Simulating the exchanges of carbon dioxide, water vapor and heat over Changbai Mountains temperate broad-leaved Korean pine mixed forest ecosystem

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Abstract A process-based ecosystem productivity model BEPS (Boreal Ecosystem Productivity Simulator) was updated to simulate half-hourly exchanges of carbon, water and energy between the atmosphere and terrestrial ecosystem at a temperate broad-leaved Korean pine forest in the Changbai Mountains, China. The BEPSh model is able to capture the diurnal and seasonal variability in carbon dioxide, water vapor and heat fluxes at this site in the growing season of 2003. The model validation showed that the simulated net ecosystem productivity (NEP), latent heat flux (*LE*), sensible heat flux (H_s) are in good agreement with eddy covariance measurements with an R^2 value of 0.68, 0.86 and 0.72 for NEP, *LE* and H_s, respectively. The simulated annual NEP of this forest in 2003 was 300.5 gC/m^2, and was very close to the observed value. Driving this model with different climate scenarios, we found that the NEP in the Changbai Mountains temperate broad-leaved Korean pine mixed forest ecosystem was sensitive to climate variability, and the current carbon sink will be weakened under the condition of global warming. Furthermore, as a process-based model, BEPSh was also sensitive to physiological parameters of plant, such as maximum Rubisco activity (V_{cmax}) and the maximum stomatal conductance (g_{max}), and needs to be carefully calibrated for other applications.

Keywords: carbon cycle, water cycle, BEPSh model, eddy covariance measurement, ChinaFLUX.

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Global warming resulted from greenhouse gases emission, such as CO_2, and the issue of fresh water shortage throughout the world has brought forward austere challenges to scientists, policy-makers and the public all over the world, which made the research on carbon and water cycles in terrestrial ecosystems become the core issues in global change science. For confidently predicting the future trend of global change and seeking effective way to manage and control water and carbon cycles in terrestrial ecosystems, it is a prerequisite to understand the processes in water and carbon cycles and the feedback mechanism among them. Dynamic modeling of energy and mass (water and carbon) fluxes in ecosystems is an effective tool for analyzing the mechanism of water and carbon cycling in terrestrial ecosystems and predicting the fluxes of water and carbon cycles. Since the 1990s, research on this field has been a scientific hotpot and significant progress has been made. Many scientists established a series of models coupling carbon and water cycles from their own disciplines. These models can be grouped into the following types: biogeographical model, biophysical model, biogeochemical model and remote sensing model, represented by BIOME-BGC[1], BATS[2], FOREST-BGC[3], AVIM[4], SiB2[5], TEM[6,7], IBIS[8], BEPS[9,10]. Among these models, the BEPS model had been widely used in studying productivity of different regions and ecosystems at different spatial scales for less parameters and strong practicability[10—14].

Although the models mentioned above can be used to simulate carbon and water cycle in terrestrial ecosystem, validation of the model is still a concern for the data availability. Eddy covariance technique, characterized by the real-time, long-term continuous measurements of carbon, water and energy fluxes between the atmosphere and ecosystems, provides the data foundation for bettering our knowledge on carbon and water cycling in ecosystems and for model parameterization and validation. In recent years, it has become a key method in several international programs studying the role of the biosphere in global biogeochemical cycles, and many flux observation networks covering different regions have been established, among which ChinaFLUX was established in 2002[15,16].

Changbai Mountains temperate broad-leaved Korean pine mixed forest is the most important forest type in northeast China, and also a typical ecosystem in eastern Northeast China transect, which is an important area in studying global change[17], and an observation tower of ChinaFLUX is located in this forest. Developing a process-based model to simulate water and carbon fluxes at this site will be helpful for the simulation of carbon and water cycles in other types of ecosystems in ChinaFLUX. Moreover, it can provide a model basis for extrapolating the site-based flux observation to large regions. The objectives of this paper are: (i) to introduce the application, adjustment and parameterization of BEPS based on observed flux data in the Changbai Mountains; (ii) to simulate the fluxes of carbon dioxide, water and heat in the Changbai Mountains temperate broad-leaved Korean pine forest ecosystem; and (iii) to analyze the sensitivity of model outputs to climate variability and physiological parameters, through which provides a foundation for the study on carbon and water cycle at regional or global scales and the interaction mechanism between it and environmental change.

1 Materials and methods

1.1 Study area description

The area selected in this study is No. 1 plot in the Changbai Mountains forest ecosystem station of the Chinese Academy of Sciences, located in the southeast of Jinlin Province, China. The topography in the region is predominantly flat, with slight undulations. The climate is temperate continental under the influence of monsoon, an annual mean temperature and annual precipitation are 3.6℃ and 713 mm, respectively (averaged from 1982 to 2000), and the prevailing wind direction is southwest. The vegetation is a mature natural Changbai Mountains temperate broad-leaved Korean pine forest, with the mainly preponderant species of *Pinus koraiensis*, *Tilia amurensis*, *Quercus mongolica*, *Fraxinus mandshurica* and *Acer mono*, etc. The mean canopy height of *Pinus koraiensis* was 26 m, mean stem diameter was 32—46 cm, and stand density was 560 stems/ha (>8 cm). The peak LAI of the canopy was about 6 m^2/m^2, which occurred in the growing season at the end of July. The soil there is an upland dark brown forest soil originated from volcanic ashes with a deep surface organic layer.

1.2 Experimental design and data acquisition

The measurement tower in the Changbai Mountains is located at 42°24′09″N, 128°05′45″E, with an elevation of 738 m. A 62-m-high tower was set up with an open path eddy covariance measurement system and 7 levels of routine meteorological profile measurement systems, through which canopy CO_2, water vapor and heat fluxes and meteorological variables above and within the forest were measured simultaneously. The open path eddy covariance system, mounted at a height of 40 m (14 m above canopy), is composed of a three-dimensional sonic anemometer (CAST3, Campbell, USA) and a fast responding open path infrared gas analyzer (LI-7500, LI-COR Inc., USA). The sensors were directed to southwest, the dominant wind direction. Soil moisture and soil temperature were also observed at the same time as flux measurements. Soil moisture was measured with TDR (CS616_L, Campbell, USA) at three different depths (5, 20, and 50 cm). Soil temperature was measured at the depths of 1, 5, 20, 50 and 100 cm with 105T (Campbell, USA).

