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Effect of Assessment Scale on Spatial and Temporal Variations in CH_4, CO_2, and N_2O Fluxes in a Forested Wetland

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Abstract Emissions of methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) from a forested watershed (160 ha) in South Carolina, USA, were estimated with a spatially explicit watershed-scale modeling framework that utilizes the spatial variations in physical and biogeochemical characteristics across watersheds. The target watershed (WS80) consisting of wetland (23%) and upland (77%) was divided into 675 grid cells, and each of the cells had unique combination of vegetation, hydrology, soil properties, and topography. Driven by local climate, topography, soil, and vegetation conditions, MIKE SHE was used to generate daily flows as well as water table depth for each grid cell across the watershed. Forest-DNDC was then run for each cell to calculate its biogeochemistry including daily fluxes of the three greenhouse gases (GHGs). The simulated daily average CH_4, CO_2 and N_2O flux from the watershed were 17.9 mg C, 1.3 g C and 0.7 mg N m^{-2}, respectively, during the period from 2003–2007. The average contributions of the wetlands to the CH_4, CO_2 and N_2O emissions were about 95%, 20% and 18%, respectively. The spatial and temporal variation in the modeled CH_4, CO_2 and N_2O fluxes were large, and closely related to hydrological conditions. To understand the impact of spatial heterogeneity in physical and biogeochemical characteristics of the target watershed on GHG emissions, we used Forest-DNDC in a coarse mode (field scale), in which the entire watershed was set as a single simulated unit, where all hydrological, biogeochemical, and biophysical conditions were considered uniform. The results from the field-scale model differed from those modeled with the watershed-scale model which considered the spatial differences in physical and biogeochemical characteristics of the catchment. This contrast demonstrates that the spatially averaged topographic or biophysical conditions which are inherent with field-scale simulations could mask "hot spots" or small source areas with inherently high GHGs flux rates. The spatial resolution in conjunction with coupled hydrological and biogeochemical models could play a crucial role in reducing uncertainty of modeled GHG emissions from wetland-involved watersheds.

Keywords Forest-DNDC · forested wetland · greenhouse gases · carbon cycling

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1 Introduction

Wetlands, including forested wetlands, are an important terrestrial methane (CH_4) source and an important carbon (C) sink (Trettin and Jurgensen 2003). Understanding production and consumption of C in wetland-dominated landscapes is important for estimating the contribution of greenhouse gases (GHG), especially CO_2, CH_4, and N_2O, to global warming. The generation and emission of GHGs from wetland-dominated landscapes are closely related to inherent biogeochemical processes which regulate the C balance (Rose and Crumpton 2006). However, those processes are strongly influenced by vegetation, chemical, and physical soil properties, geomorphology, and climate (Smemo and Yavitt 2006).

The soil moisture regime is a key factor regulating the C balance and GHG flux in forests because it affects aeration, and by extension determining whether the soil is aerobic or anaerobic. The soil environment, including moisture content, exhibits considerable spatial and temporal variation as a result of micro-topography, distribution of plant communities, climate, and soil properties (Wang et al. 2000). Correspondingly, the C balance and GHG fluxes from soils should be expected to exhibit considerable variation, especially in wetland-dominated landscapes (Sun et al. 2006).

The generation and consumption of CH_4 from soils are sensitive to soil aeration which is largely regulated by the water table in wetlands (Trettin et al. 2006). However, the water table depth is not homogeneous across a watershed because of topography, micro-topography, and surface geomorphic features. As a result, there is a heterogeneous distribution of the soil relative to the water table across a watershed (Sun et al. 2006), which in turn suggests that the CH_4 flux may correspond (Rask et al. 2002). These conditions are characteristic of many forested landscapes, especially those dominated by mosaics of uplands and wetlands. Accordingly, failure to consider the spatial heterogeneity across a forest may induce significant errors when simulating the C and GHG dynamics.

There have been a plethora of modeling studies to assess the soil C balance or GHG emissions over the past decades, and the common approach is to utilize a field-scale model to simulate one cell or catchment with averaged field conditions (Pansu et al. 2004). The size of the cell or catchment has varied considerably from plots (e.g., hundreds of m^2), to watersheds (e.g., hundreds of ha) or basins (hundreds of km^2) (Shindell et al. 2004; Huang et al. 2006). The application of a field-scale biogeochemical modeling approach across a large area will obviously overlook inherent spatial variability in the soil environment and potentially incur significant errors in predicting the C and GHG dynamics at the scale of assessment, such as over or under predicting GHG fluxes due to spatial heterogeneity in biophysical and biogeochemical characteristics regulating C balance. This consequence reflects the fact that while explicit information on spatial and temporal hydrologic dynamics is critical for simulating C and GHG dynamics in forested wetland soils, few biogeochemical models have the capability to accurately consider hydrologic dynamics across space and time. One of the solutions is to obtain the spatial and temporal hydrologic dynamics by means of physically based hydrologic models (Sun et al. 2006). This approach is applicable to a wide range of watershed conditions. Therefore, linking a physically based distributed hydrologic model to a watershed-scale biogeochemical modeling tool for estimating dynamic C, N, and GHG in forested catchments should provide an improved basis for assessing C and GHG dynamics in forested systems.

This paper reports the effort to (1) quantify CH_4, soil CO_2 and N_2O fluxes for a 160 ha forested watershed on the Santee Experimental Forest located in the lower coastal plain of South Carolina, USA, and (2) assess the differences in simulated GHG dynamics for the mosaic landscape consisting of wetlands and uplands using two biogeochemical modeling approaches, a field-scale model which employs spatial average conditions from the study site and a watershed-scale model which utilizes spatial and temporal characteristics within the watershed. This study used the biogeochemical model, Forest-DNDC (Li et al. 2000; Stang et al. 2000), and a hydrology model, MIKE SHE (DHI 2005). The results are used to contrast the spatial and temporal variations of GHG fluxes in the watershed to assess the impact of spatial heterogeneity in biophysical and biogeochemical conditions on estimating C and GHG dynamics in the landscapes with complex characteristics of topography, hydrology, soils, and vegetation.

