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Coupling a Terrestrial Biogeochemical Model to the Common Land Model

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ABSTRACT

A terrestrial biogeochemical model (CASACNP) was coupled to a land surface model (the Common Land Model, CoLM) to simulate the dynamics of carbon substrate in soil and its limitation on soil respiration. The combined model, CoLM_CASACNP, was able to predict long-term carbon sources and sinks that CoLM alone could not. The coupled model was tested using measurements of belowground respiration and surface fluxes from two forest ecosystems. The combined model simulated reasonably well the diurnal and seasonal variations of net ecosystem carbon exchange, as well as seasonal variation in the soil respiration rate of both the forest sites chosen for this study. However, the agreement between model simulations and actual measurements was poorer under dry conditions. The model should be tested against more measurements before being applied globally to investigate the feedbacks between the carbon cycle and climate change.

Key words: CoLM_CASACNP model, terrestrial carbon cycle, carbon flux

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1. Introduction

The response of the terrestrial carbon cycle to increasing atmospheric carbon dioxide and climate warming is a key uncertainty in future climate change projections (IPCC, 2007). One of the most important advances in climate prediction over the last two decades has been the implementation of global carbon cycle into climate models (Friedlingstein et al., 2006). As a result, predictions of future climate can be made for any given greenhouse-gas emission scenario, rather than atmospheric concentrations that may also vary with climate change. This advancement has made it possible to attribute the predicted climate change to emissions from different sections or countries since the industrial revolution and to integrate biophysical models of climate systems with socioeconomic drivers of greenhouse gas emissions. However, the carbon cycle has yet to be implemented in any climate models developed in China (Wang et al., 2009). The Common Land Model (CoLM; Dai et al., 2003, 2004) has recently been coupled to

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*Corresponding author: SHI Xiaoying, sxymjf@gmail.com the Global/Regional Assimilation and Prediction System (GRAPES), which is a new-generation numerical weather prediction system independently developed by the Chinese (Xu et al., 2008). Although the carbon cycle of CoLM needs to be improved further, nitrogen and phosphorus cycles were recently added into Carnegie-Ames-Stanford Approach (CASA′) carbon model (Fung et al., 2005) to create a new biogeochemical model, termed CASACNP (Wang et al., 2010). Thus, we coupled CASACNP to CoLM. In this context, this study is a first step toward the development of a climate model with a fully interactive carbon cycle element, or an earth system model, in China.

To achieve this, two existing models, the CoLM and the CASACNP model were combined to create a new model, CoLM_CASACNP. CoLM is an advanced, process-based, land-surface model that includes a comprehensive set of mechanistic descriptors of physical soil processes and biophysical vegetation processes, and that calculates gross primary productivity (GPP) and respiration from leaf and soil. It does not, however, include respiration from wood and roots nor does it take into account the nutrient limitation on carbon uptake. CASACNP is a biogeochemical model with a process-based representation of heterotrophic respiration from a number of discrete organic pools that simulates long-term changes in terrestrial carbon stocks at daily time steps. Neither model alone can meet the broader needs described above: CoLM cannot predict long-term carbon sources and sinks, and CASACNP cannot predict Net Ecosystem Exchange (NEE) on diurnal time scales, and neither can predict autotrophic respiration alone.

To drive the CASACNP component, it was necessary to provide, as inputs, daily amounts of GPP, leaf respiration, and daily mean soil temperatures and soil moisture calculated by CoLM, as well as air temperatures from observation data as meteorological forcing data. In the formulation of CASACNP, wood and root respiration is a function of wood/root pool size and air and soil temperature, and net primary production (NPP) is calculated from GPP, as computed by CoLM, and autotrophic respiration, including leaves, wood and root respiration. Coupling the two models creates a platform suitable for studying how climate and other factors affect carbon-cycle dynamics and the interactions between climate change and the terrestrial carbon cycle.

Therefore, the objectives of this study were the following: (1) to improve the carbon cycle process of CoLM to predict ecosystem carbon dynamics over decades or centuries; and (2) to compare the modeled NEE and soil respiration rates (SRP) using the new coupled model with field measurements at two chosen forest sites, the Dinghushan Biosphere Reserve (DBR) and the Walker Branch Watershed (WBW). The paper is organized as follows: the CoLM_CASACNP coupled model is described in section 2; the data, methods, and offline experimental design are described in section 3; section 4 presents an evaluation of simulated carbon fluxes compared with observation data; and finally, a discussion and conclusions are presented in section 5.

2. CoLM_CASACNP description

2.1 *CoLM*

The CoLM model has been extensively evaluated in offline and coupled modes (Dai et al., 2003, 2004; Huang et al., 2008; ?lpMeng2009; Yang et al., 2009; Zheng et al., 2009). CoLM originates from the Community Land Model (CLM) initial version. CLM has been developed by many groups and has also been coupled with the National Center for Atmospheric Research (NCAR) Community Climate Model (Zeng et al., 2002; Dai et al., 2003, 2004; Oleson et al., 2004; Bonan and Levis, 2010). Concurrent with the development of the CLM, the CoLM was undergoing further development at Beijing Normal University. CoLM has been improved over CLM in many aspects. It includes the following: a two-big-leaf model for leaf temperatures and photosynthesis-stomatal resistance (Wang and Leuning, 1998; Dai et al., 2004); a two-stream approximation for radiaitve transfer within the vegetation and soil, and the calculations for radiation absorbed by sunlit and shaded leaves separately; a treatment for canopy interception that takes into consideration of the fraction of convection and large-scale precipitation; soil thermal and hydrological processes, with consideration of the depth to bedrock; a runoff parameterization following the Topography-based Runoff Prediction Model (TOPMODEL); and a slab ocean–sea ice model (Dai, 2005).

