Model-Data Fusion for Carbon Flux Simulation in Typical Temperate and Subtropical Forest Ecosystems in China (Postprint)

Authors: Ge Rong, He Honglin, Ren Xiaoli, Zhang Li, Feng Ailin, Wang Huimin, Zhang Junhui

Date: 2017-03-22T00:00:00+00:00

Abstract

Research on the response of ecosystem carbon cycle processes to water availability has become one of the focal issues in global change studies. Based on carbon flux (NEE) and meteorological observation data from the growing seasons of 2003-2009 at the Changbai Mountain temperate mixed coniferous-broadleaved forest and Qianyanzhou subtropical artificial coniferous forest observation stations, comprehensively considering the effects of water on photosynthesis and respiration, different NEE models were constructed, and model-data fusion methods were applied to optimize model parameters and select the most suitable model, thereby systematically analyzing the influence of water factors on the carbon cycle of different forest ecosystems. The results show that: (1) The optimized model parameters can be well constrained by measured NEE data. Photosynthetic and respiratory parameter values during the growing season at Changbai Mountain are both higher than those at Qianyanzhou; models that did not consider vapor pressure deficit (VPD) overestimated the temperature sensitivity parameter (Q10) value and underestimated the base respiration rate parameter (BR) value at Qianyanzhou; (2) The model that only considered the effect of VPD on photosynthesis is the optimal model for simulating carbon flux during the growing season at Changbai Mountain, but the improvement in simulation accuracy is not significant. Differences in simulated carbon flux component results among different models are relatively small; (3) The model that considered the combined effects of VPD and soil water content on photosynthesis and respiration is the optimal model for simulating carbon flux during the growing season at Qianyanzhou, and significantly improved simulation accuracy. Models that did not consider water overestimated the total Gross Ecosystem Productivity (GEP) by 2.0% (21.85 g C/m2) during the growing season, while overestimating total Ecosystem Respiration (RE) by a larger magnitude of 4.4%

(38.02 g C/m2), resulting in an underestimation of total NEE by 7.8% (18.55 g C/m2) compared to measured values.

Full Text

Preamble

ACTA ECOLOGICA SINICA
ChinaXiv Partner Journal
Vol. 37, No. 5, March 2017
DOI: 10.5846/stxb201510132066

Carbon flux simulation of typical temperate and subtropical forest ecosystems in China based on model-data fusion approach

Ge Rong, He Honglin, Ren Xiaoli, Zhang Li, Feng Ailin, Wang Huimin, Zhang Junhui

Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
University of Chinese Academy of Sciences, Beijing 100049, China
Shenyang Agricultural University, Shenyang 110866, China
Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China

Abstract

The response of ecosystem carbon cycling processes to moisture has become a focal issue in global change research. Using carbon flux (NEE) and meteorological observation data from the Changbaishan temperate mixed forest and Qianyanzhou subtropical coniferous plantation sites during the 2003-2009 growing seasons, this study comprehensively considered moisture effects on both photosynthesis and respiration, applied model-data fusion methods to optimize model parameters, and selected the most suitable models. The optimized model parameters were well-constrained by observed data. The model without vapor pressure deficit (VPD) overestimated the temperature sensitivity parameter (Q10) for Qianyanzhou. The model considering only VPD effects on photosynthesis was optimal for simulating carbon fluxes during the growing season at Changbaishan, though the improvement in simulation accuracy was not significant. Photosynthetic and respiratory parameter values at Changbaishan were higher than those at Qianyanzhou, while the model underestimated the basal respiration rate parameter for Qianyanzhou. Simulated carbon flux components showed relatively small differences among different models. The model ignoring water factors overestimated gross ecosystem productivity (GEP) during the growing season while even more substantially overestimating ecosystem respiration. The model considering both VPD and soil water content (Sw) was optimal for Qianyanzhou, significantly improving simulation accuracy. The total GEP was underestimated by 2.0% (21.85 g C/m^2) compared to measured values, while total ecosystem respiration was overestimated by 7.8% (18.55 g C/m^2), and total NEE was overestimated by 4.4% (38.02 g C/m^2).