Collection frequency of raw flux data was 10 Hz, that of climate data was 0.5 Hz. The 30-minute averaged values of each variable, calculated online by CR5000 datalogger (Compbell Science Ins.), were used in this study. The instruments were put into operation on August 24, 2002; here we used the data in 2003. A series of pre-processing was done before using the flux data, which included coordinate rotation, Webb correction[18], and filter with friction velocity threshold u_*>0.2 m/s (for determination of the critical friction velocity see refs. [19], [20]). The effect of storage item should be considered in the calculation of net ecosystem exchange (NEE). We used the CO_2 concentration measured by LI-7500 to estimate the storage item in this study (for the estimation method see ref. [21]).

2 Model description

2.1 BEPS model description

The process model, dubbed the Boreal Ecosystem Productivity Simulator (BEPS), was originally built by Liu et al.[9] based on the framework of forest biogeochemical cycle model FOREST-BGC (Running and Coughlan, 1988), and can be used to simulate carbon, water and energy balance in ecosystems. The BEPS model, which involved many biochemical, physiological, and physical ecosystem processes, integrated ecological, biophysical, plant physiological, meteorological, and hydrological methods, was process-based and remote sensing driven. It was initially used to simulate boreal forest ecosystem productivity in Canada. After that, Bunkei[14] and Liu[1)] applied it to East-Asian and Chinese terrestrial ecosystems, respectively. The model had been refined by Liu et al. and Chen et al. many times, and formed different versions for different objectives, with the minimum temporal scale of daily[10−13].

2.2 Key equations in the model

(i) Key equations in the process of carbon cycle

(1) Photosynthesis. The simulation of photosynthesis in BEPS model was based on the instantaneous leaf-level model of Farquhar, after spatial extrapolation, Chen et al.[13] obtained the following equations:

$$A_c = \frac{1}{2}((C_a + K)g + V_m - R_d - \sqrt{((C_a + K)g + V_m - R_d)^2 - 4(V_m(C_a - \Gamma) - (C_a + K)R_d)g}), \quad (1)$$

$$A_j = \frac{1}{2}((C_a + 2.3\Gamma)g + 0.2J - R_d - \sqrt{((C_a + 2.3\Gamma)g + 0.2J - R_d)^2 - 4(0.2J(C_a - \Gamma) - (C_a + 2.3\Gamma)R_d)g}), \quad (2)$$

in eqs. (1) and (2), A_c and A_j are Rubisco-limited and light-limited gross photosynthetic rates, respectively; C_a is the CO_2 concentration in the atmosphere; V_m is the maximum carboxylation rate; R_d is the daytime leaf dark respiration; K is a function of enzyme kinetics; Γ is the CO_2 compensation point without dark respiration; J is the electron transport rate; g is the conductance to CO_2 through the pathway from atmosphere outside of leaf boundary layer to the intercellular space. The final assimilation rate is the smaller one

1) Liu, M. L., Study on land use/cover change and vegetation carbon pool and productivity in terrestrial ecosystem in China, Dissertation of Institute of Remote Sensing Applications of the Chinese Academy of Sciences, 2001.

of A_c and A_j.

With the separation of sunlit and shaded leaf group, the total canopy photosynthesis can be calculated as

$$A_{canopy} = A_{sun}\mathrm{LAI}_{sun} + A_{shade}\mathrm{LAI}_{shade}, \quad (3)$$

where A_{canopy} is the canopy photosynthesis; the subscripts 'sun' and 'shade' denote the sunlit and shaded components of photosynthesis and LAI.

(2) Respiration. Respiration of ecosystem consists of autotrophic respiration and heterotrophic respiration. Conventionally, autotrophic respiration is separated into maintenance respiration (R_m) and growth respiration (R_g). Maintenance respiration is temperature-dependent:

$$R_m = \sum_{i=1}^{3} M_i \alpha_{25}^i Q_{10}^{\frac{T-25}{10}}, \quad (4)$$

where i is an index for different plant components (1 for leaf, 2 for stem, 3 for root); M_i is the biomass of plant component i; α_{25}^i is maintenance respiration coefficient for component i; Q_{10} is the temperature sensitivity factor, and T is air temperature.

According to Bonan (1995), growth respiration accounts for 25% of gross primary productivity (GPP)[22], therefore

$$R_g = 0.25\mathrm{GPP}. \quad (5)$$

In the simulation of soil respiration, the effects of soil moisture and soil temperature were taken into consideration:

$$R_h = R_{h,10} f(\theta) f(T_s), \quad (6)$$

where $R_{h,10}$ is the soil respiration rate at 10℃.

(ii) Key equations in the process of water cycle. In the sub-model of water cycle, following processes were considered: precipitation, canopy interception, throughfall, snow melt, snow sublimation, canopy transpiration, evaporation from canopy and soil, outflow, etc. Evapotranspiration aboveground is calculated as follows:

$$ET \approx T_{plant} + E_{plant} + E_{soil} + S_{ground} + S_{plant}, \quad (7)$$

where ET is evapotranspiration; T_{Plant} is transpiration from plants; E_{plant} and S_{plant} are evaporation and sublimation from plants; E_{soil} is evaporation from soil; S_{ground} is sublimation from the snow on the ground. The revised Penman-Monteith equation was used in the calculation of the above items.

2.3 Establishment of BEPSh model and its parameterization

The minimum temporal scale of BEPS model is daily, which makes it incapable of describe daily dynamics of ecosystem fluxes at half-hourly scale. In this paper, we established the BEPSh model with temporal scale of half-hourly (fig. 1) by making adjustment on BEPS model based on part of the observed flux data in the Changbai Mountains temperate broad-leaved Korean pine forest ecosystem, and redefining some plant and soil parameters used in the model.