To calculate GPP, CoLM uses the leaf photosynthesis-stomatal conductance model [second version of the Simple Biosphere Model (SiB2)] of Sellers et al. (1996a), which in itself implemented the photosynthesis model of Farquhar et al. (1980), as formulated by Collatz et al. (1992), and relates stomatal conductance to carbon assimilation according to Ball (1988). A semi-empirical model for photosynthesis and stomatal conductance was used to represent the coupling of photosynthesis and transpiration via leaf stomata:

$$g_{\mathrm{leaf}} = m\frac{A_{\mathrm{net}}}{c_{\mathrm{s}}}h_{\mathrm{s}}p + b \tag{1}$$

where g_{leaf} is leaf stomatal conductance, m is an empirical slope from observation, c_{s} is partial pressure of CO_2 at the leaf surface, h_s is the relative humidity at the leaf surface, p is atmospheric pressure at the surface, and b is the minimum stomatal conductance. Canopy net assimilation, A_{net}, is modeled using

$$A_{\text{net}} = \text{GPP} - R_{\text{leaf}} \tag{2}$$

where GPP is gross primary production and R_{leaf} is leaf respiration. The modified Farquhar et al. (1980) enzyme kinetic model assumes that the most limiting resource (e.g., nitrogen, short-wave energy, or leaf carbon-export capacity) determines GPP (Sellers et al., 1996a, b):

$$\text{GPP} = \min(W_{\text{Rubisco}}, W_{\text{Light}}, W_{\text{Carbon}}) \tag{3}$$

where W_{Rubisco} is the Rubisco (leaf enzyme)–limited rate of assimilation, W_{Light} is the light limited rate of assimilation, W_{Carbon} is the carbon-export limited assimilation rate for C_3 plants. For C_4 plants, W_{Carbon} is the PEP-carboxylase limitation on photosynthesis.

Leaf respiration, R_{leaf}, is modeled using

$$R_{\text{leaf}} = R_{\text{d}} D_{\text{T}}(T_{\text{leaf}}) \tag{4}$$

where R_{d} is the dark respiration of the leaf at 20°C (mol m^{-2} s^{-1}) and $D_{\text{T}}(T_{\text{leaf}})$ is the temperature dependence of maximum catalytic capacity of Rubisco.

2.2 *CASACNP biogeochemical model*

Recently, a new model of N_2 fixation based on resource optimization principles was developed (Wang et al., 2007, 2010). This modeling framework has been used to explain the geographic variation in N_2 fixation globally (Houlton et al., 2008). Following this, nitrogen and phosphorus cycles were added into a carbon cycle model, CASA′ (Fung et al., 2005), to create a new model named CASACNP (Wang et al., 2010). The numbers of carbon pools of CASACNP are different than the CASA′ model: they combine surface litter with soil litter, and surface microbial biomass with soil microbial biomass. Thus, the model includes 9 carbon pools, 10 nitrogen pools, and 12 phosphorus pools. Nitrogen fixation and biochemical soil phosphorus mineralization are represented explicitly. The stand-alone version of CASACNP has been evaluated using estimates of carbon pool sizes in plants, litter, and carbon, as well as nitrogen and phosphorus pools in soil (Wang et al., 2010).

In the present study, only the carbon cycle of CASACNP was used, and Table 1 lists nine carbon pools in CoLM_CASACNP. The plant live biomass has three pools: leaf, wood, and root. Litter is separated into metabolic and structural litter and coarse woody debris. Soil organic matter is divided into microbial biomass, slow and passive pools.

Table 1. CoLM_CASACNP Carbon Pools.

Pool type	Pool name	Description
Plant	Leaf	Leaf biomass
	Wood	Woody biomass
	Root	Root biomass
Litter	Metb	Surface and soil metabolic
	Struc	Surface and soil structural
	CWD	Coarse woody debris
Soil	Mic	Soil microbial
	Slow	Soil slow
	Pass	Soil passive

The carbon cycle part of CASACNP can be described as follows. Changes in the plant C pool size are described as (Wang et al., 2007, 2010):

$$\frac{dC_i}{dt} = a_i \text{NPP} - \tau_i C_i, i = \text{l}, \text{w}, \text{r} \tag{5}$$

where the subscript i represents leaf (i = l), wood (i = w), or root (i = r). Here, a_i represents the allocation coefficients, NPP is net primary productivity in g C m^{-2} d^{-1}, and τ_i is plant mortality rate (d^{-1}).

Litter C dynamics (C_j) in the soil are modeled using

$$\frac{dC_j}{dt} = \sum_i f_{j,i} \tau_i C_i - n_j \tau_j C_j, \quad j = \text{m,s,c} \tag{6}$$

where the subscript j represents litter metabolic (j=m), litter structural (j=s), or coarse woody debris (j=c). Here, $f_{j,i}$ is the fraction of carbon from the plant pool, i, to the litter pool, j; τ_j is the litter turnover rate (d^{-1}), and n_j is the nutrient limitation on litter decomposition and is assumed to be 1. Nutrient limitation as represented in CASACNP was not used in this study.

The dynamics of soil organic C (C_k) is modeled using

$$\frac{dC_{k1}}{dt} = \sum_j f_{k1,j} n_j \tau_j C_j + \sum_{k2} f_{k1,k2} \tau_{k2} C_{k2} - \tau_{k1} C_{k1} \quad (k2 \neq k1) \tag{7}$$

where the subscript $k1$ or $k2$ represents soil microbial (k=microbial), soil slow (k=slow), or soil passive (k=passive). Here, $f_{k1,j}$ is the fraction of decomposed carbon from the litter pool, j, to the soil pool, $k1$; $f_{k1,k2}$ is the fraction of decomposed carbon from the soil pool, $k2$ to $k1$; and τ_{k1} or τ_{k2} is the soil turnover rate (d^{-1}).

Figure 1 shows the flow of carbon between pools, with carbon generally flowing from upper left to lower right. Vertical lines represent carbon losses from each pool, and horizontal arrows indicate carbon gains to

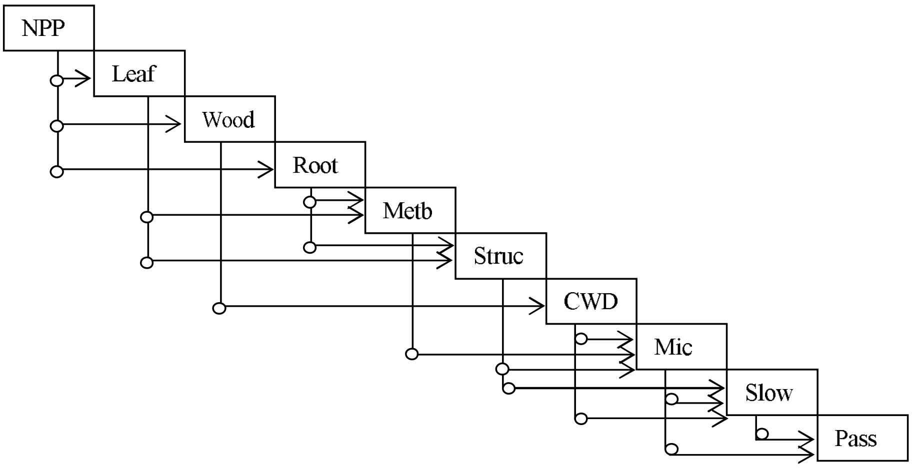

Fig. 1. The configuration of CoLM_CASACNP, with carbon flowing from upper left to lower right. Vertical lines represent pool losses; horizontal arrows represent pool gains; and open circles represent transfers between pools. The detail description of each carbon pool is presented in Table 1.