2 Materials and Methods

2.1 Watershed Description

The study site is a first-order watershed (WS80) containing both uplands and wetlands, located at 33.15° N, 79.8° W on Santee Experimental Forest, 55 km northwest of Charleston, South Carolina (Fig. 1). WS80 (160 ha) serves as the control catchment for a paired watershed system within the second-order watershed (WS79, 500 ha) draining into Huger Creek, a tributary of East Branch of the Cooper River. This reference forest has gauging records since 1967. It is characteristic of the subtropical region of the southeastern Atlantic Coast with short, warm, and humid winters and long and hot summers; the annual average temperature is 18.7°C, and the mean annual precipitation (1971–2000) is 1,350 mm (Amatya et al. 2003). The topography is planar, and the slope is less than 4%. The elevation is between 4 and 10 m above mean sea level. The site has a shallow water table, and about 23% of the watershed is classified as wetlands (Sun et al. 2000).

The soils in the catchment are typified by a loam surface and clayey subsoil, which is moderately well to somewhat poorly drained in the upland and poorly drained in the riparian zone (Long 1980). Clay content is ≤30% in topsoil (within 30 cm), 40–60% in subsoil (>30 cm) (Long 1980). Soil reaction is acidic; pH is between 4.5 and 6.5.

As is a reference watershed, the forest on WS80 has not been managed in more than five decades. However, the forest was heavily impacted by Hurricane Hugo in 1989. This site remained unmanaged after the hurricane, without biomass removal or salvage logging. The current forest stand is from residuals and natural regeneration. The current forest cover type consists of bottomland hardwoods in the riparian zone and mixed pine-hardwoods elsewhere (Hook et al. 1991; Harder et al. 2007). The dominant trees are loblolly (*Pinus taeda* L.), sweetgum (*Liquidambar styraciflua*), and a variety of oak species (*Queercus* spp.) (Hook et al. 1991; Harder et al. 2007).

2.2 Data Collections and Field Measurements

Precipitation in WS80 was measured using an automatic tipping bucket and a manual rain gauge as a backup. Air and soil temperatures, CO_2 emission, and soil moisture were also measured on-site, and used to assess Forest-DNDC performance. Additional

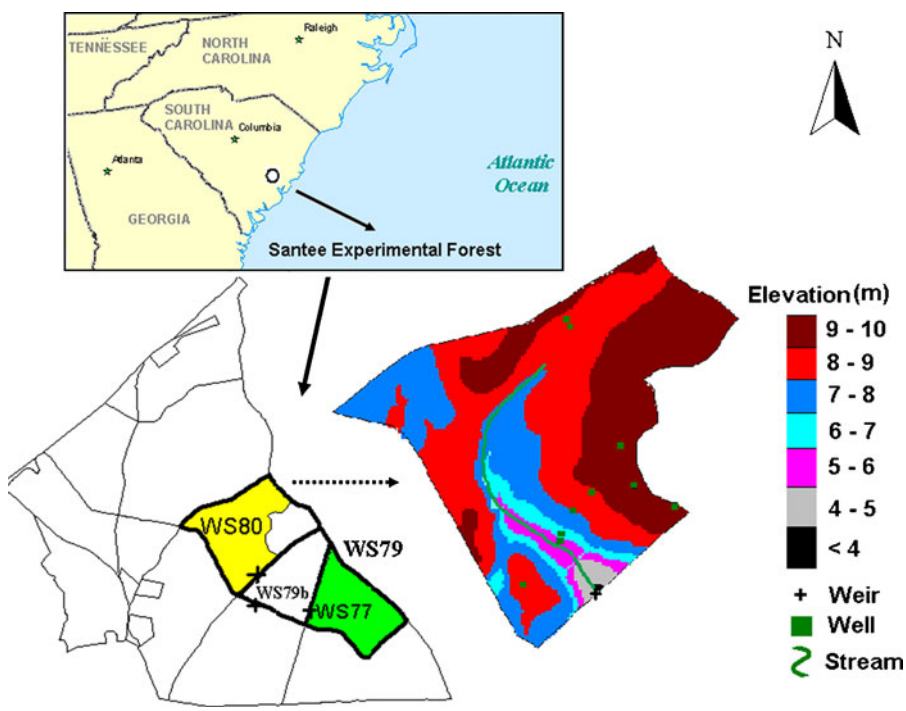

Fig. 1 Watershed WS80 on Atlantic Coastal Plain, South Carolina, USA (WS79 (500°ha) is divided into three parts; they are WS77 (155°ha), WS80 (160 ha), and the part (WS79b) between WS77 and WS80, respectively)

meteorological measurements, including solar and net radiations, wind speed, wind direction, vapor pressure, and relative humidity were collected at 30-min intervals at a weather station at Santee Experimental Forest Headquarters (SEFH) about 3 km away from WS80. The data from SEFH were processed to estimate daily potential evapotranspiration (PET) (Xu and Singh 2005). Except for leaf area index (LAI) calculated based on leaf biomass measurements (Lloyd and Olson 1974; Bréda 2003) in this study area for 2 years, LAI was also measured periodically throughout 2 years using a LiCOR-2000 plant canopy analyzer. Both PET and LAI were used for modeling hydrologic dynamics in the watershed.

Water table depth data were measured at two automatic recording wells (WL40) installed in an upland area and a lowland location to record water table elevation at 4-h intervals and by eight manual wells installed across the watershed with biweekly measurements (Fig. 1). An automatic Teledyne ISCO-4210 flow meter measured stream gauge heights above a compound V-notch weir at 10-min intervals. The discharge was calculated using a standard rating curve method developed for the compound weir, and integrated into daily and monthly values, and then converted from $m^3\ s^{-1}$ to mm d^{-1} to compare with daily precipitation. Both the measured water table depth and discharge were used to calibrate and validate the hydrologic parameters.

2.3 Forest-DNDC Model

Forest-DNDC is a process-based biogeochemical model, which is used to predict plant growth and production, C and N balance, and generation and emission of greenhouse gases (CO_2, CH_4, and N_2O) by means of simulating C and N dynamics in forest ecosystems (Li et al. 2000; Stang et al. 2000; Miehle et al. 2006). The model integrates decomposition, nitrification–denitrification, photosynthesis, and hydrothermal balance in forest ecosystems. These components are mainly driven by environmental factors, including climate, soil, vegetation, and human activities. The model has been tested and used for estimating GHG emission from forested ecosystems in a wide climatic region, including boreal, temperate, subtropical, and tropical (Stang et al. 2000; Zhang et al. 2002; Li et al. 2004; Kiese et al. 2005, 2006; Kurbatova et al. 2008).