Keywords: moisture effect; carbon cycle; model-data fusion; parameter optimization; model selection

Introduction

Models are crucial tools for understanding carbon cycling processes and their controlling mechanisms. Accurately simulating and predicting terrestrial ecosystem carbon cycle dynamics has become one of the most important research questions in global change studies. The development of flux observation technology and global observation networks has provided substantial continuous data support for terrestrial ecosystem carbon cycle modeling research. Carbon cycling process-environment response models have consequently achieved considerable development and play important roles in cross-scale biogeochemical cycle modeling. These models respond to environmental factors such as light and moisture, but rarely consider moisture effects on photosynthesis and respiration simultaneously, while substantial uncertainties remain in model structures and parameters.

Moisture is a critical factor affecting ecosystem carbon cycling processes. It influences ecosystem respiration by affecting microbial activity and temperature sensitivity, and constrains ecosystem photosynthesis by regulating plant stomatal conductance, leaf water potential, and the efficiency of carbon fixation. Under global change, increased precipitation variability has expanded drought-affected regions, particularly in moisture-limited ecosystems. Research on ecosystem carbon cycle responses to moisture has received increasing attention. Richardson et al. constructed respiration response models to temperature and moisture changes, systematically analyzing moisture effects on ecosystem respiration. Lasslop et al. explored moisture importance in different vegetation photosynthesis processes. Waglé et al. developed photosynthesis response models to light and air humidity changes based on multi-site flux data. However, while moisture variations simultaneously affect both ecosystem photosynthesis and respiration, existing carbon cycle process-environment response models rarely consider these combined effects, preventing accurate analysis of moisture impacts on ecosystem carbon cycling processes. Different moisture response formulations create structural differences among models, and model parameters are difficult to estimate accurately, leading to substantial uncertainties in simulation results.

Model-data fusion methods based on Bayesian theory, developed in recent years, provide effective technical means to reduce uncertainties in modeled results by fully utilizing observation data and prior parameter information to optimize model parameters and evaluate model structures. Markov Chain Monte Carlo (MCMC) methods have been widely applied in carbon flux simulation, primarily focusing on reducing parameter uncertainties through optimization. Sacks et al. and Zobitz et al. used Bayesian Information Criterion (BIC) to compare different respiration and photosynthesis models, demonstrating the superiority of model-data fusion in model structure evaluation and selection.

The Qianyanzhou subtropical coniferous plantation and Changbaishan temperate mixed forest represent two typical forest ecosystem types along the north-south forest transect in eastern China, with significantly different moisture conditions during the growing season, providing natural experimental conditions for studying moisture effects on carbon cycling processes in different ecosystems. Qianyanzhou experiences seasonal drought due to asynchronous rainfall and heat, creating stress on ecosystem carbon cycling processes. In contrast, Changbaishan has relatively abundant moisture during the growing season and is less affected by drought. Therefore, this study uses Qianyanzhou and Changbaishan as examples to construct different carbon cycle process-environment response models considering moisture effects on photosynthesis and respiration, optimize parameters using model-data fusion methods, select optimal models for each ecosystem, and systematically analyze moisture factor effects on carbon flux simulation to reduce uncertainties in carbon flux simulation results.

1. Site Description and Research Data

The Qianyanzhou (QYZ) observation station is located within the Red Soil Hilly Agricultural Comprehensive Development Experimental Station in Jiangxi Province (26°44 N, 115°04 E, elevation 102 m). The site is an artificial coniferous forest with trees approximately 25 years old, representing a typical subtropical monsoon climate. The Changbaishan (CBS) observation station is located within a Korean pine broadleaf mixed forest in the Changbaishan Nature Reserve (41°29 N, 128°05 E, elevation 738 m), with trees approximately 200 years old, representing a typical temperate continental monsoon climate. Both sites have undergone long-term ecological monitoring and continuous carbon flux observations through the Chinese Ecosystem Research Network (CERN) and ChinaFLUX. Basic characteristics of the sites are shown in Table 1 .

Table 1 Basic characteristics of research sites

Characteristic	Qianyanzhou subtropical coniferous plantation (QYZ)	Changbaishan temperate mixed forest (CBS)
Geographic location	26°44 N, 115°04 E	41°29 N, 128°05 E
Elevation (m)	102	738
Mean annual temperature (°C)	17.8	3.6

Characteristic	Qianyanzhou subtropical coniferous plantation (QYZ)	Changbaishan temperate mixed forest (CBS)
Mean annual precipitation (mm)	1360	695
Soil type	Red soil	Mountain dark brown forest soil
Canopy height (m)	10	26

Research data include model driving data, inversion data, and validation data. Model driving data for both sites from 2003-2009 include air temperature, soil water content, photosynthetically active radiation, and vapor pressure deficit, all obtained from conventional automatic meteorological observation systems. Inversion and validation data are quality-controlled 30-minute eddy covariance carbon flux observation data. The specific processing workflow follows Li et al. [31]. Flux data from 2005-2009 were used for model parameter optimization, while data from 2003-2006 were used for model validation.

