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CO₂ flux evaluation over the evergreen coniferous and broad-leaved mixed forest in Dinghushan, China

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Abstract The Dinghushan flux observation site, as one of the four forest sites of ChinaFLUX, aims to acquire long-term measurements of CO₂ flux over a typical southern subtropical evergreen coniferous and broad-leaved mixed forest ecosystem using the open path eddy covariance method. Based on two years of data from 2003 to 2004, the characteristics of temporal variation in CO₂ flux and its response to environmental factors in the forest ecosystem are analyzed. Provided two-dimensional coordinate rotation, WPL correction and quality control, poor energy-balance and underestimation of ecosystem respiration during nighttime implied that there could be a CO₂ leak during the nighttime at the site. Using daytime ($PAR > 1.0 \mu\text{mol}^{-1} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) flux data during windy conditions ($u^* > 0.2 \text{ m} \cdot \text{s}^{-1}$), monthly ecosystem respiration (*Reco*) was derived through the Michaelis-Menten equation modeling the relationship between net ecosystem CO₂ exchange (*NEE*) and photosynthetically active radiation (*PAR*). Exponential function was employed to describe the relationship between *Reco* and soil temperature at 5 cm depth (*Ts05*), then *Reco* of both daytime and nighttime was calculated respectively by the function. The major results are: (i) Derived from the Michaelis-Menten equation, the apparent quantum yield (α) was $0.0027 \pm 0.0011 \text{ mgCO}_2 \cdot \mu\text{mol}^{-1} \text{ photons}$, and the maximum photosynthetic assimilation rate (*Amax*) was $1.102 \pm 0.288 \text{ mgCO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. Indistinctive seasonal variation of α or *Amax* was consistent with weak seasonal dynamics of leaf area index (*LAI*) in such a lower subtropical evergreen mixed forest. (ii) Monthly accumulated *Reco* was estimated as $95.3 \pm 21.1 \text{ gC} \cdot \text{m}^{-2} \cdot \text{mon}^{-1}$, accounting for about 68% of the gross primary product (*GPP*). Monthly accumulated *NEE* was estimated as $-43.2 \pm 29.6 \text{ gC} \cdot \text{m}^{-2} \cdot \text{mon}^{-1}$. The forest ecosystem acted as carbon sink all year round without any seasonal carbon efflux period. Annual *NEE* of 2003 and 2004 was estimated as -563.0 and $-441.2 \text{ gC} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ respectively, accounting for about 32% of *GPP*.

Keywords: carbon dioxide flux, eddy covariance, Dinghushan, southern subtropical region, evergreen coniferous and broad-leaved mixed forest, ChinaFLUX.

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The steady rise in atmospheric carbon dioxide (CO_2) concentration since the industrial revolution is commonly regarded as one of the major causes of global warming^[1]. Global warming and the anticipated adverse consequences on global climate, has spawned a strong scientific and public interest in the global carbon cycle^[2]. Long-term measurement and accurate estimation of carbon exchange between terrestrial ecosystems and the atmosphere were recognized as the essential requirements to evaluate whether ecosystems function as carbon sinks or sources at regional and global scales^[3] and to carry out large scale carbon flux modeling research. Therefore, this research has become a key scientific issue concerned commonly for the related disciplines of earth science, ecology and environment sciences^[2-4]. Forest accounts for 26% of land area and 60% of net primary productivity (*NPP*) of terrestrial vegetation in the world. The amount of carbon stored in forests is triples that stored in the atmosphere^[5]. Carbon exchange between forests and the atmosphere accounts for more than 90% of the total carbon exchange that of the global terrestrial ecosystem^[6]. Therefore, CO_2 flux research over forest ecosystems has become a hot research topic in the field of global change^[7,8].