each pool. Open circles indicate carbon transfers from one pool to another. For example, carbon lost from the leaf pool is transferred to the metabolic and structural litter pools. Carbon efflux from each pool is proportional to the pool size, and the proportionality is defined as a rate constant. Rate constants for the plant pools depend on plant phenology and air temperature, and rate constants for litter and soil depend on soil temperature, moisture, soil texture, and soil management. The primary input into this system of pools is NPP, and is calculated as follows:

$$\mathrm{NPP} = \mathrm{GPP} - R_{\mathrm{leaf}} - R_{\mathrm{wood}} - R_{\mathrm{root}} \tag{8}$$

Net ecosystem exchange (NEE) is calculated using

$$\mathrm{NEE} = \mathrm{GPP} - R_{\mathrm{leaf}} - R_{\mathrm{wood}} - R_{\mathrm{root}} - R_{\mathrm{soil}} \tag{9}$$

where R_{wood}, R_{root}, and R_{soil} represent wood, root, and soil respiration, respectively.

Respiration rates of woody plant tissue and roots were modeled using

$$\begin{aligned} R_{\mathrm{wood}} &= r_1 C_{\mathrm{wood}} \exp\{308.56[1.0/56.02 - \\ &\quad 1.0/(T_{\mathrm{air}} + 46.02 - 273.15)]\} \end{aligned} \tag{10}$$

$$\begin{aligned} R_{\mathrm{root}} &= r_2 C_{\mathrm{root}} \exp\{308.56[1.0/56.02 - \\ &\quad 1.0/(T_{\mathrm{soil}} + 46.02 - 273.15)]\} \end{aligned} \tag{11}$$

where r_1 and r_2 are empirical scaling factors for the wood and root respiration rates, respectively; $C_{\mathrm{wood}}/C_{\mathrm{root}}$ represents the size of the wood/root carbon pool; T_{air} is air temperature; and T_{soil} is mean soil temperature within the rooting zone.

Soil respiration (R_{soil}) includes two components: (1) CO_2 released by litter decomposition, and (2) CO_2 released by soil carbon decomposition. The calculation was performed using

$$\begin{aligned} R_{\mathrm{soil}} = &\sum_j \left(1 - \sum_{k1} f_{k1,j}\right) n_j \tau_j C_j + \\ &\sum_{k1} \left(1 - \sum_{k2} f_{k2,k1}\right) \tau_{k1} C_{k1}\ , \quad k1 \neq k2\ , \end{aligned} \tag{12}$$

where $f_{k2,k1}$ is the fraction of decomposed carbon from the soil pool, $k1$ to $k2$.

3. Data and method

3.1 *DBR: site description and measurements*

Measurements from two sites, DBR and WBW, were used to assess the performance of the coupled model. The site at DBR is an evergreen mixed forest located in Central Guangdong Province, South China (23°10′N, 112°32′E). It has a typical, subtropical, monsoon, humid climate, with an average annual temperature of 20.9°C and average annual rainfall of 1956 mm (Wang et al., 2006). The bedrock is a mix of Devonian sandstone and shale, and the soil is classified as lateritic red earth (oxisol); it is loamy in texture and acidic, with low base saturation (Tang et al., 2006).

Half-hourly rainfall, air temperature, relative humidity, wind speed, and incident solar radiation were measured at the top of a 38-m-tall tower at DBR in 2003. Soil water content (SWC) was measured at every layer underground (Wang et al., 2006). SRP was measured using a static chamber system (Tang et al., 2006), and included the CO_2 released from the decomposition of litter, soil organic matter, microbial biomass, and root respiration. The net CO_2 flux above the canopy was measured using an Open Path Eddy Covariance (OPEC) flux system at 27 m above the ground.

3.2 *WBW: Site description and measurements*

WBW is a temperate deciduous hardwood forest located in the U.S. Department of Energy's National Environmental Research Park near Oak Ridge, Tennessee (35°57′N, 87°17′W). The mean annual temperature is 14.2°C and the long-term (50 year) mean annual rainfall is 1352 mm. The soils are primarily typical Paleudults. The depth of the bedrock is about 30 m, and deep rooting may be a source of some water (Hanson et al., 2004).

Data from studies carried out at WBW (Hanson et al., 2000, 2001, 2003a, 2004; Wilson and Baldocchi, 2001) were obtained to test the performance of model predictions at hourly and daily time steps. Eddy covariance data for hourly NEE (Wilson and Baldocchi, 2001) were selected to evaluate the diurnal model performance. Daily measurements of GPP, NEE, SRP, and mean daily NEE and SRP, as simulated by 11 ecosystem models from the Through-fall Displacement Experiment (TDE) intermodel comparison exercise (Hanson et al., 2004) were also compared with the model simulations. Observations of GPP and NEE were available from 1995 to 1998. Observed SWC data were available from periodic observations vertically integrated (0–35 cm) time-domain reflectometry rod pairs for 1995–1998, and from horizontally-installed, frequency-domain, reflectometry that was placed at a depth of between 0 and 35 cm in 1998. SRP measurements were available from periodic chamber observations and from nocturnal understory-eddy-covariance measurements for 1998 (Hanson et al., 2003b; Wilson and Meyers, 2001).

3.3 *Model performance*

The performance of the coupled model was evaluated by comparing simulated and observed hourly and daily NEE and daily SRP.

Four statistical measures, including the correlation coefficient (RR), mean bias (Bias), mean absolute bias (ABS), and modeling efficiency (EF), were calculated to qualify the model predictions. Bias, ABS, and EF were calculated according to the equations reported by Hanson et al. (2004) and Mao et al. (2007). Bias provides a measure of bias in model predictions and ABS quantifies the mean deviation of model predictions from observations. EF ranges from one to infinitely negative, with value of 1 being a perfect fit to observations and a value less than 0.5 usually considered to be a poor fit.

In this study, positive values of NEE represented carbon uptake by forests from the atmosphere. Therefore, uptake of carbon by the forests, such as GPP, is a positive flux.