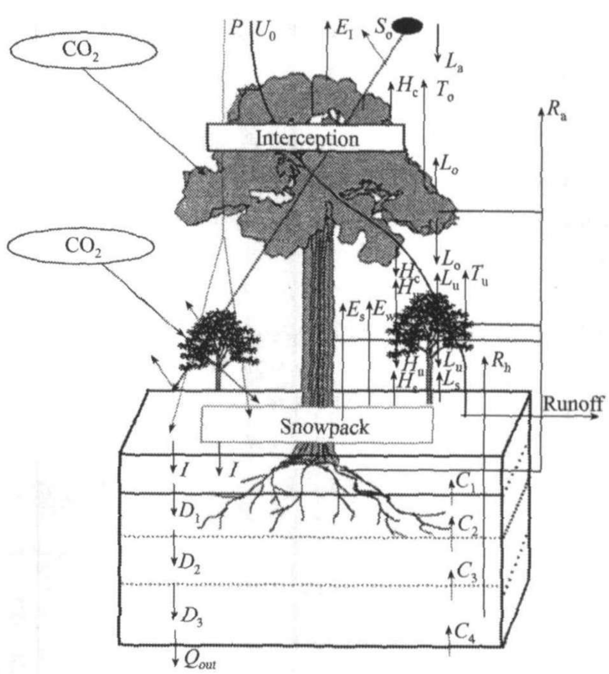

Fig. 1. The framework and major processes in BEPSh model.

(i) Establishment of the model. The BEPS model was initially developed for regional applications at daily time steps. So it simplified some biogeochemical and biophysical processes such as water transport in the soil profile and soil C decomposition dynamics. In order to improve the robustness of this model to simulate C, water and energy dynamics in terrestrial ecosystems, we adopted the strategy of the daily BEPS model for simulating photosynthesis and transpiration and enhanced the description of underground processes.

Firstly, taking the internal heat and water transfer between soil layers into consideration, we vertically divided the soil into several layers, soil water content in each layer is simulated with the method of Sellers (1996)[5] as follows:

$$\frac{d\theta_i}{dt}=\begin{cases} I-E_{\text{soil}}-Q_i-T_i, & i=1; \\ Q_{i-1}-Q_i-T_i, & i=2,3,4\cdots,N; \end{cases} \quad (8)$$

where i is the layers of soil; θ_i is the soil water content of each layer; I is the infiltration from throughfall of precipitation and snowmelt into the first soil layer; Q_i is the vertical water transfer between layers; T_i is the water loss by plant transpiration.

Studies showed that the carbon exchange between soil and atmosphere accounted for two thirds of the total carbon storage in terrestrial surface ecosystem[23]. Therefore, estimation precision of soil respiration will influence the evaluation of carbon exchange of the whole ecosystem to a large degree. Soil respiration is subjected to soil moisture, soil temperature, the chemical property of litters, and soil texture. In former BEPS, only the effect of temperature and soil moisture on heterotrophic respiration was considered. To improve the estimate of soil respiration, we replaced this component of BEPS with the soil sub-model of CENTURY[24] to divide the soil C into 9 pools, including foliage structural pool, foliage metabolic pool, soil structural pool, soil metabolic pool, woody pool, surface microbe pool, soil microbe pool, slow C pool, and passive C pool. Each pool has its own decomposition rate, which is dependent on soil temperature, soil moisture, soil texture and litter type (lignin nitrogen ratio). Soil respiration then can be described by

$$R_h=\sum_{i=1}^{9}C_iK_{\max}^i f(T_s)f(\theta)f(li)f(te), \quad (9)$$

where C_i is the size of the ith carbon pool; $K_{\max}^i$ is the maximum decomposition rate of each pool; $f(T_s)$ is the impact of soil temperature on decomposition; $f(\theta)$ is the impact of soil moisture on decomposition; $f(li)$ is the impact of lignin content of litter on decomposition (it is only effective for litter pools and equals 1.0 for other C pools); $f(te)$ is the effect of soil texture on microbial activity (it acts on soil microbial pool and equals 1.0 for other C pools).

(ii) Model parameterization. Because the detailed soil processes considered in BEPSh model, there are more soil parameters than the original model, which includes mainly the soil texture, soil bulk density, soil organic matter content, saturated soil hydraulic conductivity, etc. All these parameters can be estimated from soil texture following Saxton et al.[25]. In order to make the model suitable to simulate the flux characteristic in the Changbai Mountains temperate broad-leaved Korean pine ecosystem, we adjusted the corresponded plant parameters in BEPSh model. Table 1 lists the major vegetation parameters, their values,

Table 1 Major vegetation parameters used in the model

Parameters	Values	Resources
Maximum stomatal conductance/ mm s^{-1}	8	Ref. [26]
Clumping index	0.6	Ref. [9]
Maximum carboxylation rate at 25℃/μmol m^2 s^{-1}	50	Ref. [10]
Over story maximum LAI/m^2 m^{-2}	4.5	Data from CERN[a)]
Under story maximum LAI/m^2 m^{-2}	2.5	Data from CERN
Over story minimum LAI/m^2 m^{-2}	1.5	Data from CERN
Under story minimum LAI/m^2 m^{-2}	0	Data from CERN
Canopy height of over story/m	26	Observed value
Canopy height of under story/m	8	Observed value

a) CERN: Chinese Ecosystem Research Network.

and resources used in the model.

3 Result analyses

3.1 Characteristics of meteorological variables

Meteorological variables as solar radiation (*R*), air temperature (*T*), relative humidity (*RH*), and precipitation (*P*) are the main driving variables in BEPSh model, their variation will influence the output of the model directly. Fig. 2 shows the annual variation of solar radiation, air temperature, relative humidity, and precipitation in the Changbai Mountains temperate broad-leaved Korean pine ecosystem. As the main factor influencing the air temperature, solar radiation exhibited the same seasonal trend as air temperature (fig. 2(a), (b)). During the period of observation in 2003, the maximum value of daily incident solar radiation was 1.68×10^4 W/m^2, with an average of 7.39×10^3 W/m^2. The annual mean air temperature was 4.8℃, 1.2℃ higher than the normal. Daily mean air temperature ranged from −24.9℃ to 24.0℃. The annual precipitation was about 537 mm, lower than the normal, with 60% of which fallen during the period of June to August. Therefore, the climate in 2003 was warmer and drier compared with the average of 19 years (1982—2000).

