Optimization and Validation of the Vegetation Photosynthesis and Respiration Model in the Temperate Broadleaf-Korean Pine Forest of Changbai Mountain: Postprint

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Abstract

The determination and optimization of key parameters in the Vegetation Photosynthesis and Respiration Model (VPRM) are fundamental to accurately calculating Net Ecosystem CO2 Exchange (NEE). Using flux observation data from 2005 for a temperate broadleaf-Korean pine forest at the Changbai Mountain station of the China Flux Observation and Research Network (ChinaFLUX), four parameters of VPRM (maximum light use efficiency 0, photosynthetically active radiation value under half-saturation light conditions PAR0, and respiration parameters (α, β)) were optimized, and observation data from 2006 were used to evaluate the simulation results before and after parameter optimization. The results indicate that after parameter optimization, VPRM can satisfactorily simulate the variation of NEE during the 2006 plant growing season in the Changbai Mountain region. The mean error for 30-min NEE simulation was -1.81 mol m-2 s-1, with a correlation coefficient of 0.72; the peak value of simulated mean diurnal NEE variation was approximately 91% of the observed value, with a correlation coefficient of 0.97. However, the model' s simulation of forest NEE during the plant non-growing season was relatively poor. The mean error of simulated 30-min NEE was 0.39 mol m-2 s-1, with a correlation coefficient of only 0.10, and the simulation underestimated the daytime uptake peak of mean diurnal NEE variation by approximately 82%; the correlation coefficient between simulated and observed diurnal variation was 0.50. Through analysis of different weather cases, it was found that the model could satisfactorily simulate NEE variation under clear-sky conditions, while the simulation error for NEE was relatively large during rainy conditions. This study is beneficial for improving the VPRM model' s simulation capability for NEE in temperate deciduous broadleaf forests and holds significant importance for further improving regional terrestrial NEE simulation.

Full Text

Preamble

Optimization and Validation of the Vegetation Photosynthesis and Respiration Model in a Temperate Broad-Leaved Korean Pine Forest

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Abstract

Optimizing key parameters of the Vegetation Photosynthesis and Respiration Model (VPRM) is crucial for accurately calculating net ecosystem CO_2 exchange (NEE). This study utilized flux observation data from 2005 at the Changbai Mountain (CBS) temperate broad-leaved Korean pine forest station of ChinaFLUX to optimize four VPRM parameters: maximum light use efficiency ($_0$), half-saturation value of photosynthetically active radiation (PAR_0), and two respiration parameters (α and β). The optimized VPRM was then evaluated using 2006 observational data. With optimized parameters, the model accurately simulated NEE variation during the 2006 growing season. For 30-min NEE simulations, the mean bias was -1.81 mol m^{-2} s^{-1} and the correlation coefficient was 0.72. For daily variation, the peak NEE value was underestimated by 9% with a correlation coefficient of 0.97. However, VPRM could not accurately simulate NEE during the non-growing season, with a mean bias of 0.39 mol m^{-2} s^{-1} and correlation coefficient of only 0.10 for 30-min NEE. Daily variation simulations showed the peak was underestimated by 82% with a correlation coefficient of 0.50. Further analysis revealed that VPRM performs better on sunny days than on cloudy or rainy days. This study facilitates application of VPRM to temperate deciduous broad-leaved forests and provides important insights for improving regional terrestrial ecosystem NEE simulations.

Keywords: Vegetation Photosynthesis and Respiration Model (VPRM); net ecosystem CO_2 exchange (NEE); parameter optimization; temperate broad-leaved Korean pine forest; Changbai Mountain

1. Introduction

The interaction between global climate change and terrestrial ecosystem carbon cycling represents a major focus of scientific research. A primary objective of ecosystem carbon cycle studies is to quantify net CO_2 exchange between the atmosphere and terrestrial ecosystems and identify its driving forces across spatiotemporal scales. Eddy covariance technology can accurately measure CO_2 fluxes between terrestrial ecosystems and the atmosphere and has been widely used to determine NEE across diverse global ecosystem types. However, due to limitations in observation height, wind direction, and underlying surface conditions, the actual observation area of eddy covariance is relatively small and not spatially representative. Satellite remote sensing can sample ecosystem components at regular frequencies (typically several kilometers) and cover regional to global scales, making vegetation productivity models based on remote sensing crucial for estimating productivity across different regional ecosystems.