3.4 *Model parameterization and simulation setup*

The runs were carried out for DBR and WBW using the tower-observed meteorological forcing for each of the two forest sites, including precipitation, air temperature, relative humidity, wind speed, and incident solar radiation. For each simulation, the model was initialized using arbitrary initial conditions of 283 K vegetation surface, ground and soil temperatures, saturated soil water content, with no snow and canopy water storage. Most of the vegetation and soil parameters for the DBR site were estimated from the information in Table 1 of Yan et al. (2009), and the vegetation and soil carbon pool sizes from Zhou et al. (2006). Leaf area index (LAI) and seasonal leaf phenology for the WBW site were taken from Hanson et al. (2001, 2003c), and the soil physical and chemical conditions were from Peters et al. (1970). Carbon pool sizes of the WBW site were taken from Table 3 of Hanson et al. (2004). The model was spun up to a steady state by reusing the observed meteorological forcing before the predictions by the models were compared with observation data. A steady state was considered to have been reached when the differences between two successive spins in the annual mean soil temperature of each layer were < 0.01 K and soil moisture values for each layer were < 0.001 kg m^{-2} s^{-1}. Each CoLM_CASACNP simulation had three steps: (1) CoLM was run to generate the daily mean forcing data, including GPP, leaf respiration, soil temperature, soil moisture, and air temperature for the running of CASACNP; (2) by recycling the daily forcing data from step 1, CASACNP was run until all pools reached a steady state, i.e., the change in each pool size between two successive cycles was $< 0.01\%$; and (3) using the pool sizes at a steady state from step 2, CoLM_CASACNP was run to obtain the model output for comparing with observations.

4. Results

4.1 *Evergreen mixed forest (DBR, China)*

Modeled and observed hourly NEE data were compared for two 2-week periods—one wet period and one dry period—to assess the model's performance. The

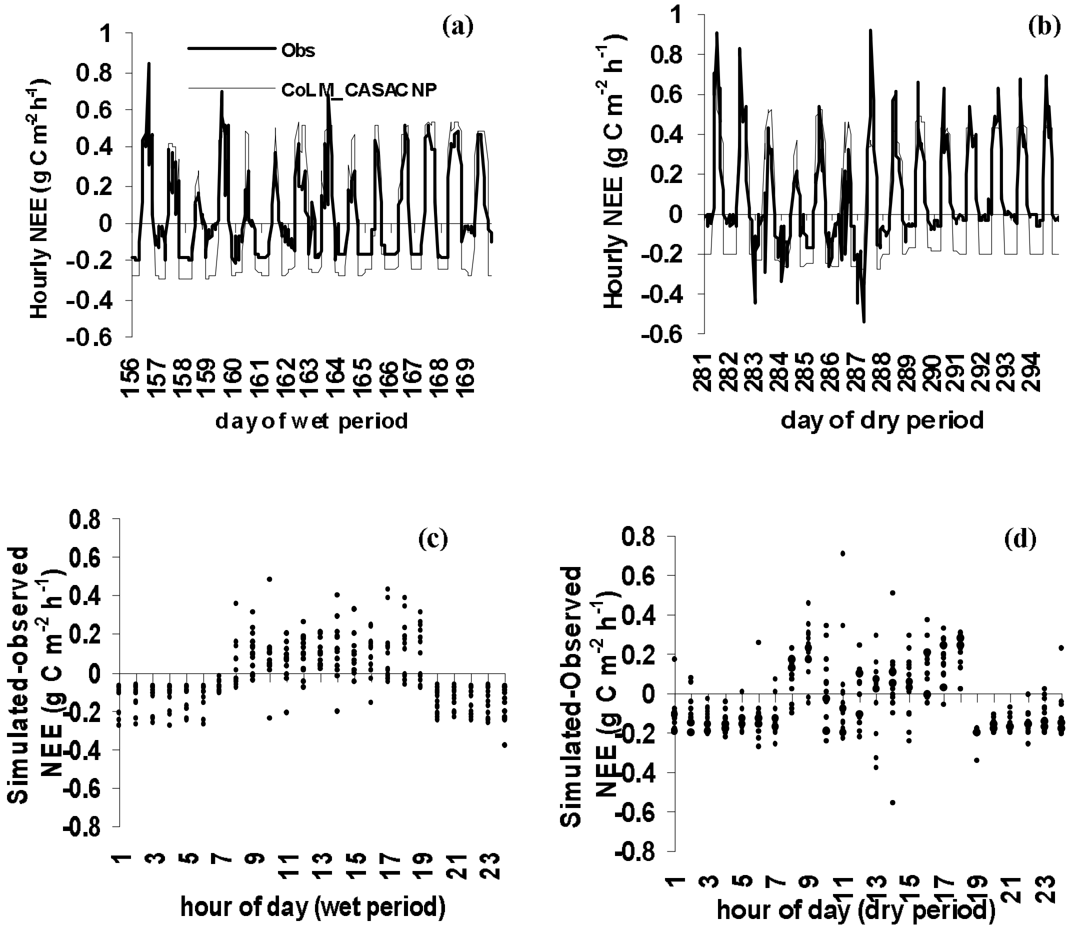

Fig. 2. Comparison of observed and CoLM_CASACNP-outputted hourly NEE (top) and simulated and observed difference plots of hourly NEE (bottom) for a 2–week wet period and dry period in 2003 at the DBR site.

wet period was from day of year (DoY) 156 to DoY 169 and the dry period from DoY 281 to DoY 294 in 2003. Figure 2 shows that the model was able to simulate the diurnal variation in NEE quite well, but it systematically overestimatesoverestimated the nocturnal respiration rate. The observed maximum hourly NEE was 0.84 g C m^{-2} h^{-1} during the wet period and 0.91 g C m^{-2} h^{-1} during the dry period, whereas the modeled maximum hourly NEE was 0.64 g C m^{-2} h^{-1} for the wet period and 0.70 g C m^{-2} h^{-1} for the drought period. Both the observed and modeled results suggest that the DBR forest maintains a substantial ability to sequester carbon, even during the relatively dry season. The model simulation performed better under wet conditions than under dry conditions (higher RR, lower bias and higher EF value; Table 2). Plots of model residuals of hourly NEE (Figs. 2c and d) show that the model errors during the day were greater than those at night because the fluxes during the day were much greater than those at night.