In the last 10 years, flux measurement technique and methodology based on eddy covariance theory has been widely applied to flux measurement of carbon dioxide, water vapor and sensible heat^[9,10], and has become a standard method in FLUXNET^[11]. At present about 150 flux observation sites over forest ecosystems are operating on a long-term and continuous basis around the world, most of them are located in Europe and America. These sites provide reliable data to analyze in order to assess the role of forest ecosystems in the global carbon cycle^[12]. Systematic observation and research of flux in China, however, actually started when Chinese Terrestrial Ecosystem Flux Observational Research Network (ChinaFLUX) was established in 2002^[3,13].

A large area near the Tropic of Cancer is covered by deserts, moist subtropical forests spread out in southern China favored by the monsoon climate in this region. With the respect of climate change, forests in this region deserve more attention^[14]. Studies of carbon dioxide flux of forest ecosystems in Dinghushan Na-

ture Reserve are significant because of the high potential productivity and remarkable ecosystem balance regulating function of this area^[15]. At present, carbon flux observation and study of forest ecosystems in Asia is mainly focused on temperate deciduous forests^[16-24], temperate larch forests^[25], temperate mixed forests^[26] and tropical rain forests^[27,28], while study on subtropical forests^[29] remains relatively rare. Particularly for the southern subtropical area in China, carbon flux study of forests has been limited to soil respiration^[30-33], while ecosystem scale research has not yielded results thus far. This paper, based on about two years (from Nov 2002 to Dec 2004) of flux measurements using the eddy covariance method, CO_2 flux of the site, and its daily and annual variation characteristics as well as its response to environmental factors were analyzed, with the goal of providing a necessary base of knowledge, technology and data for development of carbon evaluation models of both regional and national scales.

1 Material and methods

1.1 Site description

The Dinghushan Nature Reserve (hereafter referred to as DNR), with an area of 1155 hm^2 and an altitude ranging from 200 to 500 m (with the highest peak Jilongshan of 1000.3 m), is located in Zhaoqing, Guangdong Province, south China ($23^\circ 09' 21'' - 23^\circ 11' 30''\text{N}$, and $112^\circ 30' 39'' - 112^\circ 33' 41''\text{E}$). Favored by the monsoon humid climate of the southern subtropical zone, the DNR has abundant resources of radiation, rainfall and heat. Mean annual global radiation in the DNR is $4665 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$, with a mean annual sunshine duration of 1433 h; mean annual temperature is 21.0°C (lower than that of the nearest weather station (Gaoyao), 22.3°C), with a mean minimum of 12.0°C in January and a mean maximum of 28.0°C in July. Mean annual precipitation is 1956 mm (more than that of Gaoyao weather station, 1671 mm), with a distinct wet season (from Apr to Sep) during which 76% of annual precipitation occurs, and a relatively dry season (from October through March). Annual mean evaporation is 1115 mm, and annual mean relative humidity is 80%, which is fairly constant throughout the year. Prevailing wind direction varies from northeast in

winter to southwest in summer.

The study site (23°10'N, 112°32'E, altitude: 240 m above sea level) is located in the investigation plot of the evergreen coniferous and broad-leaved mixed forest, in the kernel area of the DNR. With a 10% slope in the southeast direction, the terrain is nearly flat especially in the northeast direction, which is the prevailing wind direction of the site. The vegetation is coniferous and broad-leaved forest which is the typical ecosystem occurring near the Tropic of Cancer. Dominant species in canopy layers include *Schima superba*, *Castanopsis chinensis*, *Pinus massoniana* etc., with mean canopy height of approximately 17 m above the ground surface. The forest is about 100 a old, with complicated forest structure of 4 layers: two layers of arbor, one layer of shrub, and one layer of herbage and seedlings. The soil consists mainly of lateritic red-earth with a varied depth of 30–60 cm. Surface litter covers 80%–90% of ground with a thickness of 1–3 cm and pH value of 3.86. Monsoon evergreen broad-leaved forest spreads out in the southeastern portion of the plot, and Mountain evergreen broad-leaved forest and mixed forest in the northwest portion.