3.2 Simulation results

(i) Simulation of soil temperature and soil water content. Soil temperature and soil water content are two important factors influence the decomposition of soil organic matter, on which the precision of soil respiration estimation depends. During the growing season of 2003, soil water content at 50 cm depth was higher than field capacity (26.9%) and that at 5 cm and 20 cm was higher than wilting point (12%) all the time, which implied that the forest did not endure severe drought. The comparison of simulated soil temperature and soil water content with measurements at different depths showed that the model successfully captured the variability in soil temperature and moisture. Table 2 demonstrates the regression parameters of simulated and measured soil temperature and soil water content. The BEPSh model performed better for soil temperature than for soil water content. The R^2 values for both are significant at $P<0.01$ level.

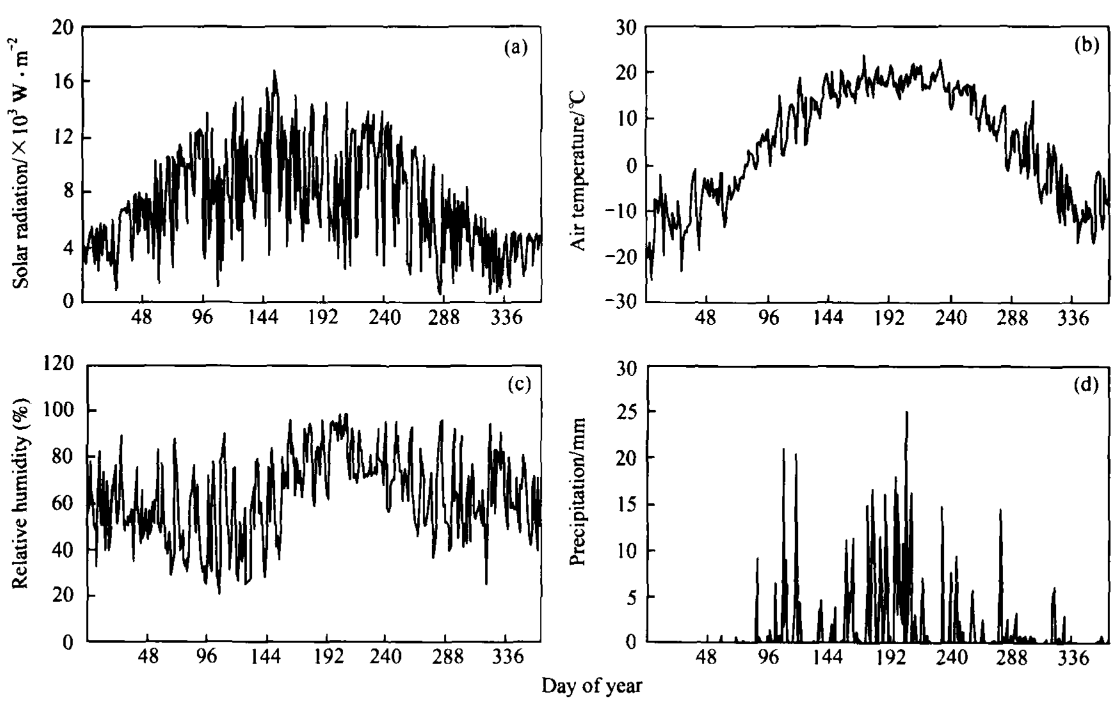

Fig. 2. Meteorological variables of the Changbai Mountains temperate broad-leaved Korean pine ecosystem in 2003. (a) Solar radiation, (b) air temperature, (c) relative humidity, (d) precipitation, where solar radiation and precipitation are daily total, relative humidity and air temperature are daily average.

Table 2 Regression parameters of simulated and measured soil temperature and soil water content

	Depth/cm	Slope	R^2	n
Soil temperature	1	1.0036	0.9407	7680
	5	1.0133	0.9164	7680
	20	0.9965	0.922	7680
Soil water content	5	1.1066	0.7398	7680
	20	0.9036	0.6005	7680
	50	0.8445	0.5089	7680

(ii) Simulation of CO_2 flux. Generally, net ecosystem carbon exchange (NEE) is used in the study of CO_2 exchange between vegetation and atmosphere. While in the context of carbon cycle, net ecosystem productivity (NEP) is usually of great importance, as from which we can easily detect one ecosystem is either a sink or a source of carbon. Therefore, we used NEP in this study. As for the value, NEP = −NEE.

Run at a pretty high temporal resolution (half hour), BEPSh model has the ability to capture the sub-daily response of NEP to meteorological variables. It explained 68% of the variations of NEP at this site. Fig. 3 shows the daily course of simulated and measured NEP at different periods (early, middle, and late growing seasons). To check the ability of the model in simulating the daily variation of NEP under different climates, here we selected 3 weeks with different weather conditions. The days 126, 128, 130, 131, 195, 241—246 were clear, the days 125, 127, 196—201, 240 were cloudy or rainy. The daily temporal patterns of NEP simulated by the model were very similar to the measured ones (fig. 3). Daytime NEP of clear day was higher than that of cloudy or rainy day because strong solar radiation enhances photosynthesis at clear day. During the middle growing season, there were 6 days with less available data and lower daytime NEP,