In order to better understand the impact of the spatial heterogeneity in biophysical and biogeochemical conditions on GHG emissions from forested ecosystems with mosaic landscape consisting of uplands and wetlands, Forest-DNDC was modified to explicitly represent spatial complexities in hydrogeological and climatic characteristics, and soil and vegetation types at watershed or regional scales.

2.4 Linking Hydrologic Model MIKE SHE

MIKE SHE (Abbott et al. 1986a, b; Graham and Butts 2005), a distributed and physically based hydrologic modeling system, was linked to Forest-DNDC to provide spatially explicit dynamic hydrologic information. MIKE SHE has the capability of simulating all major terrestrial hydrologic processes, including 3-D water movement in soil profile, 2-D water movement of overland flow and 1-D water movement in rivers/streams, and evapotranspiration (ET) (DHI 2005). It is flexibly applicable at various spatial scales, ranging from a simple soil profile to large river basins or regions with complex hydro-geologic characteristics (Graham and Butts 2005), and widely used to simulate watershed-scale hydrology (Sahoo et al. 2006; Mernild et al. 2008; Vázquez et al. 2008; Zhang et al. 2008; Lu et al. 2011). MIKE SHE has been tested to simulate hydrology for this watershed (Dai et al. 2010). Accordingly, it is an appropriate model to supply spatially and temporally dynamic hydrologic information to Forest-DNDC.

An interface was developed to transfer the MIKE SHE-modeled hydrological data to Forest-DNDC, which included daily water table depth, overland flow and subsurface flow for the entire watershed. MIKE SHE and Forest-DNDC shared a set of same GIS-based files. Elevation and other relevant topographic parameters were defined for each of the grid cells based on the WS80 DEM data.

2.5 Model setup and Parameterizations

The MIKE SHE model framework was configured to simulate dynamic water table in space and time and discharge in time. It was coupled with routing flow model MIKE 11, a one-dimensional river/channel water movement model. The data files for the simulation model setup were primarily grid and/or shape format for spatial data, including vegetation,

soil, and stream network. The other data files were time series data for precipitation and PET. MIKE SHE model setup for hydrologic modeling in this watershed was described in details by Dai et al. (2010).

Forest-DNDC was set to simulate C and N dynamics for forested wetlands (Li et al. 2004). Data files were in ASCII format, including climate, hydrology, soil, and vegetation. A set of two-dimensional grid files were created for the spatial variation in hydrology, soil and vegetation. For this study, every grid file was a dataset with 675 cells, and each cell represented 0.25 ha (50× 50 m) of the watershed. In order to identify the wetland's contribution to methane emissions from this watershed, the site was divided into wetlands (~23% of the watershed area with water table level of ≥0 in wet periods) and uplands (77%) to reflect the mosaic topography mixed with wetlands and uplands based on the water table depth during a normal wet period in 2003.

The watershed-scale simulations used the spatial and temporal water table dynamics represented by 675 cells within WS80. The field-scale approach employed daily mean water table which was calculated from the 675 cells. To assess the relative contributions of wetland and upland ecosystems within the watershed, the field-scale simulations used the daily mean water table depth for the wetland cells (155) and upland cells (520). The watershed-scale model was utilized to estimate contributions of wetlands and uplands at the watershed scale using a dynamic water table for the corresponding cells. The other spatially biophysical and biogeochemical characteristics of the catchment were directly employed by the watershed scale, and their spatial average conditions were used by the field scale.

3 Results and Discussion

3.1 Calibration and Validation

Based on a hydrology study on WS80 by Dai et al. (2010), MIKE SHE did an excellent job representing the variations of the water table and stream discharge (Table 1; Fig. 2). The simulated water table depth and discharge were in agreement with observations with the model performance efficiency ($E \leq 1$) (Nash and Sutcliffe, 1970) values ranging between 0.55 and 0.78 for discharge and 0.55–0.87 for water table depth as well as their R^2 values ranging between 0.62 and 0.83 for discharge and 0.66 and 0.88 for water table depth (Dai et al. 2010). These results demonstrate a sound basis for using MIKE SHE to provide the hydrologic context for biogeochemical simulations.

Forest-DNDC was calibrated and validated using soil CO_2 flux, soil temperature and soil moisture. While there was general agreement between the field measurements and simulated values (Fig. 3; Table 2), there were small consistent differences. The simulated soil temperature and CO_2 flux tended to be slightly lower than the field measurements, and the simulated soil moisture was slightly higher than the field measurements during wet periods. These differences may be related to the location and distribution of the measurement plots, which include both upland and wetland. It may also be influenced by the micro-topography within a measurement plot, whereby the four to six measurement points used on a plot were inadequate to representative the inherent variation within a plot. The distribution of measurement points tended to be on the slightly higher (i.e., 10–20 cm) micro-topographic positions, which would not be submerged during periods of high water table, although those events are not uncommon. Since the simulated results represent an average across the plot, it is reasonable that the simulated soil moisture could be higher than the measured values for wet periods, especially in the riparian zone.

The simulated soil temperature was in agreement with the measurements with a proper model performance efficiency (Nash and Sutcliffe 1970) being E=0.61 for the model calibration and E=0.83 for the validation (Fig. 3b; Table 2). Although there were some differences between observation and simulation, these figures (Fig. 3; Table 2) also showed that Forest-DNDC captured the spatial and temporal variation in soil temperature and CO_2 dynamics across the watershed. The E was 0.42–0.70 and R^2 was 0.44–0.83 (Table 2) from Forest-DNDC model calibration and validation. These results showed that Forest-DNDC was applicable for estimating the spatial distribution of GHG emissions with proper model efficiency.

