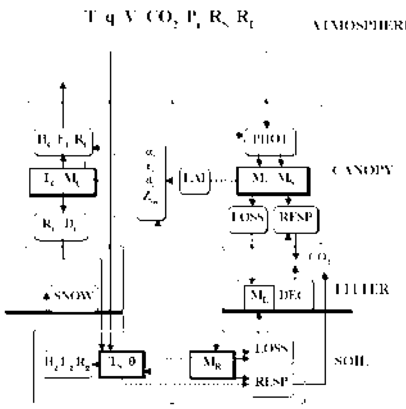

Figure 2: Schematic structure of AVIM (from Ji,1995 and Li,2001)

The physical variables T_c, M_c, T_s, and θ are the canopy temperature and water content, soil temperature and moisture, M_F, M_S, M_R and M_L are the biomass for leaf, stem, root and litter dead matter. The symbols 'PHOT', 'RESP' , 'LOSS' and 'DEC' denote the photosynthesis, respiration, loss processes and decomposition of dry matters. H, E, and R stand for the sensible latent heat, Latent heat flux and net radiation. The subscript 'c' represents the processes for canopy and 'g' for the soil, 'SNOW' stands for snow cover, 'LAI' for leaf area index, and α_c, r_c,d_c,Z_{oc} for albedo, stomatal resistance, zero plane displacement and roughness, respectively.

3.2 Improved Model

In this study, AVIM was adopted for NPP estimation because of its processing capability to describe plant physiological processes and the mechanisms of interaction between the atmosphere and vegetation. To reflect the characteristics of Poyang Lake wetland the model has been modified, in which the wetland dynamics and relevant ecological processes affected by the water level changes of Poyang Lake are described. There are two main modifications in the improved model: (1) in the LPM, a water level sub-module was added to estimate water level changes and the states of submersion or emersion of the grassland, and (2) in the PLT, the photosynthesis and respiration equations were modified based on the traits of wetlands. The modified model was developed on the basis of the following assumptions:

- The basic unit in this study is the population of a vegetation colony instead of a single plant.
- There is no restriction on nutrient supply in this fertile area. We only consider the effects of light, temperature, moisture and CO_2 concentration.
- The spatial distribution of individual plant is random.
- Only mesohydrophytic plants grow in the grassland. Plant photosynthesis will stop after wilting of the aboveground parts or being submerged in water.
- The effect of grazing is not considered.

3.2.1 Physical process model (LPM)

The LPM of AVIM describes the main physical processes including solar and infrared radiation transfer, sensible and latent heat fluxes between air, canopy and soil, interception of rainfall and drainage, surface runoff and infiltration, and canopy transpiration and surface evaporation. In LPM, a new water level sub-module was added to estimate the water level changes and the states of submersion or emersion of the grassland. The water level of Poyang Lake fluctuates seasonally under the influence of the Yangtze River and the five inflowing rivers. As a result, the grassland of the wetland is regularly submerged, which can be simulated from the difference between the ground surface elevation and the water level. Nevertheless, the level of surface water in the wetland is not always consistent with the water level of Poyang Lake, affected by micro topography, especially river embankments. Therefore, we must estimate the wetland water level, instead of directly using the lake water level. Based on the water level data extracted from remote sensing and obtained from the hydrological stations, the relationship between the wetland water level and the lake water level has been analyzed (Zhou, 2009). There are different correlations at different wetland water levels: when the water level is higher than 15.5 m, the wetland water level equals the lake water level; when the water level is between 12.5 m and 15.5 m, they have a strong positive correlation; when the water level is lower than 12.5 m, there is less correlation between them, and the grassland is usually not flooded. So in the water level sub-module, the wetland water level $z_{(x,y)}$ can be expressed as follows:

$$z_{(x,y)} = F\left(dem_{(x,y)}, wl, lh_{(x,y)}\right)$$

Equation 1

Where $dem_{(x,y)}$ is the ground elevation at the position (x,y) of the study area, wl is the water level of Poyang Lake, and $lh_{(x,y)}$ denotes the shortest distance of the wetland at (x,y) to the nearest water-body of lake. In the model, the water level of Poyang Lake is represented as an average value over three days based on three hydrological stations near the wetland, and all water levels are relative to that of the Yellow Sea (Zhou, 2009). AVIM includes two runoff-yield mechanisms: one is infiltration excess runoff-yield which occurs when the incoming rainfall intensity exceeds the soil's infiltration capacity; the other is saturation excess runoff-yield which occurs when the water table rises to the surface and the soil's storage capacity is exceeded. The saturation excess runoff-yield equation is:

$$R_{of} = P_g + S_{mg} - \frac{E_g}{\rho_w}$$

Equation 2

Where R_{of} is the runoff yield, and the symbols P_g, S_{mg}, E_g and ρ_w denote precipitation, snow melt, transpiration, and water density, respectively. In this paper, saturation excess runoff-yield happens when the grassland is flooded, and correspondingly the runoff yield is modified as:

$$R_{of} = P_g + R_{on} + S_{mg} - \frac{E_g}{\rho_w}$$

Equation 3

Where R_{on} is the water above the surface of the grassland caused by the rising lake level. The value of R_{on} can be estimated from the water level sub-module by the following equations:

$$\begin{cases} R_{on} = 0 & (wl < 12.5m) \quad \text{Equation 4} \\ R_{on} = wl - dem & (wl \geq 12.5m) \quad \text{Equation 5} \end{cases}$$

3.2.2 Plant growth model (PLT)

The PLT of AVIM involves photosynthesis, respiration, organic matter decomposition processes and so on (Ji, 1995). NPP is defined as the difference between the amounts of carbon produced from gross photosynthesis productivity (*GPP*) and autotrophic respiration (R_{ir}), and it represents the net carbon input from the atmosphere to the terrestrial vegetation (Mellilo et al., 1993); it can be expressed as:

$$NPP = GPP - R_{ir}$$

Equation 6

The gross photosynthesis rate GPP is related to the foliage temperature T_f, the CO_2 concentration in the stomata C_1 and the leaf water potential ψ, and is given by (Ji, 1995).

$$GPP = P_{max} \times f(C_1) \times f(T_f) \times f(\psi)$$

Equation 7

$$f(C_1) = \frac{C_1}{C_1 + K_1}$$

Equation 8

$$f(T_f) = \frac{(T_f - T_{min}) \times (T_f - T_{max})}{(T_{min} - T_{opt}) \times (T_{max} - T_{opt})}$$

Equation 9

$$f(\psi) = (1 - e^{-b(\psi - \psi_f)})^{-1}$$

Equation 10

Where P_{max} denotes the canopy photosynthetic rate under optimum conditions; K_1 is the C_1 at the half-saturated photosynthesis rate; $T_{\min}$, P_{max} and T_{opt} are the minimum, maximum and optimum temperatures for photosynthesis, respectively; w stands for the average soil moisture in the root system layer; w_i is the wilting moisture of soil; and b is a constant. In this study area, the vegetation is mainly herbaceous. Consequently, in the model the vegetation is only divided into two biomass compartments: aboveground and underground. As mentioned above, the growth of mesohydrophytic plants in grassland is affected by the water level dynamics. In flooding season, the plants will die as the lake water level rises. In order to reflect the effect of flooding, a controlling factor φ was added to the photosynthesis model as follows:

$$GPP = P_{\max} \times f(C_1) \times f(T_f) \times f(Y) \times \varphi$$

Equation 11

Where φ is related to the exposed or flooded status of the grassland. When the grassland is completely flooded, φ equals zero. Otherwise, φ equals unity. Whether the grassland is flooded or not can be determined from the water level sub-module. In equation (6), R_{ir} denotes respiration, which includes maintenance respiration R_m and growth respiration R_g. Maintenance respiration serves to maintain all kinds of physiological activities, and is related to temperature. Growth respiration fuels growth and formation of organs, and is proportional to the growth rate of tissue dry matter (Li, 2001). Therefore, R_{ir} can be written as:

$$R_{ir} = R_m + R_g = a \cdot BM + b \cdot \frac{dBM}{dt}$$

Equation 12

Where BM is the total biomass (aboveground and underground), and a and b are constants. When grassland is completely submerged, the aboveground parts of the plants die, and the aboveground biomass BM' equals zero; thus, the aboveground maintenance respiration R_m' can be modified as:

$$R_m' = R_m \times \varphi$$

Equation 13

At the same time, the underground parts enter a dormant state.

3.3 Model Parameters and Data Acquisition

The model parameters include the ecological and physiological parameters of plants, physical and chemical parameters of soil, meteorological data, elevation, water level and so on, which are acquired from remote sensing images, field experiments, meteorological stations, hydrological stations, the natural reserve management bureau or other related studies (Table 2). Vegetation photosynthesis parameters are originally from the study of Larcher (Larcher, 1995) and were further modified by our field experiments; respiration parameters were taken from the results of Larcher (Larcher, 1995) and Penning (Penning, 1982); soil parameters were obtained from NASA and Peilke's studies (Peilke, 1984). Other land surface parameters, such as the initial biomass, vegetation coverage, leaf area index, surface albedo, surface temperature and humidity and so on, were mainly extracted from remote sensing data. In this study, MODIS and LANDSAT/TM were used. After geometric correction and atmospheric correction, the grassland was extracted from the remote sensing images with the help of the digital elevation model (DEM), field experiments and a priori knowledge (Zhou et al., 2007). Then, the land surface parameters were derived by remote sensing quantification models (Zhou, et al., 2007, Liang et al., 2007 and Liang et al., 2008). Meteorological data was obtained from the China.

Table 2: Some model parameters and their sources

Parameters	Value	Sources
Distributive coefficient of dry matter	1:4.5	Field experiment
Growth respiration coefficient	0.3	Penning de Vries, et al. , 1982
Maintenance respiration coefficient of aboveground	0.015	Penning de Vries, et al. , 1982
Maintenance respiration coefficient of underground	0.022	Penning de Vries, et al. , 1982
The maximum photosynthetic temperature	320 K	With reference from Cui and field experiment
The minimum photosynthetic temperature	279 K	With reference from Cui and field experiment
The optimum photosynthetic temperature	290 K	With reference from Cui and field experiment
Canopy optimum photosynthetic rate	5.5 $mol.m^{-2}.d^{-1}$	Larcher,1995
Saturated soil water potential	-0.2bar	NASA; Peilke,1984
Wilting soil moisture	0.17	NASA; Peilke,1984

National Meteorological Information Center and interpolated using the Kriging method in order to match the model scale. Water level data was obtained from the Xiushui, Xingzi and Hukou hydrological stations near the study area. Elevation data was from the 1:10,000 digital elevation maps of the study area. In order to calibrate the model parameters, two field experiments were carried out on 15–31 October 2005 and 1–11 April 2006 at Poyang Lake wetland. Spectroscopic features of land surface objects, surface temperature, micro-climate, soil characteristic parameters, and physiological and structure parameters of the vegetation were measured.

3.4 Modeling Scales

In running the improved model, the simulation was based on the integration of various important processes, including physical processes, photosynthesis or respiration processes and biomass accumulation. The time scales were set to 30 min, 1 h and 1 day, respectively, while the spatial scale was set to 30 m × 30 m.