1.2 Flux measurements

The observation mast (cross-section 80 cm×80 cm) is 38 m tall. Two levels of Open Path Eddy Covariance (OPEC) flux measurement systems were fixed at two heights of 27 and 2 m (moved down from 9 m height on April 1, 2003), representing two interfaces of above and below canopy respectively. Three component wind speed and virtual temperature were measured with a three-dimensional sonic anemometer (Model CSAT-3, Campbell Scientific, Inc., USA). Fluctuations of the carbon dioxide and water vapor concentration in the air were measured with a fast response infrared gas analyzer (IRGA; Model LI-7500, LI-COR Inc., USA) using the open-path approach running at 10 Hz. According to eddy covariance theory^[34], half-hourly flux of CO₂ (F_c), latent heat (LE) and sensible heat (H_s) as well as other covariance variables were computed online by a CR5000 data logger (Campbell Scientific, Inc., USA). The 10 Hz raw measurements were also stored for further analysis. During on-line flux calculations of F_c , LE and H_s , appropriate corrections for

cross-wind contamination of virtual temperature^[35] and air density fluctuations^[36] were considered, but the coordinate rotation due to tilt of terrain or sensors was not applied, therefore, two-dimensional coordinate rotation^[37,38] was applied to align the vertical velocity measurement normal to the mean wind streamlines following the local terrain (i.e. bringing the mean lateral and vertical velocity components to zero). In the following sections, F_c , LE , and H_s are reported as positive if directed away from the surface.

Based on analysis of flux measurements as well as eddy covariance theory and its technical limitations, a data-screening procedure was used to remove possible eddy covariance instrumentation and sampling problems. The screening procedure consisted of removal of periods with (i) rainfall; (ii) weak turbulence conditions ($u^* < 0.2 \text{ ms}^{-1}$); (iii) signals outside specified instrumentation limits. In light of data-screening criteria recommended by ChinaFLUX, valid ranges accepted in this paper were -2.0 – $2.0 \text{ mgCO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for CO₂ flux (F_c), 500 – $800 \text{ mgCO}_2\cdot\text{m}^{-3}$ for CO₂ concentration, and 0 – $40 \text{ g}\cdot\text{m}^{-3}$ for water vapor concentration respectively; (iv) lack of sufficient sampling over the entire half hour ($n < 15000$); (v) excessive spikes in the sonic and IRGA data. Taking flux measurements above canopy for example, about 55% of the half-hourly records remained available after data-screening.

1.3 Climate measurements

Routine Meteorological (RMET) measurements include: (i) air temperature, relative humidity (model HMP45C, Vaisala, Helsinki, Finland) and wind speed (model A100R, CSI) fixed at seven levels of 4, 9, 15, 21, 27, 31 and 36 m high above ground; (ii) radiation measurements including downward/upward short/long wave radiation, net radiation (R_n) (model CNR-1, CSI), downward total and diffuse solar radiation (S_r) (model CM11, Kipp&Zonen) installed at 36 m; (iii) photosynthetically active radiation (PAR) measured at 4 heights of 4 m (2 sensors), 9 m (2 sensors), 21 m and 36 m with quantum sensor (model LI190SB, CSI for 36 m; model LQ70-10, CSI for other levels); (iv) wind direction (model W200P, CSI) and rainfall (model 52202, R.M YOUNG Company, Michigan, USA) measured at 36 m; (v) soil heat flux measured at two

depths of 3 and 5 cm with 2 Heat-Flux-Plates (model HFP01, Hukseflux Thermal Sensors); (vi) soil temperature measured at different depths with two types of probes (model 107-L, CSI for 5 depths of 20, 40, 60, 80 and 100 cm; model 105T for 5 depths of 5, 10, 15, 20 and 40 cm); (vii) soil volumetric water content (SWC) measured with TDR probes (model CS615-L, CSI) at 3 depths of 5, 20 and 40 cm.