The simulated daily CH_4 flux was also comparable to the measurements from adjacent watersheds. Renaud (2008) found that the minimum daily methane flux was −1.9 mg C m^{-2} from WS79b (an adjacent watershed, about 200 m away from the measurement plot to our study site) in Nov. of 2007, approximate to the simulated value (−2 mg C m^{-2} day^{-1}) for WS80 in

Table 1 The measured and simulated water table and discharge during the periods of calibration and validation for MIKE SHE and rainfall in WS80

Year	Rainfall (mm)	Discharge (mm day^{-1})				Water table depth from ground surface (m)[a]			
		O	*P*	R^2	*E*	*O*	*P*	R^2	*E*
2003	1671	2.01	1.90	0.62	0.55	0.58	0.63	0.88	0.87
2004	962	0.30	0.37	0.63	0.56	0.88	0.98	0.79	0.76
2005	1,540	0.84	0.82	0.66	0.63	0.77	0.86	0.77	0.75
2006	1,255	0.38	0.50	0.83	0.81	1.02	1.09	0.66	0.65
2007	923	0.16	0.21	0.78	0.78	1.07	1.15	0.73	0.56

[a] The water table depth is the distance from ground surface to water table level where is below the ground surface, and annual average water table depth from all wells. The unit of discharge is mm/day, normalized from cubic meters per second (cm^3/s)

O observation, *P* prediction, R^2 coefficient of determination, *E* Nash–Sutcliffe model efficiency

same period. However, this result was only about 27% of the maximum methane uptake rate (7.3 mg C m^{-2} day^{-1}) in another adjacent watershed (Turkey Creek, about 3 km away) found by Renaud (2008). The simulated daily flux from wet areas (averaged from 155 of total 675 cells) for WS80 in 2007 ranged from −2 to 88 mg C m^{-2} day^{-1} with average of 8.7 mg C m^{-2} day^{-1}, higher than the observed average (4.2 mg C m^{-2} day^{-1} averaged from seven samples) from the adjacent watershed WS79b in the same year (Renaud 2008). The simulated maximum flux from a cell located the wettest area in the study site (see Fig. 4) was 220 mg C m^{-2} day^{-1}, higher than the observed maximum flux of 137.8 mg C m^{-2} day^{-1} from Turkey Creek in 2007 found by Renaud (2008). The differences in daily maximum methane flux between the simulation for this catchment and the observation from those adjacent watersheds were likely related to long sampling intervals (2–4 weeks) that failed to capture emission peaks, and the manual sampling procedure which could not be carried out while the sampling point and adjacent area were flooded.

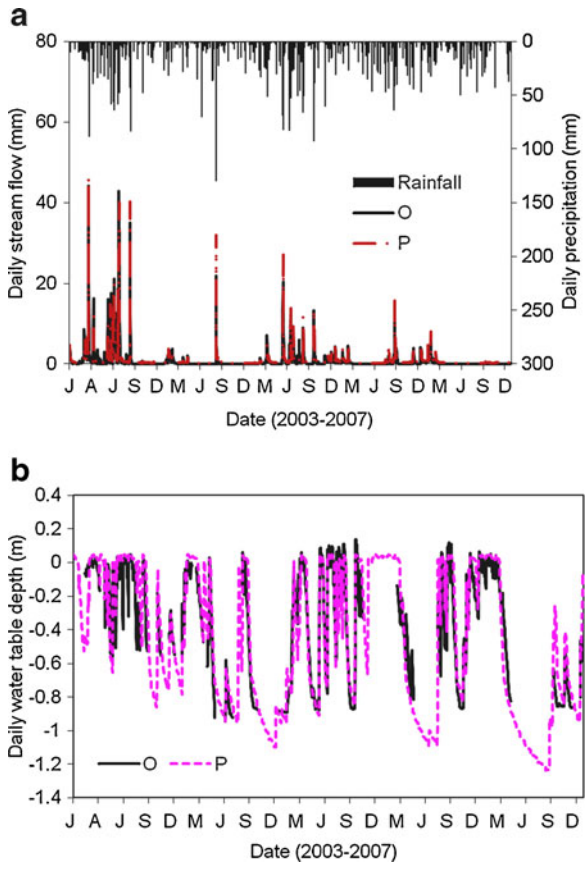

Fig. 2 **a** Simulated and measured daily discharge in calibration period (2003–2004) and validation period (2005–2007). **b** Measured and simulated daily water table for an automatic well in calibration period (2003–2004) and validation period (2005–2007). *O* observation, *P* prediction

3.2 Comparison of the Results from Field Scale and Watershed Scale Approaches

There was a substantial difference between results from field-scale and watershed-scale simulations, especially for CH_4 flux (Table 3). The arithmetic mean CH_4 flux was 170.9, 39.9, 50.8, 53.8, and 10.5 kg C ha^{-1} year^{-1} from the watershed-scale simulation in the period from 2003 to 2007, respectively: −0.7, −4.4, −4.3, −4.5, and −4.8 kg C ha^{-1} year^{-1} from the field-scale mode in the same period. The completely contrastive results in CH_4 flux between the two approaches, showing a methane source from the watershed-scale simulation

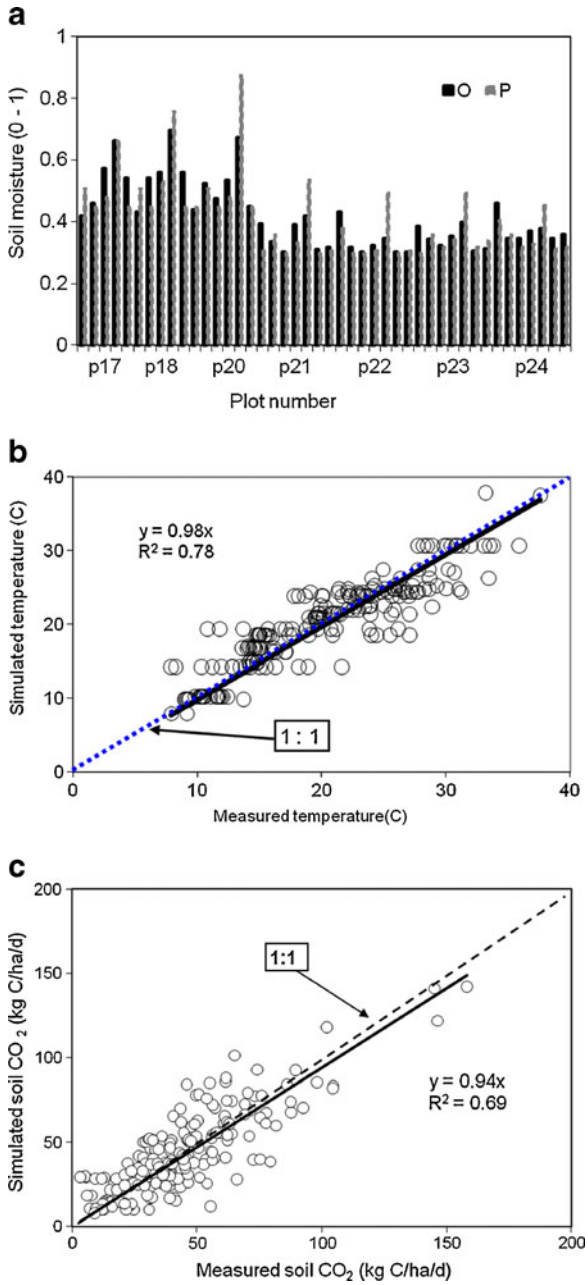

Fig. 3 **a** Simulated vs. observed daily soil moisture for calibration and validation (*O-moist* observed soil moisture, *P* prediction). **b** Simulated and observed daily soil temperature for calibration and validation. **c** Simulated and observed daily soil CO_2 flux for calibration and validation