Figure 3 compares the modeled and observed daily NEE and SRP in 2003 at the DBR site. Both observed and predicted daily NEE values were positive for most days, suggesting the forest was a carbon sink for most days in the year 2003. Both the modeled and observed daily NEE fluxes during the dry season (DoY 273–365, October–December) were higher than those in the wet season (DoY 182–243, June–August). The lowest carbon uptake occurred between February and March 2003, which was also reported by Yan et al. (2009) when they investigated only daytime NEE at this forest site. The measures of model performance in Table 2 show that the simulated daily NEE agreed well with the observed (RR=0.82, EF=0.53). Difference plots of predicted minus measured daily NEE (figure omitted) and negative bias (Table 2) suggest that CoLM_CASACNP underestimated daily carbon flux. In conclusion, CoLM_CASACNP can generally reproduce the observed seasonal variation in daily NEE in 2003 at the DBR site.

Table 2. Performance of simulated hourly NEE (g C m^{-2} h^{-1}) during the wet (and dry) periods, daily NEE and daily SRP (g C m^{-2} d^{-1}) for the DBR site.

Variable	RR	Bias	ABS	EF
Hourly NEE	0.91 (0.83)	−0.02 (−0.04)	0.13 (0.15)	0.55 (0.51)
Daily NEE	0.82	−0.58	0.89	0.53
Daily SRP	0.89	0.17	0.47	0.77

Figure 3b compares the simulated and observed daily SRP at the DBR site in 2003. SRP is calculated as the sum of respiration from the decomposition of litter and soil organic matter and root respiration. Different from the seasonal variation in daily mean NEE, the observed daily SRP during the wet season was higher than that in the dry season, as a result of changes in water limitation. This seasonal variation was reproduced well by the model, with very high RR and EF values (RR=0.89, EF=0.77 in Table 2), but the model overestimated the value for most days throughout the whole year, especially the days at the beginning of the dry season (Julian day 275–315), and with a positive bias in comparison to the actual measurements.

4.2 *Deciduous Forest* (*WBW, USA*)

Figure 4 shows the comparison of the modeled and observed diurnal cycles of hourly NEE for the selected 2-week wet (DoY 151–164) and dry (DoY 238–251) periods in 1998. The observed maximal hourly NEE over the dry period was 1.1 g C m^{-2} h^{-1}, ∼20% lower than the maximal hourly NEE during the wet period. This difference suggests that soil water deficits had a significant influence on the diurnal NEE, which was also reported by Greco and Baldocchi (1996) and that drought reduced the daily rate of carbon uptake by 25%–30%. Simulations using the coupled model in the present study also suggest a reduction of ∼35% of hourly NEE as a result of water stress at the WBW site during the dry period. However, NEE was overestimated during the night compared to observations under the two wet and dry extreme conditions. Generally, the agreement between modeled and observed hourly NEE was better under wet conditions than under dry conditions, with a smaller bias value of −0.05 (g C m^{-2} h^{-1}) and higher EF value of 0.79 (Table 3). The absolute differences between observations and model predictions were higher during daytime both under wet and dry conditions (Figs. 4c and d), similar to the results from the DBR site.

Figure 5a compares the modeled daily mean NEE with the observed data and the model mean predicted over several years. The comparison shows that observed daily NEE was a negative value before the growing season (DoY 0–120) of each year, before becoming a positive carbon flux after DoY 120, increasing with time until between DoY 150–180, and then decreasing to a negative value again after DoY 300. These seasonal cycle characteristics of NEE relate closely to the seasonal variations in canopy LAI at this site, and they were quite well reproduced by the coupled model and the model mean. Compared to the model mean, CoLM_CASACNP had a smaller bias response to the observations and a higher EF value (CoLM_CASACNP bias=−0.67, EF=0.73; model mean bias=−0.94, EF=0.68; Table 3). Figures 5b and c shows that the model underestimated daily

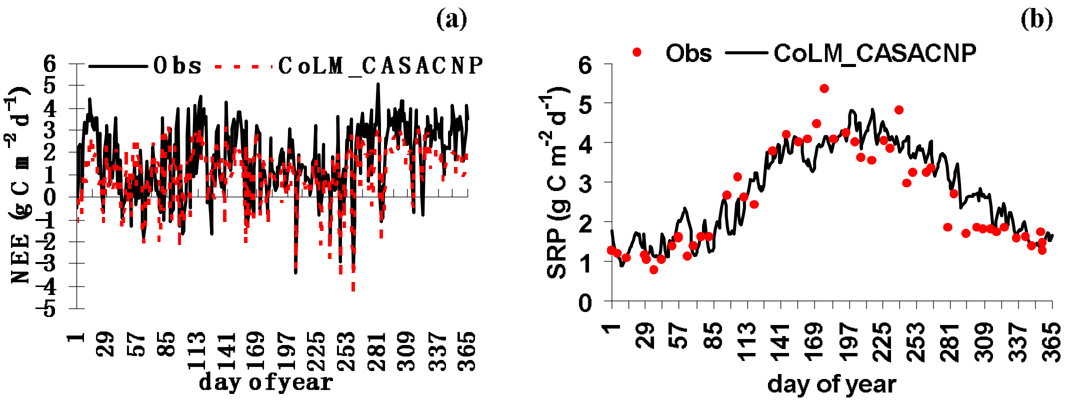

Fig. 3. (a) Daily NEE and (b) SRP in 2003 at the DBR site. The 365 days for SRP were made up arbitrarily of the months January–April 2004 and May–December 2003.

Table 3. Performance of simulated hourly NEE (g C m^{-2} h^{-1}) of wet (and dry) periods, daily NEE and daily SRP (g C m^{-2} d^{-1}) for the WBW site.

Variable	RR	Bias	ABS	EF
Hourly NEE	0.90 (0.92)	−0.05 (−0.13)	0.15 (0.15)	0.79 (0.65)
Daily NEE	0.88	−0.67	1.30	0.73
	0.88$^{\mathrm{m}}$	−0.94$^{\mathrm{m}}$	1.32$^{\mathrm{m}}$	0.68$^{\mathrm{m}}$
Daily SRP	0.59 (0.81)	0.59 (−0.70)	0.47 (0.88)	0.02 (0.40)
	0.65 (0.85$^{\mathrm{m}}$)	0.55 (−0.46$^{\mathrm{m}}$)	0.71 (0.82$^{\mathrm{m}}$)	−0.27 (0.51$^{\mathrm{m}}$)

Note: superscript m represents the model mean; the numbers in the daily SRP row indicate predicted SRP vs. (chamber-based observed SRP) (n=28) and predicted SRP vs. (eddy covariance observed SRP) (n=365), respectively.

NEE during the growing season (DoY 120–300), but the model overestimated the observed daily NEE near the beginning (DoY 100–120) and near the end (DoY 300–320) of the growing season.