Running at 0.5 Hz, RMET measurements mentioned above are calculated on-line and stored half hourly by a datalogger (model CR23X-TD/CR10X-TD, CSI, Logan, UT). Contrary to flux of F_c , LE and H_s measured by OPEC, a positive value for net radiation (R_n) and soil heat flux (G) indicates a net flux of energy downward to the surface.

1.4 Calculation of net ecosystem CO_2 exchange (NEE)

NEE is the change in carbon storage of an ecosystem due to photosynthesis of vegetation, carbon storage in air of the canopy, and ecosystem (both biotic and abiotic) respiration^[39]. Employing a single set of instruments the eddy covariance method relies on the assumption of horizontal homogeneity of fluxes, when NEE reduces to the sum of the vertical net exchange and the storage flux:

$$NEE = F_{ca} + F_s = -(GPP - Reco), \quad (1)$$

where F_{ca} is CO_2 flux measured by OPEC at the interface of the ecosystem and the atmosphere, F_s is the storage flux which reflects the accumulation and depletion of CO_2 in the canopy volume (using the micrometeorological sign convention that upward fluxes and accumulation of CO_2 in the canopy volume are positive while downward fluxes and CO_2 depletion in the canopy are negative), GPP is the gross primary productivity of the ecosystem, and $Reco$ is ecosystem respiration. Signs of GPP and $Reco$ are always positive following conventions. The assumption of eq. (1) is horizontal eddy flux as well as horizontal advection may be neglected^[40,41] and therefore that NEE can be estimated from eddy flux and storage measurements. However, under certain conditions (at night in particular) this assumption may be violated^[42]. Recently a few groups^[43-45] have attempted to measure nighttime horizontal advection in a forest ecosystem, but both the experimental methodology and theory still require

considerable refinement before they will be routinely applicable^[43,46].

The storage flux (F_s) was calculated by the simple approach^[47,48] using only the change in CO_2 concentration measured at 27m by OPEC system:

$$F_s = \Delta C(z)/\Delta t \times \Delta z, \quad (2)$$

where $\Delta C(z) = [CO_2]_t - [CO_2]_{t-\Delta t}$, is the change of CO_2 concentration at the height of z , Δt is the time period (1800 s), and Δz is the height of the layer (27 m). A previous study^[47] shows that the storage term F_s determined from the full profile measurements^[42] validates this simple approach (the largest discrepancies occur in the morning and early evening due to the inaccuracy of the simple approach associated with transitory conditions), and the associated discrepancies in annual sums of NEE are negligible.

In order to remove these events for systematic treatment, a test excluded data for which

$$|[CO_2]_t - [CO_2]_{t-\Delta t}| > 20 \text{ mgCO}_2 \cdot \text{m}^{-3}.$$

This test therefore limited the storage term (F_s) to a maximum absolute value of $0.3 \text{ mgCO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. Relative importance of F_s to F_c , denoted by $F_s/(F_s + F_c)$, varies with friction velocity u^* . When u^* is low, $F_s/(F_s + F_c)$ is approximately equal to 1 implying that most ecosystem respiration is stored in the canopy and F_c can be neglected; however, when u^* is high, $F_s/(F_s + F_c)$ is approximately equal to 0 implying that F_s can be neglected.

Ecosystem respiration is mainly influenced by the soil and the canopy. Generally, ecosystems release CO_2 during the nighttime due to respiration of vegetation and soil, and CO_2 concentration in the lower part of flux layer^[49] is higher than that in higher part, therefore, CO_2 flux measured by OPEC should be positive indicating an upward transition of CO_2 . On the contrary, CO_2 flux measured during the daytime is negative because of downward transition when canopy absorbing CO_2 through photosynthesis. Respiration of both soil and vegetation is mainly influenced by temperature, therefore, CO_2 flux measured above the canopy usually increases exponentially with increasing temperature in the soil and the air^[50]. One efficient approach to estimate nighttime CO_2 flux is to employ the statistical exponential models describing the relationship between ecosystem respiration and tempera-

ture. The models are derived from nighttime CO₂ flux measured under windy condition (when the eddy covariance system is supposed to capture the “true” biological flux) by OPEC or CO₂ flux measured by chamber method^[50–52].