versus a sink from the field scale, were primarily as a result that the different water table dynamics were used by the two modeling approaches. The field-scale model utilized the average daily water table across the watershed, while the watershed-scale approach employed the spatially daily water table dynamics. Although this watershed is planar, there are substantial differences in water table depth relative to the soil surface, especially after heavy rain and during dry periods (Fig. 5). The largest difference in water table was more than 2 m. The wetland areas will have a water table that is near or above the surface during wet periods, while the water table would be below the surface in the other part of this watershed (Fig. 4). Accordingly, the soil biogeochemical processes for CH_4 generation and consumption were substantially different from place to place within the catchment. A daily average water table depth over the watershed used for predicting C and N dynamics in this site would miss the "hot spots" for CH_4 generation and emission.

There were smaller differences in the simulated results from different approaches for annual soil CO_2 and N_2O fluxes than for CH_4, about 25% of difference for N_2O, and 10% for soil CO_2. These smaller differences, compared with CH_4, might show that soil CO_2 and N_2O were less sensitive to the small changes in water table depth. Despite of the smaller differences in the simulated results from different modeling approaches for annual average soil CO_2 and N_2O fluxes, the spatial differences in the fluxes (0.04–5.13 kg N ha^{-1} $year^{-1}$ for N_2O and 0.25–9.9 Mg C ha^{-1} $year^{-1}$ for soil CO_2 in 2003–2007) across the watershed were large (see additional discussion in spatial distribution). These results may show that a higher resolution biogeochemical modeling mode, which can employ biophysical and biogeochemical characteristics in space and time over study catchments, is better to capture the spatial variations in GHG flux in wetland-dominant ecosystems, especially for CH_4 flux.

3.3 CH_4, CO_2, and N_2O Fluxes and their Variations in Time

Methane flux varied largely among years, and the annual flux was positively correlated with annual precipitation ($P<0.01$). The correlation between precipitation and CH_4 flux is attributed to the planar topography and shallower water table over the watershed; as a result, the soils across large portions of the watershed are nearly saturated during rainy periods. However, there was not a significant relationship between daily precipitation and daily arithmetic average CH_4 flux. The annual arithmetic average flux (170.9, 39.9, 50.8, 53.8, and 10.5 kg C ha^{-1} $year^{-1}$ in 2003–

Table 2 Observed and simulated soil temperature, moisture, and CO_2 for the calibration and validation of Forest-DNDC

Modeling	Items	*O*	*P*	R^2	*E*
Calibration	Temperature (°C)	23.5	22.3	0.68	0.61
	Moisture (m^3 m^{-3})	0.42	0.41	0.83	0.68
	Soil CO_2 (kg C ha^{-1} day^{-1})	66.6	62.2	0.63	0.55
Validation	Temperature (°C)	19.7	19.9	0.83	0.83
	Moisture (m^3 m^{-3})	0.54	0.53	0.44	0.42
	Soil CO_2 (kg C ha^{-1} day^{-1})	39.6	39.4	0.66	0.61

O observation, *P* prediction, *Soil CO_2* the CO_2 which includes organic matter decomposition in soil and forest floor, root respiration, and moss respiration

2007) was larger than the median (122, 8, 11, 12, and −2 kg C ha^{-1} $year^{-1}$), about 30% higher than the median in 2003, an extreme wet year, and about 80% higher in other climatic years (Table 3). This difference was related to the heterogeneously spatial distribution of CH_4 flux associated with spatial water table distribution influenced by topography.

The average N_2O flux was 2.16–3.04 kg N ha^{-1} $year^{-1}$, the median was 2.13–3.20, and geometric mean was 1.58–2.87 in the 5-year period (2003–2007) (Table 3). The arithmetic mean was slightly higher than geometric value, only about 12% on average. The variation of year-to-year N_2O flux was much smaller than for CH_4. The increase in N_2O emissions in dry years is attributed to an increase in soil organic matter decomposition and a decrease in plant N uptake.

Soil CO_2 flux in this watershed was obviously affected by climatic conditions. The flux in 2003 (a wet year, 320 mm of precipitation was higher than the long-term average of 1,350 mm) was about 33.4% of the flux in 2007 (a dry year, 430 mm of precipitation was less than the long-term average, 750 mm less than the precipitation in 2003). The difference in soil CO_2 flux between wet and dry years showed that the soil respiration in wet years was substantially lower than dry years. It was shown that soil respiration was influenced by changes in soil moisture. Annual soil CO_2 flux was significantly and linearly correlated ($p << 0.01$) to the annual mean water table in the watershed (Fig. 6), the higher annual average water table, the lower annual mean soil CO_2 flux. High soil CO_2 flux in dry years is primarily as wetlands loss to a decrease in the water table level regulated by precipitation in this forest. This result was similar to the finding of Pietsch et al. (2003) that water table level decrease in their sites led to an increase in soil carbon loss.