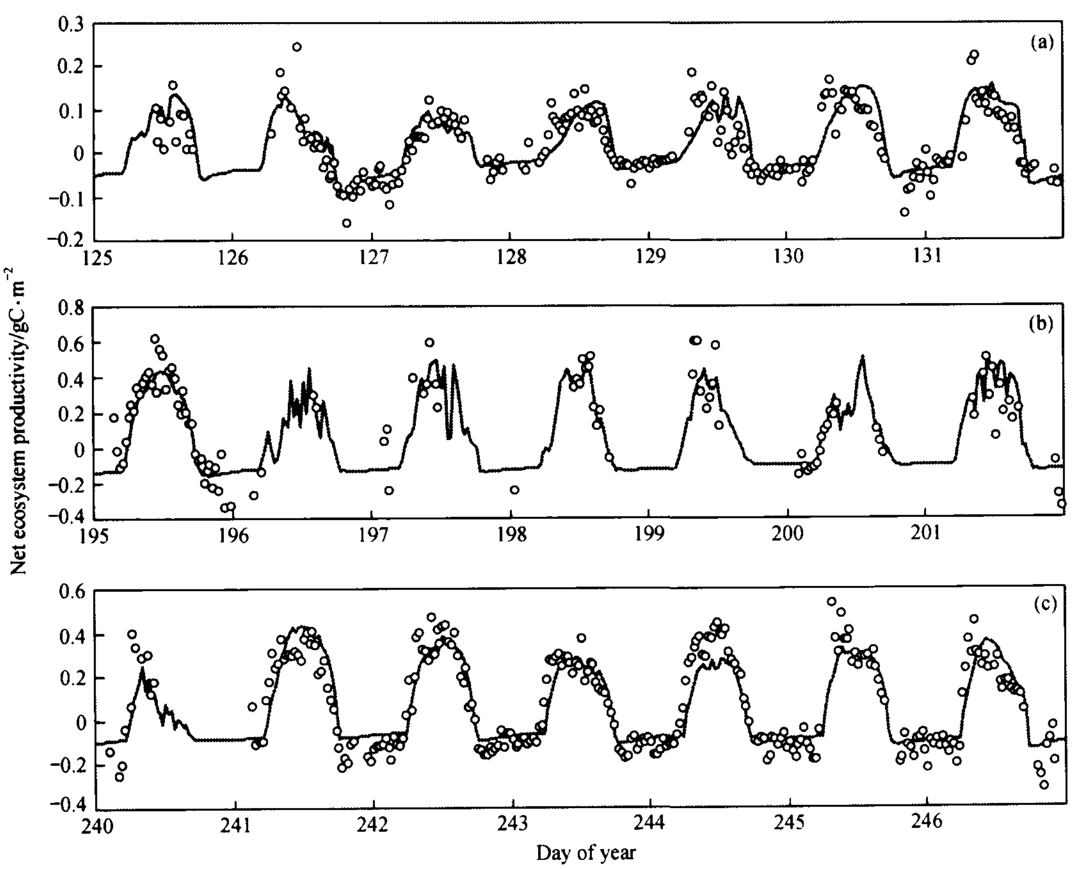

Fig. 3. The daily variation of CO_2 flux of the Changbai Mountains temperate broad-leaved Korean pine ecosystem at different periods during the growing season in 2003. (a) Early growing season (DOY 125—131), (b) middle growing season (DOY 195—201), (c) late growing season (DOY 240—246), the dots are the measured values, and the line represents the simulated one.

but the model could still capture the NEP variations (fig. 3(b)). During the whole growing season, the simulated NEP at noon was occasionally lower than the measured one, which might be attributed to the determination of vegetation parameter V_{cmax}. In addition, both simulated and measured NEP showed distinct seasonality. In the middle growing season, when vegetation had strong photosynthesis, NEP at noon reached 0.6 gC/m^2, higher than that of the early growing season (0.24 gC/m^2) and the late growing season (0.53 gC/m^2).

(iii) Simulation of latent and sensible heat fluxes. Simulated and measured latent heat flux (*LE*) usually had the same diurnal variation characteristics (fig. 4). *LE* was close to 0 at nighttime; at daytime, *LE* increased gradually from early morning, reached the maximum value at noon, and then, *LE* decreased near to zero at sunset. It obviously followed the diurnal variation of solar radiation. Similar to NEP, the seasonal change in *LE* was clear due to the tight correlation between photosynthesis and transpiration. During the middle growing season, *LE* was above 400 W/m^2 at noon of clear day, higher than that of early growing season (230 W/m^2) and late growing season (390 W/m^2). In addition, *LE* at clear day was obviously higher than that at cloudy and rainy day. Simulated