Data from this site show that eddy covariance measurements of F_c during the daytime were negative. During the nighttime F_c measured both above and below the canopy had varied sign and there was no significant relationship between F_c and soil temperature measured at 5 cm depth, indicating that eddy covariance measurements during the nighttime at this site cannot represent the true condition of CO₂ flux of the evergreen mixed forest ecosystem. Given the above situation, Michaelis-Menten model based on kinetics theory^[53,54] was applied to eddy covariance measurements during the daytime in order to simulate the response of NEE to photosynthetically active radiation (PAR):

$$NEE = -\frac{\alpha \cdot A_{max} \cdot PAR}{\alpha \cdot A_{max} + PAR} + Reco, \quad (3)$$

where NEE (calculated by $F_{ca}+F_s$) represents net ecosystem CO₂ exchange measured above the canopy during the daytime, α is the apparent quantum yield (when $PAR = 0$, the slope of the best fitted line), A_{max} is the asymptotic value of gross primary productivity at saturation irradiance ($PAR \rightarrow \infty$), and $Reco$ is the ecosystem respiration. PAR is the photosynthetically active radiation measured above the canopy at 21 m above the ground (on the fourth platform). The three parameters of A_{max} , α and $Reco$ of the model were constrained monthly by daytime ($PAR > 1$) eddy covariance measurements with sufficient turbulent condition ($u^* > 0.2 \text{ m}\cdot\text{s}^{-1}$). The model was applied to (i) fill gaps of daytime CO₂ flux; (ii) constrain the exponential function^[55] between $Reco$ (extrapolated from eq. (3) monthly) and soil temperature of 5 cm deep, calculate ecosystem respiration including both daytime and nighttime; (iii) obtain monthly and yearly NEE and, (iv) analyze characteristic of temporal variation of parameters of α and A_{max} , and their affecting factors.

2 Results and analysis

2.1 Seasonal variation of RMET

Daily mean temperature (Ta_{-5}), soil temperature

(Ts_{05}) and precipitation show similar seasonal variation (Fig. 1(c)), implying that climatic resources of radiation, heat and water vary nearly synchronously at the study site. Wet seasons (Apr. to Sep.) has higher temperature, more radiation and rainfall than dry season (Oct. to Mar.). 2003 and 2004 were relatively warmer and drier than normal years. Annual total rainfall of 2003 and 2004 were 1290 and 1297 mm respectively, which were 25.1% and 17.4% less than normal respectively. Annual mean temperature of the two years were 0.6°C and 0.3°C higher than normal respectively. However, SWC at 5 cm deep remained higher than 0.1 $\text{m}^3\cdot\text{m}^{-3}$ throughout the observation period (Fig. 1(c)), indicating that soil of the mixed forest has the ability to retain relatively high soil water content even in the dry season, which is entirely different from conditions observed in the coniferous forest of Dinghushan^[32,33]. Annual average of vapor pressure deficit (VPD) of the canopy was $0.7\pm 0.43 \text{ kPa}$ (Fig. 1(d)). VPD is higher in the wet season than in the dry season. Daily average VPD in the canopy and its annual variation are relatively low, suggesting the forest is free from water deficit. With a similar trend tracking annual variation in temperature, PAR is higher in the wet season than in dry season (Fig. 1(b)), with a maximum of $52.9 \text{ molphotons}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in July and an annual average of $15.7\pm 8.6 \text{ molphotons}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. There is abundant radiation of $11.4\pm 7.4 \text{ molphotons}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ even in the relatively dry season which deserves more attention.