4. Results and Discussion

4.1 Model Validation for NPP

The grassland NPP of Poyang National Natural Reserve in 2006 was estimated with the improved model. Figure 3 shows the estimated results for the first half, the second half and the full year of 2006, respectively. It is obvious that the NPP of the first half was greater than that of the second half. In order to validate the results, 25 plots of 30 m × 30 m size were set to measure the aboveground biomass in the grassland. The latitude and longitude of the plots were measured using GPS. In each plot, two 1 m ×1 m samples were chosen to harvest the aboveground vegetation on 6 April 2006. All samples were oven-dried at 70 °C to constant weight in the laboratory, and then the dry matter was weighed. The average aboveground biomass (dry matter) of each plot was the average value of two samples. Before the experiment, there was no harvesting in the grassland, so the biomass can be taken as the NPP of the year. We converted the biomass units to carbon units ($gC·m^{-2}·a^{-1}$) using a mass fraction of 0.475 (Raich et al, 1991; Scurlock et al, 1999). On the basis of the ratio between aboveground and underground biomass which can be deduced from related research (Cui, 1999), we obtained the total NPP. The results show that the estimated NPP in the most plots was close to the observed value; the R^2 value reached 0.6829. The estimated NPP was lower than the measured NPP, because the measured biomass contained some overwintering roots.

4.2 Results Analysis

4.2.1 The NPP of grassland

The simulation result shows that the grassland NPP is about 150~2600 $DM·m^{-2}·a^{-1}$ with the highest value in May, and more than 60% of the grassland has an NPP of 1250~2000 $DM·m^{-2}·a^{-1}$. In April and May, the first growth peak appeared. In July and August, the plants stopped growing, but in September they again started to grow slowly. The second growth peak appeared in October and November. These growth processes reflect the plants' response to temperature and water level.

4.2.2 Effects of environmental factors on NPP

The Elevation: Figure 5 shows the correlation between NPP and the elevation of the grassland. The higher the grassland elevation is, the larger the value of NPP. The reason is that the emersion time of the grassland lengthens with the elevation increasing, and accordingly the vegetation's growth period is extended. When the elevation is higher than 14.5 m, the NPP decreases slightly; this may be related to decreased soil moisture.