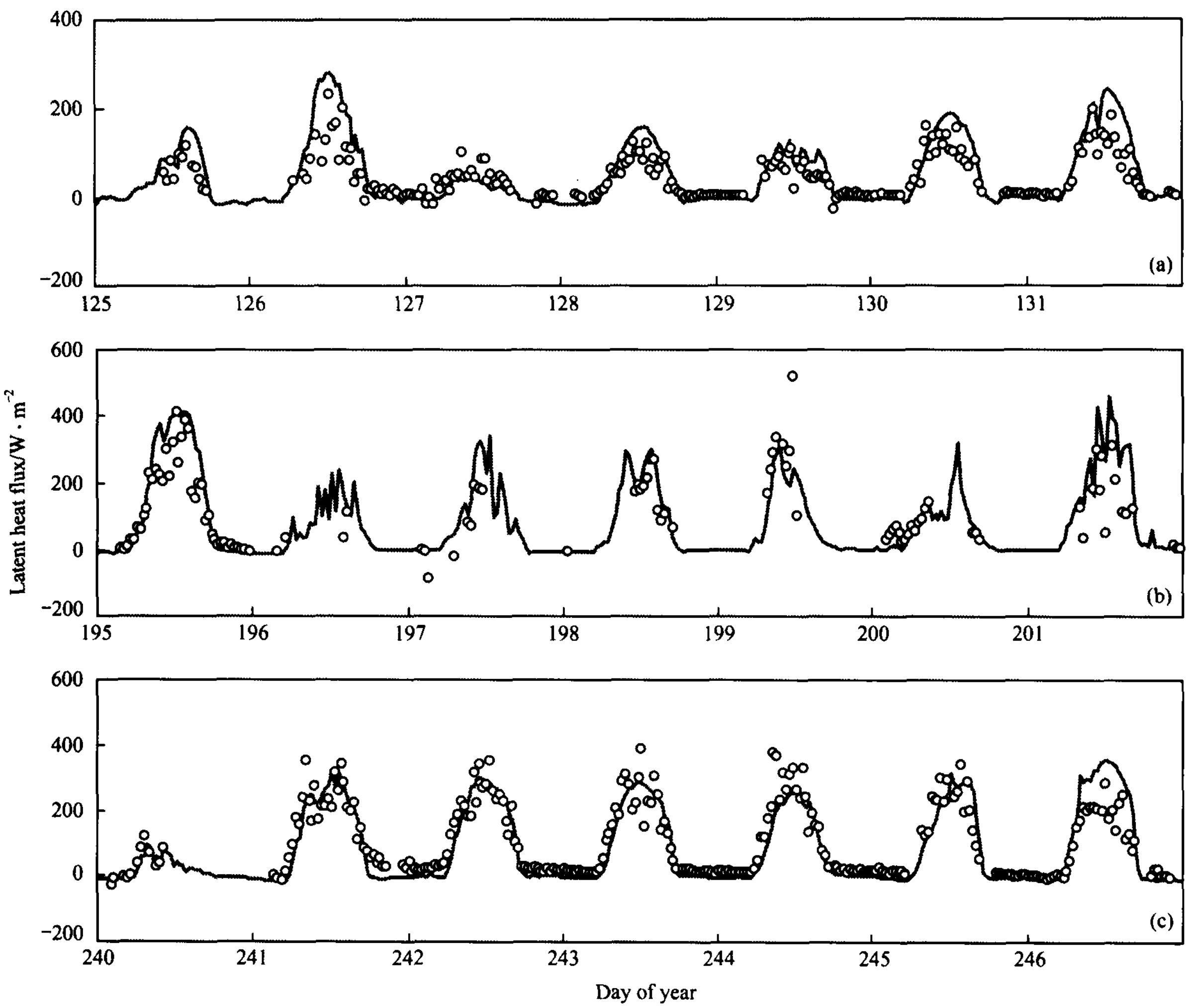

Fig. 4. The daily variation of latent heat flux of the Changbai Mountains temperate broad-leaved Korean pine ecosystem at different periods during the growing season in 2003. (a) Early growing season (DOY 125—131), (b) middle growing season (DOY 195—201), (c) late growing season (DOY 240—246), the dots are the measured values, and the line represents the simulated one.

and measured LE fluxes were in good accord during the whole growing season and the model could explain 86% of the variation of measured LE. Simulated LE during early and middle growing seasons was higher than the measured value, while it was slightly lower during the late growing season (fig. 4). This discrepancy between simulated and simulate LE resulted possibly from the errors in soil water content.

Evapotranspiration from forest consists of plant transpiration and soil evaporation. He[27] pointed out that 60% of the heat will be consumed for plant transpiration in the total evapotranspiration. We can hardly partition different components in evapotranspiration through experiment, however, model simulation could easily do. The simulated results in this study indicated that annual evapotranspiration was 297 mm in 2003, where plant transpiration was 189 mm, accounting for 63.6% of the total evapotranspiration, which was in agreement with the above proportion.

Comparison between simulated and measured sensible heat flux indicated that the model could explain 72% of the daily variation of H_s during the growing season in 2003. In general, the simulated value was lower than the measured one (fig. 5).

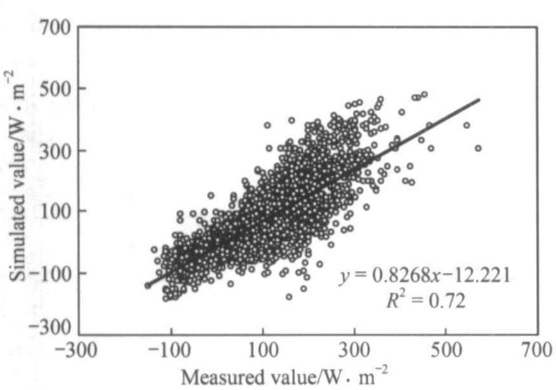

Fig. 5. The comparison of the simulated and measured sensible heat flux of the Changbai Mountains temperate broad-leaved Korean pine ecosystem during the growing season in 2003.

3.3 Sensitivity analysis of the model

(i) Effects of climate change on the flux of CO_2 and water vapor. In order to investigate the possible effect of climate change on C sequestration, water and energy balances, we run the model under several different climate changing scenarios with current solar radiation, air relative humidity, and precipitation changed by ±20%, and air temperature changed by ±2℃.

Figure 6 demonstrates the seasonal variation of accumulative NEP and ET under present and changing climate conditions simulated by the model. NEP was sensitive to the variability of all meteorological variables except solar radiation. Through varying the length of growing season, air temperature exerts influence on NEP. When air temperature increased, the growing season became longer, *vice versa*. Furthermore, under the scenario of increasing temperature, annual total of NEP trended to decrease due to the enhancement of respiration. Relative humidity impacted on NEP through its control on stomatal conductance. Increased relative humidity made stomata open wider, consequently enhanced carbon assimilation and increased NEP. The precipitation had reverse influence on NEP from temperature. ET was most sensitive to precipitation. The variability of ±20% in precipitation caused +14%—−16% changes in ET. Either increase or decrease in relative humidity will make the ET decrease to different degree. This is due to the fact that large relative humidity decreases the gradient of water vapor pressure between the atmosphere and canopy while small relative humidity increases stomatal resistance. Both effects may decrease transpiration. We should keep in mind that there are strong correlations among various meteorological variables, their influence on the fluxes of CO_2, water vapor and heat of ecosystem usually interweaves together, so it is not enough to only consider the variability of single variable here, integrated analysis are needed in future study.