2.2 Daily variation of carbon flux

Photosynthesis is driven by radiation energy, while respiration is mainly affected by soil temperature and air temperature, therefore, daily variation of NEE (Fig. 2) is co-affected by PAR , Ts_{05} and Ta_{-5} (Fig. 3). During the nighttime ($PAR < 1.0 \text{ }\mu\text{molphotons}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), NEE equals $Reco$, the ecosystem therefore is a carbon source with increasing CO₂ concentration in the canopy, F_s has more positive value than negative value on this condition. On the contrary, during the daytime, NEE variation was evidently controlled by PAR , the ecosystem is a carbon sink with decreasing CO₂ concentration in the canopy, F_s has more negative values than positive ones. The daily maximum value of downward flux of CO₂ occurs at

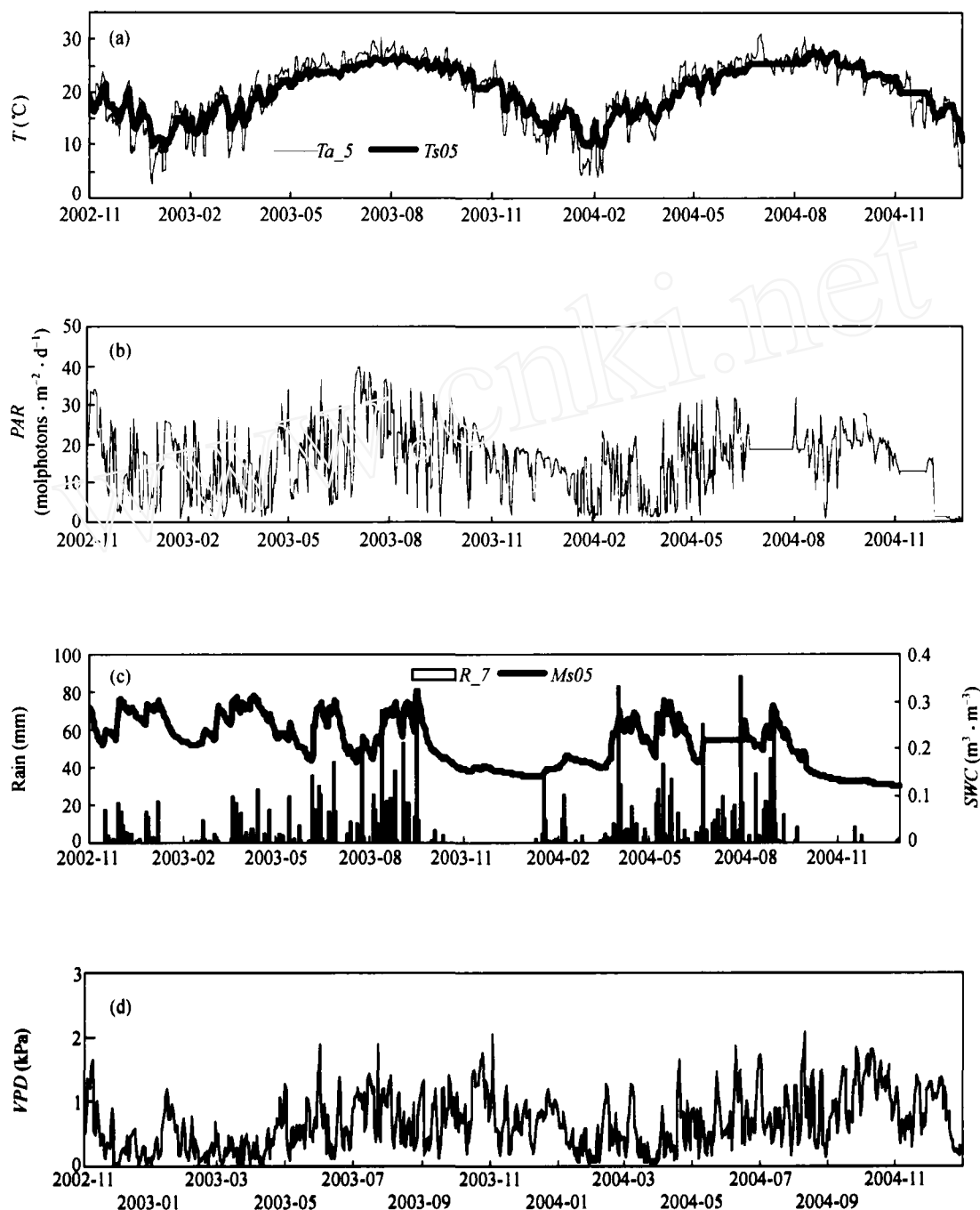


Fig. 1. Daily meteorological elements of Dinghushan flux site. (a) Daily averaged air temperature above canopy (T_{a5}) and soil temperature of 5 cm deep (T_{s05}); (b) daily total photosynthetically active radiation (PAR); (c) daily total precipitation (R_7) and daily averaged soil water content (SWC) of 5 cm deep (M_{s05}); (d) daily averaged vapor pressure deficit (VPD). Data from Nov. 2002 to Dec. 2004, with some small gaps of (a) T_{s05} , (b) PAR and (c) M_{s05} filled by MDV (mean deviation variation) method. Measuring height of T_{a5} , VPD are 27 m (at fifth platform), PAR is 21 m (fixed at the fourth platform), and rain is measured at 36 m (fixed at seventh platform).