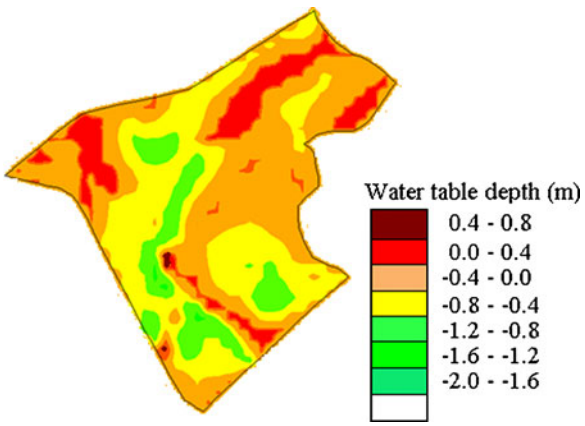

Fig. 4 Water table level in the wet period of 2003 (a week after a heavy rain)

The pattern of daily soil CO_2 flux was seasonal. The high daily soil CO_2 flux occurred in summers although precipitation did influence the flux. The changes in soil CO_2 flux were primarily as a result of increasing soil temperature in the summer, and changes in precipitation associated with altering soil moisture regime increasing or decreasing soil respiration. Although the effect of water table on daily soil CO_2 flux was similar with annual flux, the relationship between daily soil CO_2 flux and daily water table depth was different from that between annual average soil CO_2 flux and annual average water table depth, appearing to be a semi-logarithmic relationship (Fig. 7).

3.4 Spatial Variations

The spatial variation of CH_4 flux in the watershed was large (Fig. 8a). The flux spatially ranged from −4

Table 3 Simulated annual CH_4, soil CO_2, and N_2O fluxes in WS80 (2003–2007)*

Year	2003	2004	2005	2006	2007	Mean
CH_4-a (kg C ha^{-1} $year^{-1}$)	170.9	39.9	50.8	53.8	10.5	65.2
CH4-m(kg C ha^{-1} $year^{-1}$)	122.0	8.0	11.0	12.0	−2.0	31.0 (13.0)[a]
CH_4-f (kg C ha^{-1} $year^{-1}$)	−0.7	−4.4	−4.3	−4.5	−4.8	−3.7
N_2O-a (kg N ha^{-1} $year^{-1}$)	2.16	3.04	2.34	2.26	2.47	2.45
N_2O-m (kg N ha^{-1} $year^{-1}$)	2.13	3.20	2.37	2.20	2.53	2.49 (2.47)[a]
N_2O-g (kg N ha^{-1} $year^{-1}$)	1.58	2.87	2.12	2.11	2.39	2.21
N_2O-f (kg N ha^{-1} $year^{-1}$)	2.32	2.48	1.57	1.57	1.56	1.90
Soil CO_2-a (Mg C ha^{-1} $year^{-1}$)	2.48	5.37	3.41	4.58	7.42	4.65
Soil CO_2-m (Mg C ha^{-1} $year^{-1}$)	2.51	5.39	3.27	4.52	7.40	4.62 (4.83)[a]
Soil CO_2-g (Mg C ha^{-1} $year^{-1}$)	1.91	4.78	2.73	3.99	7.21	4.13
Soil CO_2-f (Mg C ha^{-1} $year^{-1}$)	2.51	5.36	3.39	4.74	7.96	4.79

There was no geometric average for CH_4 because there were zero and negative fluxes in space in the watershed

-a arithmetic average from watershed scale, *-g* geometric average from watershed scale, *-m* median, *-f* result from field-scale model

[a] The value in braces is the median obtained from all results simulated by watershed-scale model for the 5-year period (2003–2007); the value out of the braces is arithmetically averaged from five yearly medians

to +716, −4 to +332, −4 to +590, −4 to +384, and −5 to +114 kg C ha^{-1} $year^{-1}$ in the watershed in 2003–2007, respectively. The difference in CH_4 flux across the watershed was related to the topography. The high CH_4 flux occurred at the places that were very flat or depressional, thereby holding topsoil saturated for a long time during wet periods. There was no or negative CH_4 flux on surfaces with slope (≥1%), and in general the flux was low across most of the places in the watershed. Therefore, CH_4 flux in space was heterogeneous in the watershed, the distribution was skewed (Fig. 8b). This result was similar with that reported by Trettin and others (2006), a geometric average for CH_4 flux was much less than the arithmetic mean. Although CH_4 flux distribution in the wetland was skewed, geometric average was not available for this catchment since there were zero and negative fluxes for CH_4. Therefore, the median of CH_4 flux should be better than arithmetic average to reflect the mean level of CH_4 flux in the watershed for normal and wet years. However, the median was not good for dry years, such as 2007. The median was −2 kg C ha^{-1} $year^{-1}$ in 2007, an extreme dry year, which indicated that this catchment was overall a methane sink. However, the total methane emission from wetlands (2 Mg C) in

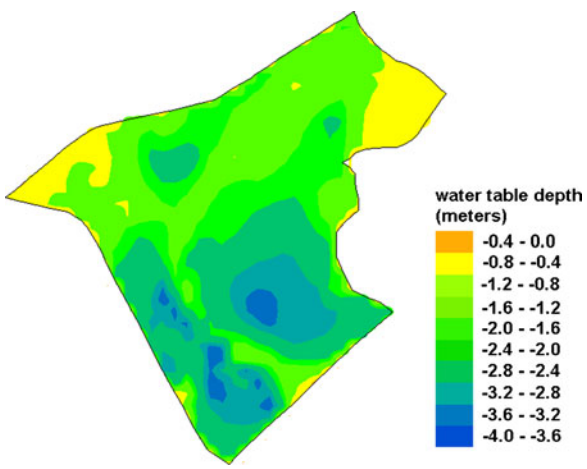

Fig. 5 Water table in a dry period on WS80

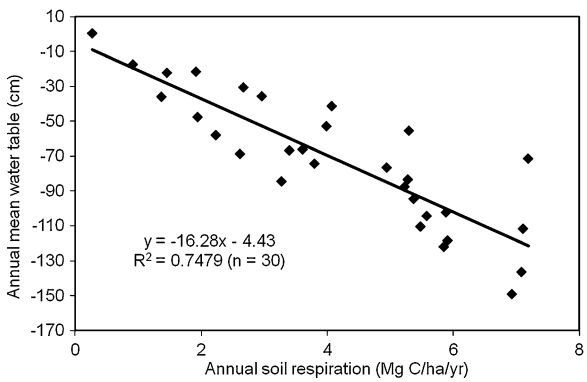

Fig. 6 The relationship between annual soil CO_2 flux and annual mean water table on WS80

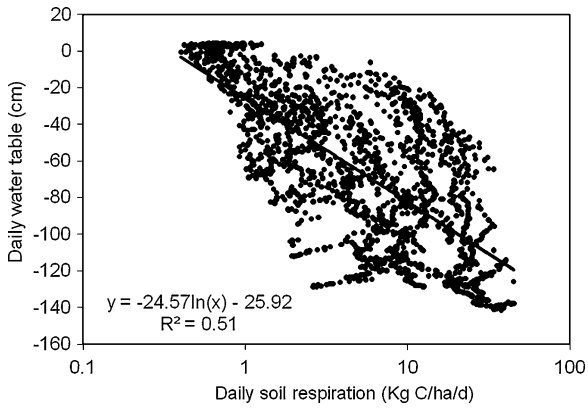

Fig. 7 Effect of daily water table on daily soil CO_2 flux in five plots

2007 was much higher than the uptake in uplands (0.4 Mg C).