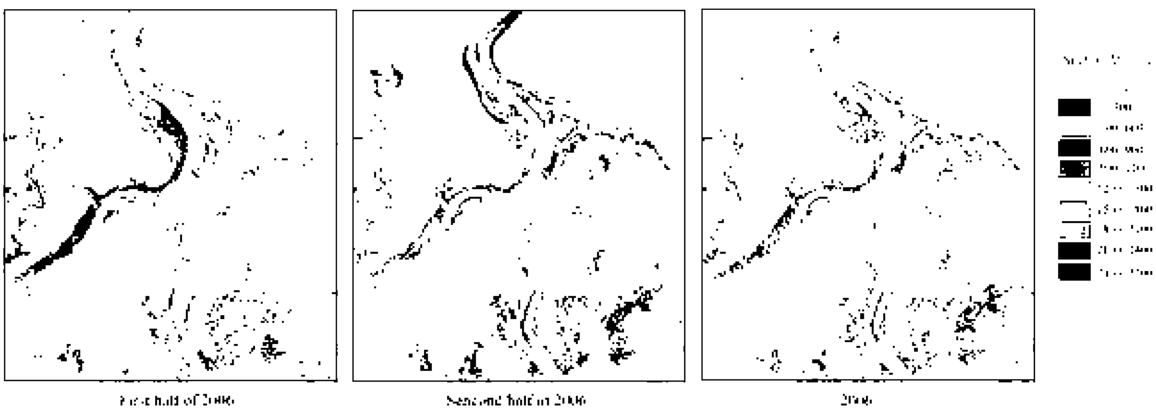

Figure 3: Estimated NPP in 2006

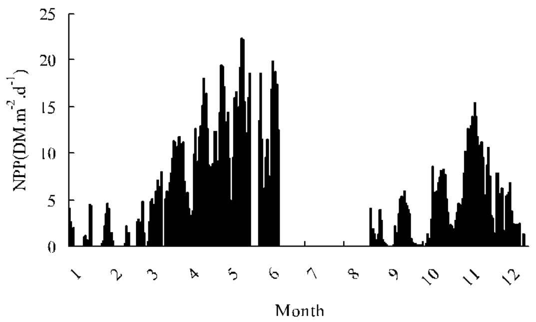

Figure 4: The changes of NPP in a year

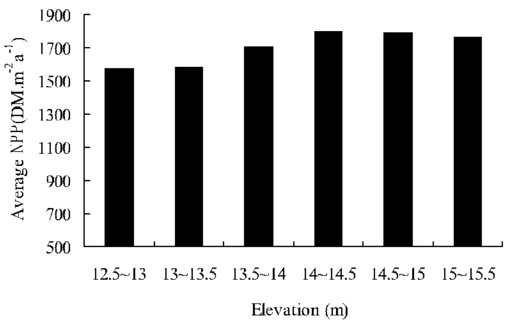

Figure 5: The average NPP at different elevations

Table 3: Correlation analysis between climate factors and NPP

Period	Temperature	Humidity	Rainfall	Sunshine
The first half-year	0.58**	0.19**	0.19	0.09*
The second-half year	-0.17*	0.33**	0.07	-0.39

The highest NPP occurs in the grassland at 14.0~14.5 m elevation; thus, these areas are the most suitable regions for vegetation growth in the Poyang Lake wetland.

Meteorological factors: The impacts on NPP from meteorological factors, such as temperature, humidity, sunshine and rainfall and so on, were analyzed. In order to eliminate the impact of water level changes, the data from the flood period (June, July and August) were not used, and the impacts in the first half-year and the second half-year were analyzed separately. Overall, temperature and humidity have a significant correlation with NPP. In spring, temperature has a great impact on NPP, with a correlation coefficient close to 0.6. In autumn, both have a lower correlation, but there is a relatively high positive correlation between NPP and humidity. The impact of rainfall on NPP is not significant. The sunshine also has a lower effect on NPP. The above results suggest that the two main meteorological factors which contribute to the variation of NPP are temperature and humidity. In spring, the plants start to germinate, and grow rapidly as the temperature increases. Consequently, there is a positive correlation between NPP and temperature. In autumn, however, the plants begin to grow when the water level falls. Hence, the NPP is lower in the initial stage of growth even though the temperature is higher at that time. That causes a negative correlation between temperature and NPP in the second half-year. Since the study area is located within a lake region, the soil and air humidity are high, and the impact of rainfall on vegetation growth is not significant. Similarly, the study area has sufficient sunshine throughout the year, so the impact of sunshine on vegetation growth is not evident.

5. Conclusions

A land-atmosphere interaction model - AVIM was explored extensively in this paper. There are two important modifications that were made to adapt the estimation of the NPP in a seasonally-flooding wetland area of Poyang Lake. In the LPM component of AVIM, a water level sub-module was newly presented to estimate the changes of water level of wetlands and the runoff yield under saturated storage. In the PLT component, a controlling factor of plant growth was introduced to simulate the plant growth process, responding to water level changes. With remote sensing images, DEM, and simultaneous ground observations of meteorological and water level data, the grassland NPP of the wetland was estimated using the improved model. The results show the improved model simulate plant growth in the Poyang Lake wetland well, meaning that the incorporation of the impact of water level changes on plant growth into the model eliminates the model disadvantage. The correlation analysis also reveals the significant relationships between the grassland NPP and grassland elevation, temperature and humidity. There is an interesting finding that the temperature dominates plant growth in the first half year, while the humidity mainly works in the second half. For lack of long-term positioning observations, the parameterization of our model partly referred to previous studies or experiences, which might affect the model accuracy to some extent. In addition, the model only simulated the growth process of the mesohydrophytic plants, neglecting the competition and succession of the hygrophyte plants. These problems should be resolved in future work.

Acknowledgements

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