Remote sensing-based vegetation productivity models have been used to simulate gross primary productivity (GPP). Early models established statistical relationships between ground-observed vegetation productivity and remote sensing-derived vegetation indices. Paruelo et al. used the relationship between aboveground vegetation productivity and Normalized Difference Vegetation Index (NDVI) to estimate productivity in central U.S. grasslands. However, such models neglect plant physiological processes and are highly empirical, requiring re-parameterization when applied outside study areas. Light use efficiency models utilize NDVI to estimate the fraction of photosynthetically active radiation absorbed by vegetation (FAPAR), enabling GPP estimation based on plant physiological processes. Examples include the first-generation Carnegie-Ames-Stanford Approach (CASA) model, the C-Fix model, and the EC-LUE model that integrates eddy covariance observations.

Xiao et al. developed the VPM (Vegetation Photosynthesis Model) using Enhanced Vegetation Index (EVI) and ground-based eddy covariance data, which improved simulation of GPP for different vegetation types by considering phenological effects on light use efficiency. Mahadevan et al. further developed VPRM (Vegetation Photosynthesis and Respiration Model) by adding a respiration term, enabling direct NEE simulation. VPRM incorporates nonlinear light response, temperature sensitivity of photosynthesis, and phenological influences, making it suitable for regional NEE simulation. However, accurate simulation requires optimization of parameters representing vegetation physiological characteristics.

Mahadevan et al. optimized VPRM parameters using 25 North American flux sites, obtaining parameters suitable for different North American vegetation types. However, these parameters may not apply to monsoon-affected regions like China. Previous studies have optimized VPRM parameters for subtropical coniferous forests, but few have focused on China’ s climate-sensitive temperate forest ecosystems. Temperate coniferous-broadleaf mixed forests represent a major forest type widely distributed in northeast China’ s temperate climate zone. This study aims to optimize VPRM parameters using flux data from the Changbai Mountain temperate broad-leaved Korean pine forest station of ChinaFLUX, evaluate model performance for temperate mixed forests, and develop parameter sets suitable for this forest type to improve VPRM simulation capability and provide references for future regional applications.

2. Study Area

The Changbai Mountain temperate Korean pine broad-leaved forest flux observation station is located in Erdaobaihe Town, Antu County, Yanbian Korean Autonomous Prefecture, Jilin Province, within the Changbai Mountain Nature Reserve. The geographical location, climate, and vegetation conditions are summarized in .

The geography, climate and vegetation condition in ChangBai station

Parameter	Description
Location	Erdaobaihe Town, Antu County, Yanbian Korean Autonomous Prefecture, Jilin Province
Latitude and longitude	42°24 9 N, 128°05 45 E
Altitude	738 m
Climate type	Temperate monsoon climate
Annual mean precipitation	713 mm
Annual sunshine hours	2271–2503 h
Annual mean temperature	3.6°C
Frost-free period	109–141 days
Vegetation types	Temperate coniferous-broadleaf mixed forest
Dominant species	Korean pine, Mongolian oak, Manchurian ash, etc.