From fig. 6, we found that carbon sequestration and evapotranspiration in the Changbai Mountains temperate broad-leaved Korean pine ecosystem increased sharply after the start of growing season (after snowmelt and leaf emergency). The NEP and ET accumulated before growing season did not have much effect on the values for the rest of the year, which indicated that growing season was the key period determining NEP and ET accumulation. Simulated results showed that the accumulative NEP of this ecosystem

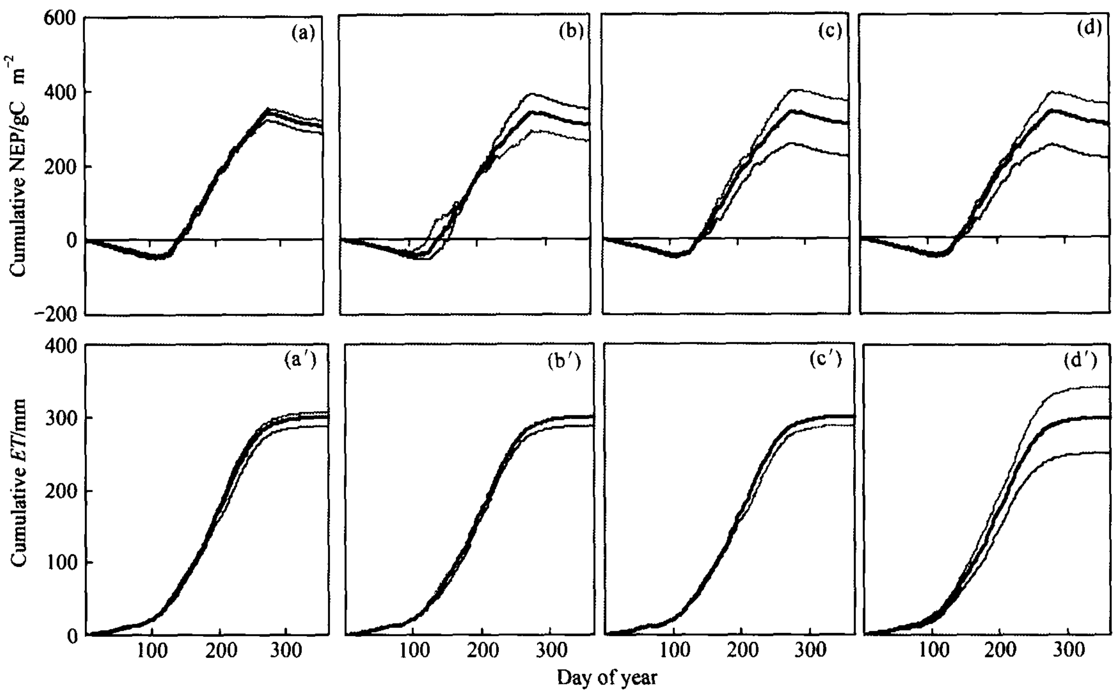

Fig. 6. The responses of simulated accumulative net ecosystem productivity (NEP) and evapotranspiration (*ET*) of the Changbai Mountains temperate broad-leaved Korean pine ecosystem in 2003 under different climate changing scenarios. Thick lines are for present climate, thin grey lines are for increase in the values of meteorological variables, thin black lines are for decrease in the values of meteorological variables. (a)(a'), solar radiation (±20%), (b)(b'), air temperature (±2℃), (c)(c'), relative humidity (±20%), (d)(d'), precipitation (±20%).

was 300.5 gC/m^2 in 2003, within the scope of the measured values 222±92 gC/m^2[21)]. This evidence proved further that the model had high enough precision in simulating carbon flux. Simultaneously, we could conclude that the forest ecosystem in the Changbai Mountains is still acting as a significant carbon sink although it is a mature one, and this was in accordance with the results of Zhang et al.[28].

(ii) Sensitivity of model parameters. As a process-based model, simulation with BEPSh model is subjected to the determination of parameters. Therefore, sensitivity of key plant physiological parameters in the model was also evaluated. Parameters tested in the sensitivity analysis included the maximum carboxylation rate (V_{cmax}) and maximum stomatal conductance (g_{max}). The results showed that 20% of increase in V_{cmax} will produce 5.7% increase in NEP, 20% decrease of V_{cmax} will lead to 8.2% decrease in NEP. NEP will decrease when g_{max} either increase or decrease. While for *ET*, g_{max} had significant influence on it, 20% increase in g_{max} will make *ET* increase 1.9%, 20% decrease in g_{max} will cause *ET* decrease 2.2%. Thus, we should be careful in determination of parameters V_{cmax} and g_{max} when applying the BEPSh model to simulate carbon and water fluxes.

4 Conclusions

In this study, we established a model, BEPSh, which can describe the daily dynamics of ecosystem fluxes at half-hourly scale, based on BEPS model and the process mechanism of the Changbai Mountains temperate broad-leaved Korean pine ecosystem. With the model, we simulated the CO_2, water vapor and heat fluxes of the Changbai Mountains temperate broad-leaved Korean pine ecosystem. The results showed that: net ecosystem productivity, latent heat flux, and sensible heat flux simulated and measured

1) Zhang, J. H., Han, S. J., Yu, G. R., Seasonal variation in carbon dioxide exchange over a 200-year-old Chinese broad-leaved Korean pine mixed forest, Agricultural and Forest Meteorology, 2004 (submitted to *Agricultural and Forest Meteorology*).

were highly correlated, with the R^2 value of 0.68, 0.86 and 0.72, respectively. The simulated and measured daily and seasonal variation of NEP, *LE* and H_s were in good agreement. However, deviation still existed between the simulated and measured values, especially at noon, which suggested that further improvements for the model are needed.

The accumulative NEP of the Changbai Mountains temperate broad-leaved Korean pine ecosystem in 2003 simulated by the model was 300.5 gC/m^2, which provided an evidence supporting the conclusion that the forest ecosystem in the Changbai Mountains acting as a carbon sink although it is a mature one. Simulated annual accumulative evapotranspiration was 297 mm in 2003, accounting for 55.3% of the total precipitation. Partitioning the evapotranspiration into plant transpiration and soil evaporation with the model made it clear that plant transpiration in the ecosystem was 189 mm, accounting for 63.6% of the total evapotranspiration.