The CH_4 fluxes from wetland and upland components of WS80 were simulated using the watershed-scale model with spatially distributed water table dynamics within each component. The arithmetic mean flux was 425, 125, 168, 150, and 31 kg C ha^{-1} $year^{-1}$ from the wetlands and 32, 4, 18, 6, and 0 from uplands for 2003, 2004, 2005, 2006, and 2007, respectively. The CH_4 flux from wetlands was over 90% of the total flux from this watershed. The results from these divisions demonstrated that the wetlands were the dominant CH_4 source. The small amount of CH_4 from uplands was primarily as the result that the topsoil in a large area of this catchment was saturated during wet periods due to this watershed having a shallow water table and flat topography and that their some places are adjacent to wetlands.

The CH_4 flux from field-scale modeling for uplands (−3.7, −4.4, −4.3, −4.5, and −4.7 kg C ha^{-1} $year^{-1}$) was significantly lower than those from the watershed-scale approach (32, 4, 18, 6, and

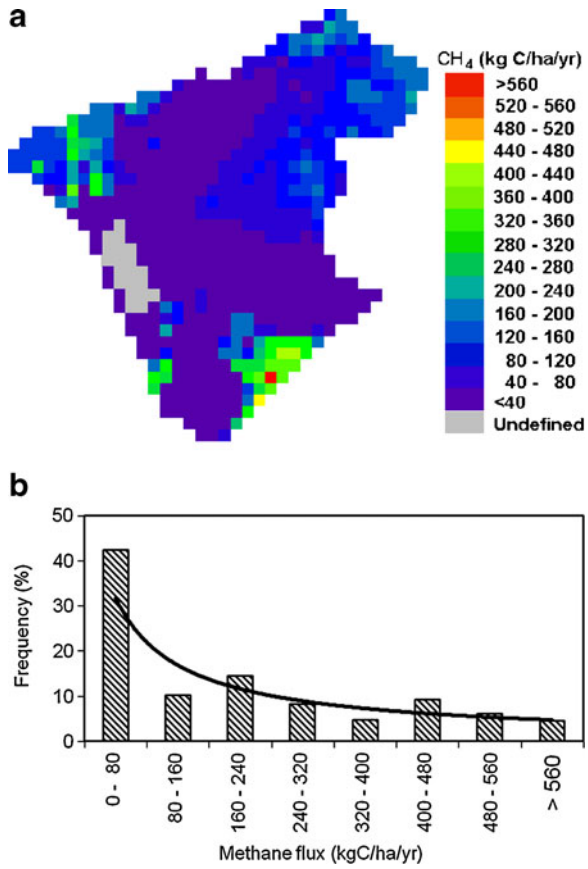

Fig. 8 **a** Spatial distribution of annual methane flux on WS80 in 2006. **b** Distribution frequency of methane flux over the watershed in 2003

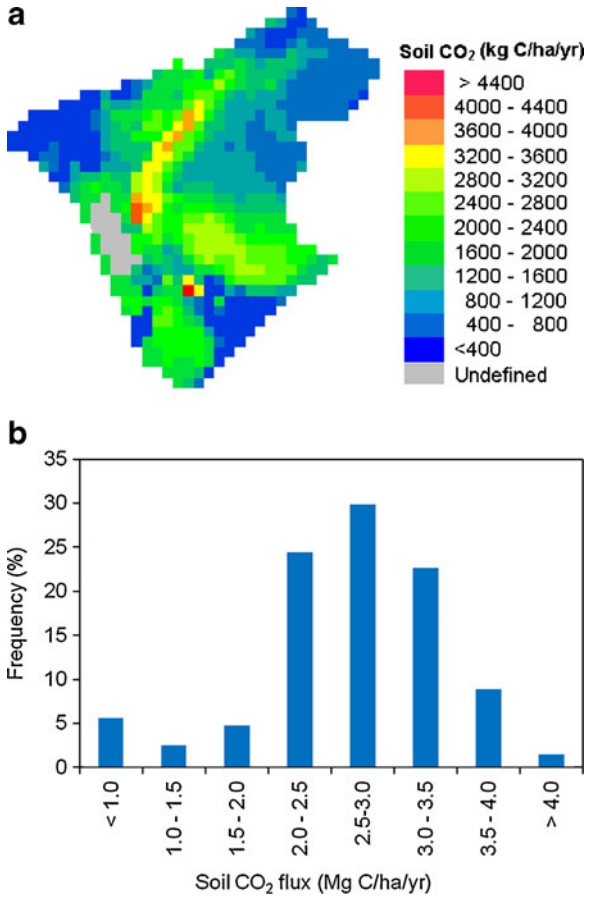

Fig. 9 **a** Spatial distribution of soil CO_2 flux on WS80 in 2003. **b** Distribution frequency of soil CO_2 flux over the watershed in 2003

0 kg C ha^{-1} $year^{-1}$). However, there was a small difference in methane flux from wetlands between two approaches (425, 125, 168, 150, and 31 kg C ha^{-1} $year^{-1}$ simulated by the watershed scale and 497.4, 114.6, 105.8, 123.6 ,and 32.1 modeled by the field scale). The large difference in CH_4 flux from uplands between the two approaches is due to large differences in water table level location to location. Therefore, the average water table condition from uplands dismissed CH_4 emissions from the upland edges near the riparian zone and those flat areas where the soils were saturated during wet periods. An approximate CH_4 flux from the wetland areas predicted by both the field-scale and watershed-scale modeling approaches is primarily as a result of shallow water table and planar topography, especially within wetlands. The topsoil in wetlands is saturated during wet periods in this watershed, but the topsoil in uplands is only saturated in the durations with consecutively proper precipitation and becomes unsaturated rapidly after raining. The difference in water table within most of wetlands is small. The spatial difference in CH_4 flux in this catchment showed the substantial impact of spatial heterogeneity in the biogeochemical conditions within the catchments on generation and emission of methane. These results indicated that the consideration of the spatial heterogeneity across a catchment, especially across a large catchment with mosaics of wetlands and uplands, was needed to estimate C balance and GHG emissions in wetland-dominated landscape ecosystems. Although the uncertainty of modeling GHG emissions from wetland-dominated watersheds can be reduced by using the high resolution modeling approach, the data input requirements for each cell and computation time are onerous. Accordingly, an alternative is to divide the catchment into several sub-catchments to reflect major differences in hydrology, soils, vegetation, and topography.