3. Model Description

The Vegetation Photosynthesis and Respiration Model (VPRM) was developed based on the VPM model. Detailed model description is available in the literature; this paper provides a brief overview. The model structure is shown in

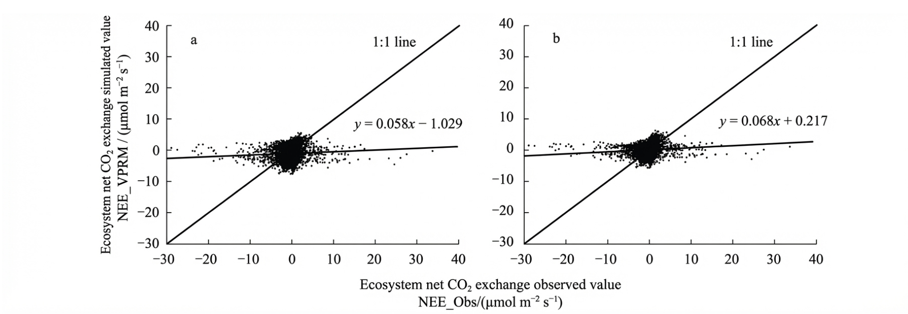

Figure 1: Figure 1

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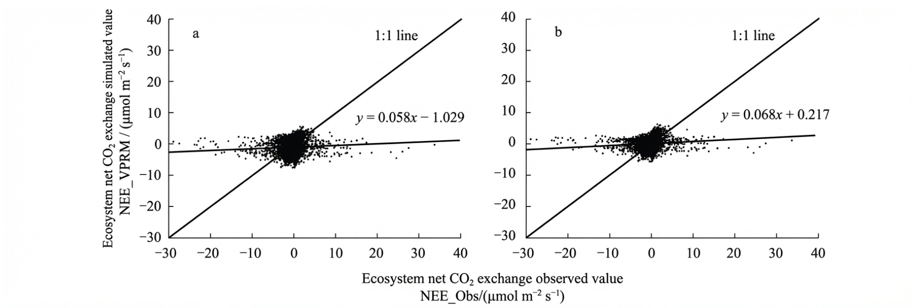

Figure 2: Figure 1

Schematic diagram of the Vegetation Photosynthesis and Respiration Model (VPRM)

NEE is calculated as the sum of two components: gross ecosystem exchange (GEE) driven by light, and ecosystem respiration (R) driven by temperature:

$$NEE = -GEE + R_e$$

The negative sign indicates CO_2 uptake by the ecosystem. GEE is calculated as:

$$GEE = \varepsilon \times \frac{PAR}{PAR_0 + PAR} \times FAPAR \times PAR$$

where is light use efficiency under low light conditions, PAR is photosynthetically active radiation, PAR_0 is the half-saturation value of PAR, and FAPAR is the fraction of PAR absorbed by vegetation.

In VPRM, light use efficiency is calculated as:

$$\varepsilon = \varepsilon_0 \times T_{scale} \times W_{scale} \times P_{scale}$$

where $_0$ is maximum light use efficiency, and T_{scale}, W_{scale}, and P_{scale} represent temperature sensitivity, water availability, and phenology effects on photosynthesis, respectively.

T_{scale} is calculated as:

$$T_{scale} = \frac{(T - T_{min})(T - T_{max})}{(T - T_{min})(T - T_{max}) - (T - T_{opt})^2}$$

when T_{min} < T < T_{max}; otherwise T_{scale} = 0. T_{min}, T_{max}, and T_{opt} represent minimum, maximum, and optimum temperatures for photosynthesis.

For this study, T_{opt} was determined by analyzing temperature intervals and corresponding NEE values from Changbai station data, yielding T_{opt} = 28°C. T_{min} and T_{max} were set to 0°C and 40°C, respectively.

W_{scale} is calculated as:

$$W_{scale} = \frac{1 + LSWI}{1 + LSWI_{max}}$$

where LSWI is land surface water index and LSWI_{max} is the maximum LSWI during the growing season.

P_{scale} represents phenological status, ranging from 0 to 1.

VPRM simplifies ecosystem respiration as a linear function of air temperature:

$$R_e = \alpha \times T + \beta$$

where α and β are respiration parameters, along with $_0$ and PAR_0, that can be optimized using local observations.