Analysis on CO_2 and water vapor fluxes of this ecosystem under different scenarios with the model showed that: NEP was sensitive to climate change, when temperature increased, accumulative NEP tended to decrease, which indicated that the sink function of the ecosystem would be weakened under the condition of global warming.

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References

1. Running, S. W., Hunt, E. R. Jr., Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models (eds. Ehleringer, J. R., Field, C.), Scaling Processes Between Leaf and Landscape Levels, Prlando: Academic Press, 1993, 141—158.
2. Dickinson, R. E., Henderson-Sellers, A., Kennedy, P. J. et al., Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR CCM, NCAR/TN-275-STR, National Center for Atmospheric Research, Boulder, Colorado, 1986.
3. Running, S. W., Coughlan, J. C., A general model of forest ecosystem processes or regional applications I. Hydrological balance, canopy gas exchange and primary production processes, Ecol. Model, 1988, 42: 125—154.
4. Ji, J. J., A climate-vegetation interaction model: simulating physical and biological processes at the surface, J. Biogeography, 1995, 22: 445—451.
5. Sellers, P. J., Randall, D. A., Collatz, G. J. et al., A revised land surface parameterization (SiB2) for atmospheric GCMs, Part I: Model formulation, J. Climate, 1996, 9(4): 676—705.
6. McGuire, A. D., Melillo, J. M., Kicklighter, D. W. et al., Equilibrium responses of global net primary production and carbon storage to doubled atmospheric carbon dioxide: Sensitivity to changes in vegetation nitrogen concentration, Global Biogeochem. Cycles, 1997, 11: 173—189.
7. McGuire, A. D., Melillo, J. M., Randerson, J. T. et al., Modeling the effects of snowpack on heterotrophic respiration across northern temperate and high latitude regions: Comparison with measurements of atmospheric carbon dioxide in high latitudes, Biogeochemistry, 2000, 48: 91—114.
8. Foley, J. A., Prentice, I. C., Ramankutty, N. et al., An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics, Global Biogeochem. Cycles, 1996, 10(4): 603—628.
9. Liu, J., Chen, J. M., Cihlar, J. et al., A process-based boreal ecosystem productivity simulator using remote sensing input, Remote Sens. Environ., 1997, 62: 158—175.
10. Liu, J., Chen, J. M., Cihlar, J. et al., Net primary productivity distribution in the BOREAS region from a process model using satellite and surface data, J. Geophys. Res., 1999, 104(27): 735—754.
11. Liu, J., Chen, J. M., Cihlar, J. et al., Net primary productivity mapped for Canada at 1-km resolution, Global Ecol. Biogeog., 2002, 11: 115—129.
12. Liu, J., Chen, J. M., Cihlar, J, Mapping evapotranspiration based on remote sensing: An application to Canada's landmass, Water Resour. Res., 2003, 39(7): 1189.
13. Chen, J. M., Liu, J., Cihlar, J. et al., Daily canopy photosynthesis model through temporal and spatial scaling for remote sensing applications, Ecol. Model., 1999, 124: 99—119.
14. Bunkei, M., Tamura, M., Integrating remotely sensed data with an ecosystem model to estimate net primary productivity in East Asia, Remote Sens. Environ., 2002, 81: 58—66.
15. Yu, G. R., Zhang, L. M., Sun, X. M. et al., Advances in carbon flux observation and research in Asia, Science in China, Series D, 2005, 48(suppl. I): 1—16.
16. Sun, X. M., Zhu, Z. L., Xu, J. P., Determination of averaging period parameter and its effects analysis for eddy covariance measurements, Science in China, Series D, 2005, 48(suppl. I): 33—41.
17. Jin, C. J., Guan, D. X., Zhu, T. Y., Spectral characteristics of solar radiation in broad-leaved Korean pine forest in Changbai Mountains, Chin. J. Appl. Ecol. (in Chinese), 2000, 11(1): 19—21.
18. Webb, E. K., Pearman, G. I., Leuning, R., Correction of flux measurements for density effects due to heat and water vapor transfer, Quart. J. R. Meteorol. Soc., 1980, 106: 85—100.
19. Goulden, M. L., Munger, J. W., Fan, S. M. et al., Measurements of carbon sequestration by long-term eddy covariance: Methods and a critical evaluation of accuracy, Global Change Biol., 1996, 2: 169—182.

20. Guan, D. X., Wu, J. B., Yu, G. R. et al., Meteorological control on CO_2 flux above broad-leaved Korean pine mixed forest in Changbai Mountains, Science in China, Series D, 2005, 48(suppl. I): 116—122.
21. Yu, G. R., Wen, X. F., Li, Q. K. et al., Seasonal patterns and environmental control of ecosystem respiration in subtropical and temperate forests in China, Science in China, Series D, 2005, 48(suppl. I): 93—105.
22. Bonan, G. B., Land-atmosphere CO_2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model, J. Geophys. Res., 1995, 100: 2817—2831.
23. Post, W. M., Emanuel, W. R., Zinke, P. J. et al., Soil carbon pools and life zones, Nature, 1982, 298: 156—159.
24. Parton, W. J., Scurlock, J. M. O., Ojima, D. S. et al., Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide, Global Biogeochem. Cycles, 1993, 7(4): 785—809.
25. Saxton, K. E., Rawls, W. J., Romberger, J. S. et al., Estimating generalized soil-water characteristics from texture, Soil Sci. Soc. of Am. J., 1986, 50: 1031—1036.
26. Kelliher, F. M., Leuning, R., Raupach, M. R. et al., Maximum conductances for evaporation from global vegetation types, Agric. For. Meteorol., 1995, 73: 1—16.
27. He, Q. T., Meteorology (in Chinese), Beijing: Forestry Publishing House, 1991.
28. Zhang, N., Yu, G. R., Zhao, S. D. et al., Study on ecosystem productivity process model for landscape using remote sensing and surface data, Chin. J. Appl. Ecol. (in Chinese), 2003, 14(5): 643—652.