2. Model Development

Net ecosystem carbon exchange (NEE) is the balance between gross ecosystem productivity (GEP) and ecosystem respiration (RE). Based on temperature-response respiration models and light-response photosynthesis models, this study comprehensively considered soil moisture and air moisture factors to develop four different NEE models describing different forms of carbon cycling process responses to moisture.

2.1 Respiration Model

The Lloyd & Taylor model is widely recognized and applied as a temperature response model for ecosystem respiration, better describing ecosystem respiration variability with strong response capacity to temperature changes under both low and high temperature conditions. The model uses temperature and soil water content as driving variables to describe the synergistic effects of temperature and moisture on ecosystem respiration, assuming that the temperature sensitivity factor Q10 is closely related to soil moisture status. Compared to other temperature-moisture models (such as multiplicative models), this model shows stronger sensitivity to temperature and moisture under dry soil conditions.

The respiration model is expressed as:

$$RE = BR \times Q_{10}^{\frac{T-10}{10}}$$

where RE is ecosystem respiration (mol m ^{2} s ^{1}), BR is basal ecosystem respiration at reference temperature, Q_{10} is the temperature sensitivity factor of ecosystem respiration representing the relative increase in respiration for a 10°C temperature rise, and T is air temperature (°C).

When considering soil water content effects:

$$RE = BR \times Q_{10}^{\frac{T-10}{10}}$$

$$Q_{10} = a + b \times Sw$$

where Sw is soil water content, and a and b are experimental parameters. When b is positive, it indicates that ecosystem respiration temperature sensitivity increases with increasing moisture.

2.2 Photosynthesis Model

Ecosystem photosynthesis intensity shows significant correlation with photosynthetically active radiation, typically following a rectangular hyperbolic equation. Based on the Michaelis-Menten model, this study replaced the maximum photosynthetic rate A_{max} with an exponential decay function considering VPD to express the synergistic response to photosynthetically active radiation and vapor pressure deficit. Higher VPD indicates drier air and weaker ecosystem CO uptake capacity.

The photosynthesis model is expressed as:

$$GEP = \frac{A_{max} \times LUE \times PAR}{A_{max} + LUE \times PAR}$$

When considering VPD effects:

$$A_{max} = A_{max0} \times \exp(-k \times (VPD - VPD_0)) \quad \text{for } VPD > VPD_0$$

where GEP is gross ecosystem productivity (mol m ^{2} s ^{1}), LUE is initial light use efficiency (mol CO / mol light), A_{max} is maximum photosynthetic rate at light saturation, PAR is photosynthetically active radiation (mol light m ^{2} s ^{1}), VPD is air saturation vapor pressure deficit at canopy height (hPa), $VPD_0 = 10$ hPa, A_{max0} is maximum photosynthetic rate under VPD constraints, and k is the maximum coefficient of ecosystem carbon uptake response to VPD.

2.3 Model Combinations

Four model combinations were developed by integrating different photosynthesis and respiration models (Table 2).

Table 2 Four combinations of photosynthetic and respiration models

Model	Respiration Model	Photosynthesis Model	Parameters
Model 1	Lloyd & Taylor	Michaelis-Menten	A_{max}, LUE, BR, Q_{10}
Model 2	Lloyd & Taylor	Michaelis-Menten-VPD	A_{max0}, LUE, k, BR, Q_{10}
Model 3	Lloyd & Taylor-Sw	Michaelis-Menten	A_{max}, LUE, BR, Q_{10}, a, b
Model 4	Lloyd & Taylor-Sw	Michaelis-Menten-VPD	A_{max0}, LUE, k, BR, Q_{10}, a, b

3. Parameter Estimation Method

The Markov Chain Monte Carlo (MCMC) method employed in this study is based on Bayesian theorem and uses computer simulation. It infers parameter posterior information by constructing Markov chains to iteratively search for global optimal solutions. Compared to traditional methods such as least squares and maximum likelihood, MCMC can solve complex nonlinear problems with numerous parameters, combines prior ecological model parameter knowledge with observation sample information for more accurate parameter estimation, and provides parameter posterior distributions and confidence intervals for uncertainty analysis.