Figure 6 shows that CoLM_CASACNP reproduced the observed seasonal pattern of SRP quite well from 1995 to 1998, with peak values occurring in summertime; however, the model underestimated some peak values during that season. Furthermore, both CoLM_CASACNP and the model mean did not capture well the temporal dynamics of the subcanopy eddy covariance daily soil respiration data, with quite substantial model errors in 1998 (see Table 3 and Fig. 6). Based on the standard of good fit being an EF value > 0.45 in this study, CoLM_CASACNP did not do a good job of capturing daily SRP as measured by chamber and subcanopy eddy covariance observations, and the model mean simulations did a good job of predicting the chamber-based daily soil respiration rate, but demonstrated a bad performance compared to the eddy covariance measurements.

5. Discussion and conclusions

5.1 *Discussion*

CoLM_CASACNP reproduced the diurnal cycle of NEE at both selected forest sites reasonably well, but overestimated nocturnal NEE for both sites. Under insufficient turbulent conditions, especially during calm

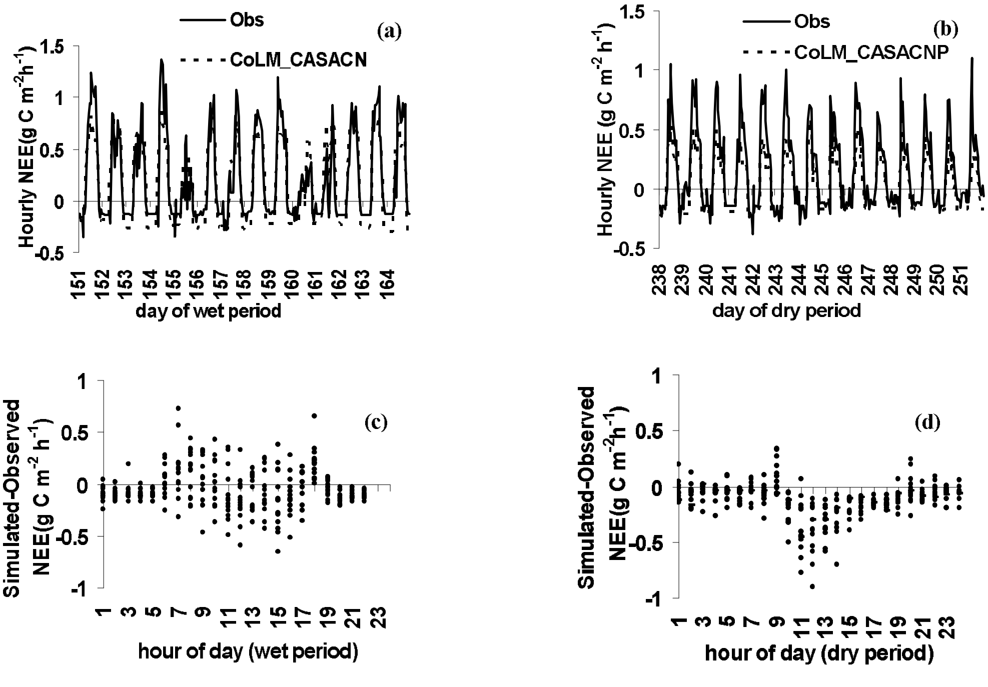

Fig. 4. Comparison of hourly NEE measurements and CoLM_CASACNP output (top), and difference plots of simulated minus observed hourly NEE (bottom) for the 2-week wet and dry periods in 1998 at the WBW site.

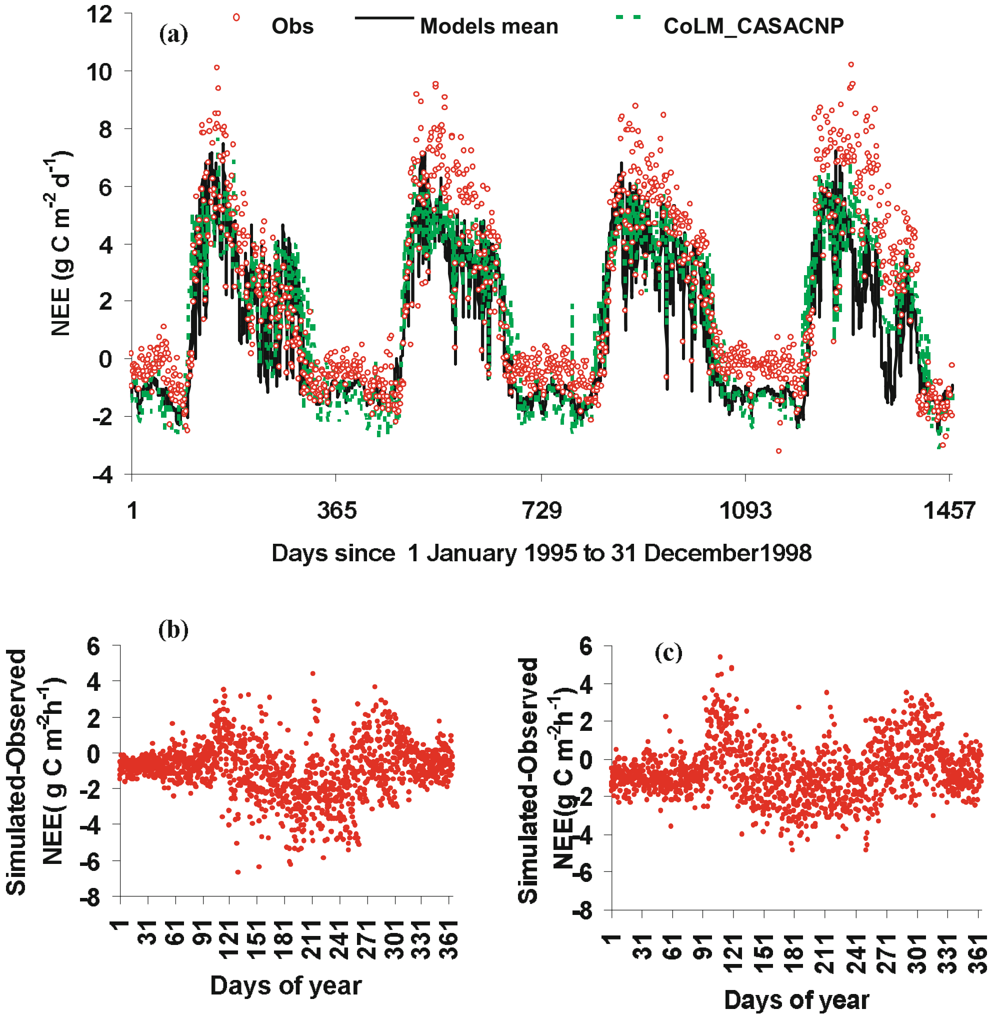

Fig. 5. CoLM_CASACNP and model mean prediction for daily NEE plotted together with available daily observations from 1995–1998 at the WBW site (a), and difference plot of model mean (b) and CoLM_CASACNP (c) predictions minus measurements for the period 1995–1998.