4. Remote Sensing Data Acquisition

Satellite data were extracted from MODIS09A1 (500 m spatial resolution, 8-day temporal resolution) covering the observation site. EVI and LSWI were calculated using blue (459-479 nm), red (620-670 nm), near-infrared (841-875 nm), and shortwave infrared (1628-1652 nm) bands:

$$EVI = G \times \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + C_1 \times \rho_{red} - C_2 \times \rho_{blue} + L}$$

where G = 2.5, C_1 = 6, C_2 = 7.5, and L = 1. represents surface reflectance for each band.

$$LSWI = \frac{\rho_{nir} - \rho_{swir}}{\rho_{nir} + \rho_{swir}}$$

where swir represents the shortwave infrared band (1628-1652 nm).

5. Flux Observation and Microclimate Data

NEE flux data were obtained from an open-path eddy covariance system installed on a meteorological tower within the sample plot. The system consisted of a three-dimensional sonic anemometer (CSAT3, Campbell, USA) and an infrared gas analyzer (Li-7500, Li-Cor, USA) with a sampling frequency of 10 Hz. Flux averaging time was 30 min. Detailed tower descriptions and data processing followed ChinaFLUX protocols.

The meteorological tower included a multi-level conventional meteorological observation system measuring air temperature, humidity, wind speed, soil temperature, soil moisture, soil heat flux, and total radiation. Photosynthetically active radiation was measured by a quantum sensor.

6. Data Preprocessing

Data processing followed ChinaFLUX standard procedures for the 2005–2006 Changbai Mountain dataset, including: - Quality control: removal of precipitation-period data, outliers beyond thresholds, and data deviating by more than 3 standard deviations - Coordinate rotation - Calculation of storage term - Application of friction velocity threshold for nighttime data

7. Parameter Optimization and Validation

The optimization scheme consisted of two steps: 1. **Respiration parameter optimization**: Using 2005 nighttime NEE data (when no photosynthesis occurs), α and β were obtained through linear regression between NEE and temperature. 2. **Photosynthesis parameter optimization**: Using daytime data with known α, β, T_{scale}, W_{scale}, P_{scale}, EVI, and PAR, $_0$ and PAR_0 were fitted.

Validation involved comparing simulated and observed NEE for both growing season (May–September) and non-growing season (January–April and October–December) using both original and optimized parameters. Statistical analyses included regression analysis, comparison of mean diurnal variations, and evaluation under different weather conditions.

8. Results and Analysis

8.1 Parameter Optimization

Using 2005 Changbai Mountain observations, VPRM parameters were optimized for the broad-leaved Korean pine forest. Original parameters were from Mahadevan et al.' s North American sites. Optimized parameters showed substantial differences, reflecting local climate and vegetation characteristics ().

Parameters of VPRM

Parameter	Original	Optimized
$_0$ (mol CO_2/ mol PPFD)	0.127	0.351
PAR_0 (mol m^{-2} s^{-1})	570.0	279.6
α (mol CO_2 m^{-2} s^{-1} °C^{-1})	0.271	0.246
β (mol CO_2 m^{-2} s^{-1})	0.250	1.541

The optimized $_0$ (0.351) was 2.76 times the original value, while PAR_0 decreased to 49% of the original. These differences reflect distinct photosynthetic physiological characteristics between ecosystems.

8.2 Growing Season Simulation

During the 2006 growing season, optimized parameters substantially improved NEE simulation ([FIGURE:2], [FIGURE:3]). For 30-min NEE, the mean bias improved from -3.19 to -1.81 mol m^{-2} s^{-1}, and correlation increased from 0.488 to 0.72. The regression slope improved from 0.488 to 0.911.

For mean diurnal variation ([FIGURE:3], [FIGURE:4]), optimized parameters captured the peak NEE of -13.27 mol m^{-2} s^{-1} (observed: -14.66 mol m^{-2} s^{-1}), compared to the original parameter simulation of -6.32 mol m^{-2} s^{-1}. Mean error decreased from 5.77 to -0.06 mol m^{-2} s^{-1}, and RMSE decreased from 6.76 to 2.17 mol m^{-2} s^{-1}. The model showed slight underestimation of nighttime respiration, likely due to the linear temperature response function.