The flux of soil CO_2 spatially ranged from 0.25 to 5.7, 0.73 to 6.9, 0.32 to 7.5, 0.88 to 7.8, and 5.4 to 9.9 Mg C ha^{-1} $year^{-1}$ in 2003–2007, respectively, in the watershed. The spatial difference in the flux was large in wet years, such as 2003 (Fig. 9a) and 2005, ≤23 times among cells, but it was smaller in dry years, such as in 2007, ≤1.8 times among cells. Although the spatial difference in soil CO_2 flux was substantially large and the variation of the year-to-year flux was also large (Table 3), the spatial distribution of the flux was almost same in the 5-year period, a normal distribution in this watershed (Fig. 9b). Therefore, the arithmetic average was approximate to the geometric average and median. The difference in soil CO_2 flux in space was mainly influenced by water table in this watershed, the higher water table, the lower soil CO_2 flux. Therefore, lower soil CO_2 flux was occurred in wet years, the flux in 2007 was about three times of that in 2003 (wet years, 750 mm of precipitation higher than 2007).

There was a large spatial difference in N_2O flux across the watershed (ranged from 0.04 to 5.13, 0.15 to 4.30, 0.06 to 3.92, 0.23 to 3.71, and 1.33 to 3.86 kg N ha^{-1} $year^{-1}$), ≤100 times among cells (Fig. 10a). The spatial distribution of N_2O flux may be complicated. Its distribution may be skewed in extreme wet years, such as 2003 (Fig. 10b), and normal in other climatic

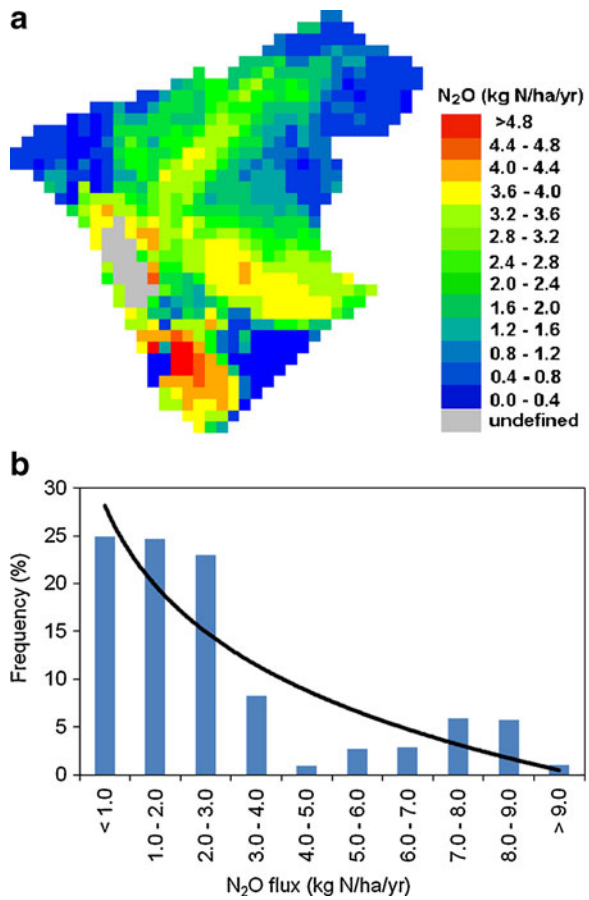

Fig. 10 **a** Spatial distribution of N_2O flux on WS80 in 2003. **b** Distribution frequency of N_2O flux over the watershed in 2003

years. The spatial difference in the flux of N_2O was larger than that of CH_4 and soil CO_2. The difference was primarily as the results that CH_4 and soil CO_2 fluxes were mainly impacted by water table and soils, but N_2O flux was also influenced by plant N uptake and precipitation (Li et al. 1992a, b).

4 Conclusions

There was considerable information gained regarding GHG fluxes from soils by conducting the simulations at a fine scale as opposed to the whole watershed. The simulation results showed that the soil CO_2, CH_4, and N_2O fluxes were highly variable across the watershed. The spatial distribution patterns of the gas fluxes were different, being a skewed distribution for CH_4, a normal distribution for soil CO_2, whereas distribution of N_2O flux was variable, skewed in wet years and normal in other climatic years. The substantial variation in spatial distribution of the gas fluxes reflects that the "hot spots" of biogeochemical process cannot be ignored to estimate these fluxes from a watershed using a biogeochemical model, especially from a large watershed with low-relief topography and complex characteristics of hydrology, vegetation, and soil.

The comparison of the results from the both field-scale and watershed-scale biogeochemical modeling approaches and the spatial differences in the fluxes of soil CO_2, CH_4, and N_2O across the watershed showed that the watershed-scale model was better than the field-scale assessment for understanding the GHG generation and emissions in a forested wetland watershed, especially for estimating CH_4 flux. The results from watershed divisions into wetlands and uplands indicated that the consideration of soil moisture conditions of the ecosystems was needed to estimate C balance and GHG emissions from the watershed, no matter which scale of biogeochemical modeling is chosen for the estimations. However, the cost may be high to simulate C and GHG dynamics for large catchments or regions using the high spatial resolution modeling approach. The results from the simulations for the watershed divisions demonstrated that an alternative way is to partition the catchment, especially large mosaic landscapes containing uplands and wetlands, into several components to reflect the major differences in biophysical and biogeochemical conditions to simulate C and GHG.

The variation of the year-to-year N_2O flux was small although the spatial variation in flux was large. In contrast, the variations of year-to-year CO_2 and CH_4 fluxes were large, and the large difference may be related to large alternation of year-to-year water table influenced by the substantial difference in precipitation in the watershed.

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