and stable nights, CO_2 flux measured by the eddy covariance technique is often underestimated (Lee et al., 1999; Falge et al., 2001; Carrara et al., 2003). Wang et al. (2006) reported the same problem at the DBR site, and Wilson and Baldocchi (2001) showed the same problem at the WBW site. It is therefore reasonable to attribute part of the current model's overestimation of observed nocturnal respiration to measurement errors. Model performance was typically better for wet conditions compared to dry conditions, and the coupled model overestimated SWC during dry periods (Figs. 7b and 8c), suggesting that the response of stomatal conductance or soil respiration to water stress contains large errors.

As stated previously for the DBR forest site, the highest daily NEE occurred during the autumn–winter season, not during the summer season (July–August), and the lowest during February–March. The lowest observed daily NEE could be attributed to the lowest photosynthetically active radiation (PAR; Figs. 3a and 7a). During the summer season from July to August, the observed carbon absorption ability was depressed due to high temperatures (Fig. 7a) and high PAR (peak value 52.9 mol photons m^{-2} d^{-1}). At the same time, some rainfall aggravated soil respiration and reduced plant photosynthesis, which together could explain why this forest site acted as a relatively weak carbon sink during this period. The highest observed daily NEE occurred during October–December, which could be attributed to the relatively high PAR (peak value 37.7 mol photon m^{-2} d^{-1}) and lower SRP (Fig. 3b). For the lowest modeled daily NEE appearing during the same period, the minimum GPP predicted by the model appeared in February and the second smallest value appeared in March (figure omitted), which could explain this point. Others

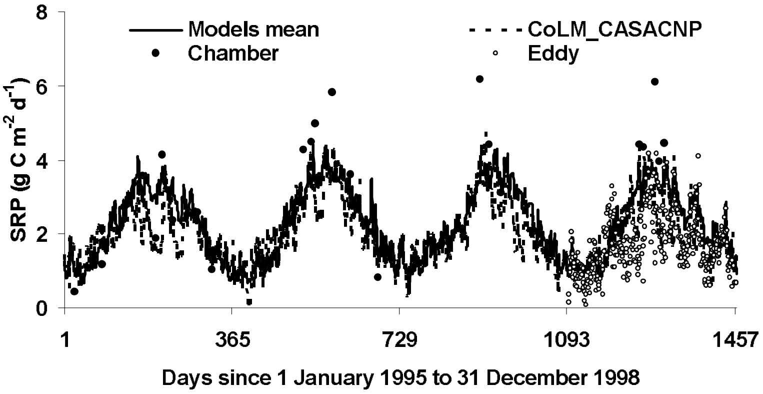

Fig. 6. Daily chamber-based SRP, 1.5-m eddy covariance observations, model mean and CoLM_CASACNP simulations from 1995–1998 at the WBW site.

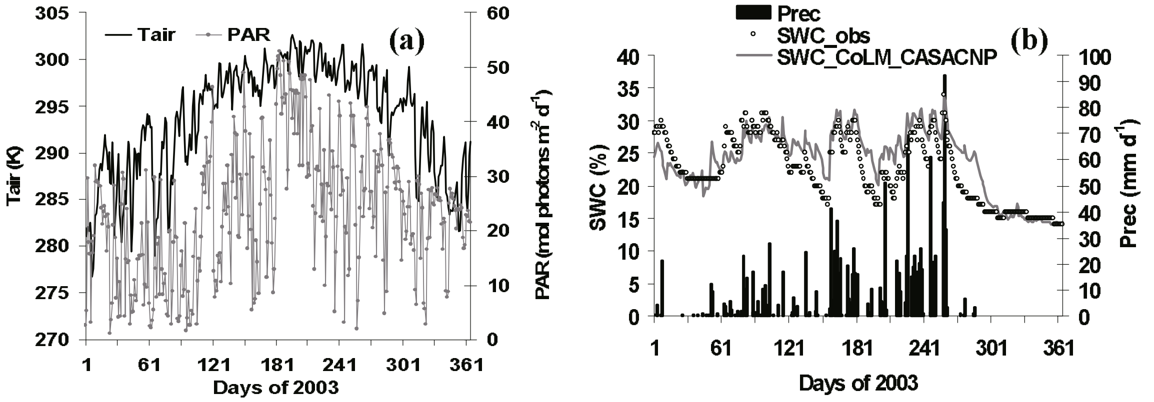

Fig. 7. (a) Daily observed air temperature (Tair) and PAR; (b) observed precipitation (Prec), observed soil water content (SWC) and predicted SWC from CoLM_CASACNP at DBR site.

have also reported that the minimum GPP of the DRB forest occurred in March (Yu et al., 2008). Despite the highest predicted daily NEE also appearing during the October–December period, the simulations were lower than the observations. The overestimations of SWC by CoLM_CASACNP (Fig. 7b) induced overestimations of SRP (Fig. 3b), might explain this. Whether leaf and wood respiration contributed to the underestimation of daily NEE because of the unavailability of observed datasets could not be verified. Under dry conditions, the predicted SWC did not decrease as rapidly as the measured values (Fig. 7b), and this phenomenon might be attributable to a common failure of simple soil water models (Ragab et al., 1997; Harding et al., 2000; Mao et al., 2007).

As noted previously for the WBW forest site, CoLM_CASACNP captured reasonably well the daily temporal dynamics of NEE, despite an underestimation during the growing season and an overestimation at the beginning and end of the growing season. To demonstrate the possible reasons, observed and predicted data for the year 1998 were used with the following explanation. Figure 8a shows that daily GPP from CoLM_CASACNP predictions was comparable with observation data during the growing season. However, CoLM_CASACNP overestimated autotrophic respiration throughout almost all days of the year, especially during the growing season, which could be one reason for the underestimation of daily NEE during the growing season (Fig. 8b). The overestimated daily GPP from the model (Fig. 8a) could be the contributing factor in the overestimation of daily NEE at the beginning and end of the growing season. At the same time, the model overestimated the SWC during the dry period (DoY 225–265, 1998), which could also be a factor in the differences between predicted and measured daily NEE (Fig. 8c). Hanson et al. (2004) also reported that the initiation of leaf-out, the onset of leaf senescence, and the appropriate approximation of mid-season drought responses, were responsible for model deviations from the observed daily NEE data at the WBW forest stand.