8.3 Non-Growing Season Simulation

Both original and optimized parameters performed poorly during the non-growing season ([FIGURE:5], [FIGURE:6], [FIGURE:7]). For 30-min NEE, mean biases were 0.39 and -0.86 mol m^{-2} s^{-1}, respectively, with correlation coefficients of only 0.10 and 0.25. Daily peak NEE was underestimated by 82% with optimized parameters.

The poor performance stems from the linear temperature-respiration relationship, which does not capture the exponential temperature dependence of ecosystem respiration at low temperatures. Additionally, respiration correlates more strongly with soil temperature than air temperature in temperate forests.

8.4 Weather Effects

Analysis of sunny (DOY 204–210) and cloudy/rainy (DOY 160–166) periods revealed distinct performance differences ([FIGURE:8], [FIGURE:9]). Under sunny conditions with $PAR > 1200$ mol m^{-2} s^{-1}, the model accurately simulated NEE dynamics, capturing the delayed GEE peak (1–2 hours after solar noon) and stable respiration patterns.

Under cloudy/rainy conditions ($PAR < 1200$ mol m^{-2} s^{-1}), the model failed to reproduce observed NEE fluctuations. Simulated peaks were -4.77 to -10.14

mol m^{-2} s^{-1} versus observed -18.45 to -24.67 mol m^{-2} s^{-1}. The model also could not capture the increased respiration caused by nighttime cloud cover and downward longwave radiation. Cloudy/rainy days accounted for 63 days (41.2% of the growing season), significantly impacting overall simulation quality.

9. Discussion

The optimized $_0$ (0.351 mol CO_2/ mol PPFD) for Changbai Mountain's temperate broad-leaved Korean pine forest exceeds values reported for North American deciduous broad-leaved forests (0.127-0.156). This likely reflects the monsoon climate with abundant water resources that enhance photosynthetic capacity. Parameter optimization significantly improved growing season simulations but revealed limitations in non-growing season performance, consistent with previous studies.

The linear respiration-temperature relationship is inadequate, as ecosystem respiration increases exponentially with temperature and correlates more strongly with soil temperature (explaining ~70% of variation) than air temperature (~50%). Future model improvements should incorporate exponential temperature functions and soil temperature data. Additionally, the model does not account for soil moisture effects on respiration or enhanced photosynthesis under diffuse radiation during cloudy conditions, contributing to simulation uncertainties.

Data quality issues during cloudy periods, including noise in remote sensing data, further affect model performance. While Mahadevan et al. and Hilton et al. achieved better correlations (0.91) using multiple North American sites, their studies did not address non-growing season limitations. This study's single-site, two-year dataset limits generalizability; multi-site, long-term observations would better capture climate and vegetation variations.

10. Conclusion

This study optimized VPRM parameters for the Changbai Mountain broad-leaved Korean pine forest using ChinaFLUX data. Key findings:

1. Optimized parameters ($_0$ = 0.351 mol CO_2/ mol PPFD, $PAR_0 = 279.6$ mol m^{-2} s^{-1}, $\alpha = 0.246$ mol CO_2 m^{-2} s^{-1} °C^{-1}, $\beta = 1.541$ mol CO_2 m^{-2} s^{-1}) effectively simulated growing season NEE with mean bias of -1.81 mol m^{-2} s^{-1} and correlation of 0.72.

2. Non-growing season simulation remained poor (correlation = 0.10–0.25) due to the linear temperature-respiration formulation.

3. The model performed well under sunny conditions but showed large uncertainties during cloudy/rainy periods, which constitute over 40% of the growing season.

These results improve VPRM applicability to temperate mixed forests and highlight needs for model structural improvements, particularly respiration parameterization and weather-dependent processes, to enhance regional carbon cycle simulations.

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