The Metropolis-Hastings algorithm is the most commonly used MCMC method. Its main steps are: (1) initialize parameter values θ within prior ranges (random or specified), set iteration count $t = 0$; (2) generate parameter proposals Y from proposal distribution; (3) calculate acceptance probability $\alpha = \min\left(1, \frac{q(\theta_t|Y)}{q(Y|\theta_t)}\right)$; (4) generate uniform random number $U(0, 1)$, accept parameter proposal if $U < \alpha$, otherwise reject; (5) repeat until sufficient samples are obtained.

According to Bayesian theory, solving for parameter set posterior probability density can be transformed into solving the likelihood function. This study assumes observation errors follow a normal distribution and uses a simple log-likelihood function:

$$LL = -\frac{N}{2}\ln(2\pi) - \frac{N}{2}\ln(\sigma^2) - \frac{1}{2\sigma^2}\sum_{i=1}^{N}(x_i - \eta_i)^2$$

where N is the number of observations, x_i and η_i are the ith observed and simulated values respectively, and σ is the standard deviation of observations.

4. Model Evaluation Method

Traditional model evaluation methods include comparing likelihood values, coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE) between simulated and observed values, but these ignore differences in parameter composition and number caused by different model structures. The Bayesian Information Criterion (BIC) used in this study considers not only model-data matching but also parameter count and number of data points used in fitting, thereby avoiding model structure redundancy and data overfitting, and enabling selection of the most parsimonious model with best simulation performance from different candidates.

$$BIC = -2LL + K\ln(n)$$

where n is the number of data points used in optimization, K is the number of optimized parameters, and LL is the log-likelihood value. Smaller BIC values indicate better models.

5. Results and Discussion

5.1 Parameter Optimization Results

Based on meteorological and carbon flux observation data from 2003-2009 at both forest ecosystems, the four model parameters were optimized to obtain posterior distributions and optimal parameter sets. All parameter posterior distributions were normally distributed with small standard deviations: photosynthetic parameter standard deviations were controlled within 5% of mean values, while respiratory parameter standard deviations were within 10%, indicating that optimized parameters were well-constrained by observed data (Table 3).

Table 3 Parameter optimization results

[Parameter optimization table with posterior values, prior ranges for QYZ and CBS sites across four models]

Comparing ecosystem photosynthetic parameters revealed minor variations among different models but significant differences between ecosystems. As an artificial forest ecosystem, QYZ has strong photosynthetic capacity, with light use efficiency (LUE) of 0.03 mol CO / mol light and maximum photosynthetic rate (A_{max}) of 2.20 mol CO m ^{2} s ^{1} during the growing season. In contrast, CBS, as temperate deciduous forest distinct from subtropical evergreen coniferous forest, has distinct growing and non-growing seasons. Therefore, during the limited growing season, vegetation exhibits characteristics of efficiently utilizing available water and heat resources. However, CBS is influenced by the subtropical high-pressure belt in summer, easily forming high temperature and drought conditions that limit photosynthetic capacity.

Comparing ecosystem respiratory parameters, variations among models mainly appeared in BR and Q_{10} parameters. The BR and Q_{10} values for CBS ecosystem were significantly higher than those for QYZ. When moisture factors were considered in models, Q_{10} values decreased (-0.89 to -0.97). Strong negative correlations existed between BR and Q_{10} across all four models because respiration temperature sensitivity is positively correlated with moisture. The model considering VPD effects on photosynthesis could obtain parameters with physical meaning. The model considering Sw effects showed similar parameter scatter distributions, indicating that moisture-considering models can correct Q_{10} values.

Ecosystem differences in respiratory parameters reflected that BR and Q_{10} values during the growing season at CBS were significantly higher than at QYZ (45% and 37% higher respectively), accurately reflecting carbon cycling characteristics of temperate versus subtropical forests during the growing season. This is mainly because QYZ is at lower latitude with higher temperatures, and both BR and Q_{10} decrease with decreasing latitude and increasing temperature. Additionally, the Korean pine forest at CBS is older with higher soil organic matter content, thus having relatively more respiratory substrates and higher respiratory parameter values.

5.2 Optimal Model Selection

Using optimized parameters and meteorological observation data, the four models simulated carbon fluxes for both forest ecosystems. BIC was applied to quantitatively compare simulation performance of models with different moisture considerations (Table 4).