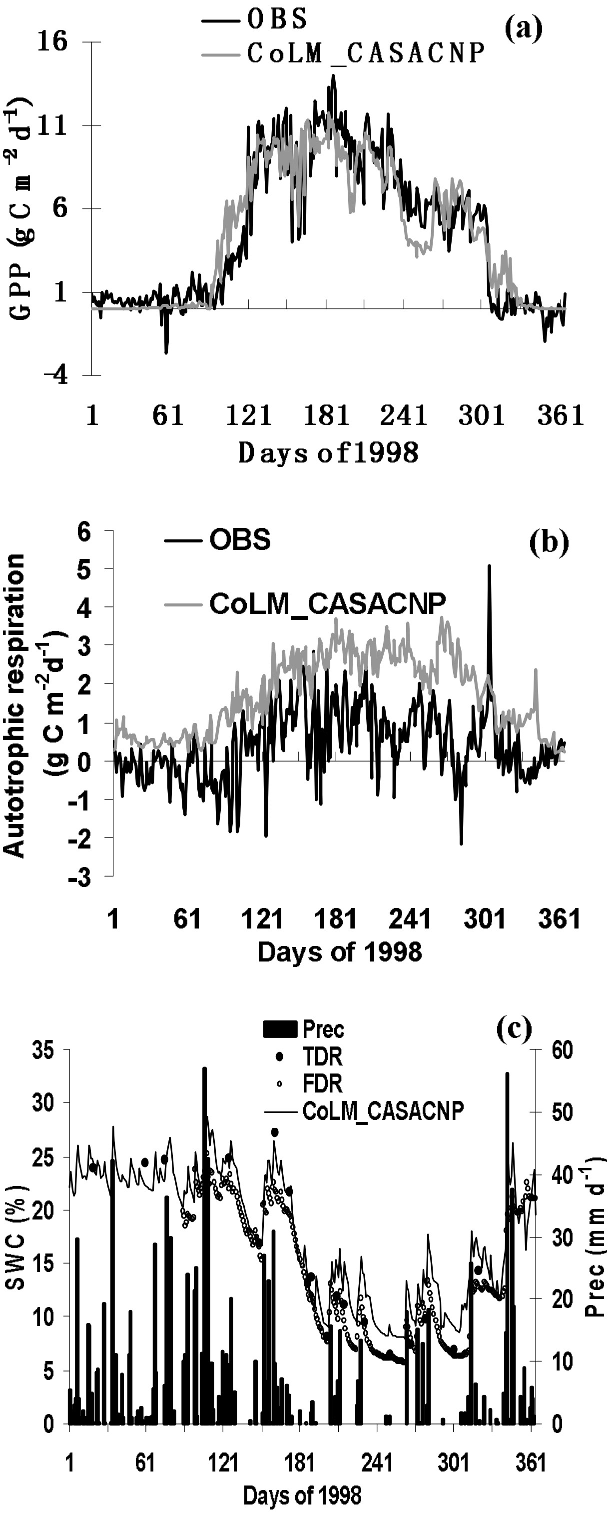

Fig. 8. Observed and predicted daily GPP (a) and autotrophic respiration (b), and (c) observed precipitation (Prec), SWC measured by frequency domain reflectometry (FDR), and periodic time domain reflectometry (TDR) and predicted SWC from CoLM_CASACNP at WBW site.

The SRP results from CoLM_CASACNP showed better agreement with chamber-observed data (RR=0.81, EF=0.40) than with eddy-covariance-observed data (RR=0.59, EF=0.02) at the WBW forest (Table 3). The chamber-based soil respiration measurements included litter-layer decomposition. The CoLM_CASACNP model also considered litter decomposition dynamics, which could have contributed to the relatively good agreement between simulations and chamber-based measurements. One possible reason for the disagreements between the predictions and the understory eddy covariance data may be related to footprint differences between the conceptual eddy covariance footprint and the model simulations (Hanson et al., 2004; Mao et al., 2007). Other factors affecting soil respiration include soil temperature, substrate quality and land use/cover and disturbance regimes (Xu and Qi, 2001a, b; Reichstein et al., 2003). However, in-depth research on these potential contributions is beyond the scope of the present paper.

5.2 *Conclusions and future work*

This paper has demonstrated the successful integration of the biogeochemical model, CASACNP, into the land surface model, CoLM, to produce the hybrid model, CoLM_CASACNP. This coupled model is closely linked to simulate full water, energy and carbon cycles. Hence, it can run “off-line” with different meteorological forcing data for a variety of process-based studies relating climate to the carbon cycle. Furthermore, it can also be directly coupled with an earth system model to fulfil carbon–climate interaction simulations in one integrated system.

CoLM_CASACNP can predict long-term carbon sources and sinks that CoLM could not. The combination of the two models also allows explicit estimation of autotrophic respiration, which is absent in both CoLM and CASACNP. The new model, CoLM_CASACNP, has been tested in two selected forest ecosystems. The model was found to reproduce the diurnal and seasonal dynamics of NEE and the seasonal variation in SRP. However, the model overestimated SWC under dry conditions, and the agreement of carbon fluxes between simulated and observed data was relatively poor.

In this study, it was difficult to make a statistically accurate determination of the optimal parameter combinations. By tuning some important key vegetation parameters, such as maximum Rubisco capacity at top canopy at 25°C per leaf area ($V_{\rm cmax}$) and Q_{10} (fractional change in rate with a 10°C increase in temperature) temperature coefficient, no better results were obtained. Inappropriate parameterization will remain a serious issue for future model applications to ecosystems without adequate reference data. It has been reported that nutrient limitation has a significant influence on carbon uptake in land ecosystems (Vitousek and Howarth, 1991; Wang et al., 2007; Else et al., 2007; Thornton et al., 2007; LeBauer and Tereseder, 2008; Sokolov et al., 2008; Thornton et al., 2009; Wang and Houlton, 2009; Matear et al., 2010). Thus, the next steps in future work by the current authors will involve not only focusing on parameter optimization, but also on calibrating the model using independent estimates of soil carbon, nitrogen, and phosphorus pools, as well as measurement of surface atmospheric CO_2 concentrations. Having done this, uncoupled and coupled simulations for studying carbon–climate feedbacks and constraints of nutrient limitation on the magnitude of these feedbacks between the carbon cycle and climate at time scales from decades to centuries will be conducted.

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