Table 4 Model selection results based on BIC method

[Model selection table showing LL and BIC values for four models at both sites]

For Changbaishan, the model considering only VPD effects on photosynthesis (Model 2) was optimal for growing season carbon flux simulation, but its performance improvement was minimal (BIC decreased by only 0.83). Precipitation and temperature show consistent unimodal seasonal variation at CBS. As a temperate continental monsoon climate with lower annual temperatures and strong soil water holding capacity, VPD remains at relatively high levels without clear limitation on ecosystem respiration. However, less precipitation from March-May with maintained temperatures creates distinct bimodal seasonal variation, limiting photosynthesis during the growing season. Studies also indicate that northern forest ecosystem photosynthesis is more sensitive to precipitation changes. Therefore, models considering moisture effects on photosynthesis can more accurately simulate temperate forest ecosystem responses to global change.

For Qianyanzhou, the model considering both VPD and Sw effects (Model 4) was optimal for growing season carbon flux simulation, with significantly improved performance (BIC decreased by 0.14, a 21% improvement). QYZ has a typical subtropical monsoon climate, controlled by subtropical high pressure in summer with obvious asynchronous water-heat patterns, easily forming summer droughts that significantly limit both photosynthesis and respiration during the growing season. The BIC method successfully selected parsimonious models, demonstrating its superiority in model selection.

5.3 Effects of Moisture Factors on Carbon Flux Simulation

Using optimized parameters, the four models decomposed annual growing season carbon flux simulations (2003-2009) and analyzed responses of different carbon flux components (NEE, RE, GEP) to moisture (Table 5).

Table 5 The sum of NEE, GEP and RE modeled by different models during growing season

[Carbon flux component totals table for QYZ and CBS across four models]

At Qianyanzhou, the optimal model considering both VPD and Sw effects (Model 4) produced simulations closest to observed values, with total GEP during the growing season only 2.0% (21.85 g C/m²) lower than measured values. The model without moisture factors performed worst, overestimating total GEP by 7.8% (18.55 g C/m²) and even more substantially overestimating total RE by 4.4% (38.02 g C/m²), resulting in overall NEE underestimation. Different moisture response models showed relatively small simulation differences at CBS.

Moisture factors affected carbon flux components differently. At QYZ, the VPD factor mainly caused GEP overestimation, while the Sw factor mainly caused RE overestimation. The model considering both factors could accurately simulate the asymmetric diurnal variation trend of NEE during drought periods, while the model ignoring water factors could not simulate this asymmetry and underestimated NEE. During extreme drought years (2003, 2007), models considering moisture factors significantly reduced simulation errors, with RMSE decreasing markedly compared to normal years.

6. Conclusion

Using Qianyanzhou subtropical coniferous plantation and Changbaishan temperate mixed forest ecosystems as examples, this study applied model-data fusion methods to optimize parameters for different carbon cycle process response models, select optimal models, and systematically analyze moisture effects on carbon flux simulation in different ecosystems. Main conclusions are:

1. Optimized photosynthetic and respiratory parameters were well-constrained by observed data with normally distributed posteriors and small standard deviations. Parameter differences among models were minor, but ecosystem differences were significant. The model without VPD overestimated QYZ' s Q10 values and underestimated basal respiration rates. Respiratory parameter differences accurately reflected carbon cycling characteristics of temperate versus subtropical forests during growing seasons.

2. The model considering both VPD and Sw effects, and the model considering only VPD effects, were optimal for QYZ and CBS respectively. Moisture factors significantly improved QYZ simulation performance but contributed minimally to CBS improvement. For CBS, considering moisture effects on photosynthesis was the main reason for simulation improvement, while for QYZ, both VPD and Sw were important controlling factors for growing season carbon flux exchange.
3. Different moisture response models showed small differences in carbon flux component simulation at CBS. The model ignoring water factors overestimated GEP during the growing season while substantially overestimating RE, leading to NEE underestimation by 2.0% (21.85 g C/m^2). At QYZ, the VPD factor mainly affected GEP while Sw mainly affected RE.

The integrated model-data fusion method proposed in this study can be further applied to complex terrestrial ecosystem processes, providing an effective approach for improving ecosystem model structures and reducing simulation uncertainties.

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Note: Figure translations are in progress. See original paper for figures.