noontime, with maximum CO_2 flux above canopy (F_{ca}) of -0.5 – $-0.8 \text{ mgCO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. Compared with other sites (Table 1), maximum F_{ca} of the forest in winter was lower than that of a boreal aspen forest in the growing season^[52], higher than that of a temperate

broad-leaved forest and a subtropical evergreen coniferous plantation in the growing season^[29], and similar to a temperate broad-leaved forest^[34], temperate black spruce forest^[53] and subtropical evergreen coniferous plantation^[29] in the growing season. In conclusion, the

evergreen coniferous and broad-leaved mixed forest in Dinghushan maintains a substantial ability to sequester carbon even in the relatively slowly growing season (winter).

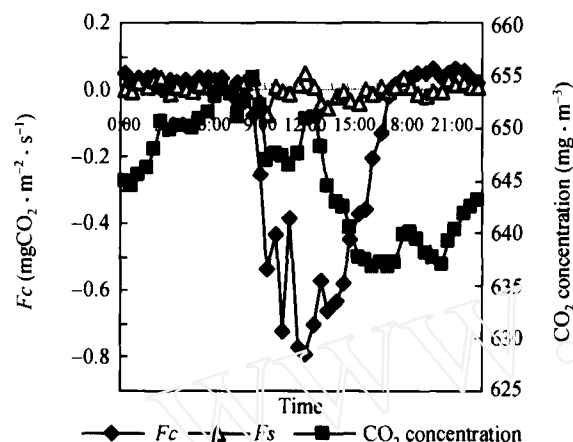


Fig. 2. Daily variation of F_c , F_s and CO_2 concentration measured above canopy of Dinghushan mixed forest, data shown are averaged over Jan. 13 to 23, 2003.

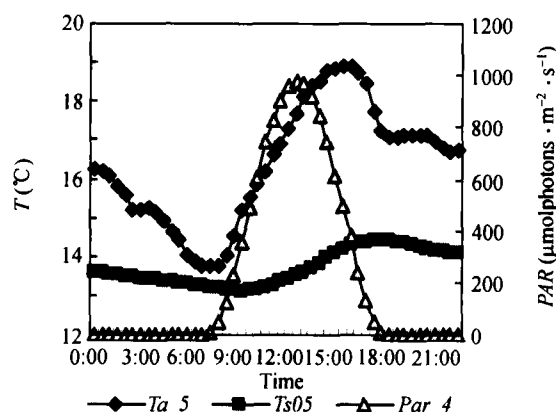


Fig. 3. Daily variation of air temperature of 27 m high (T_{a_5}), soil temperature of 5 cm deep (T_{s05}) and photosynthetically active radiation (PAR) of 21m high. Data shown are averaged over Jan. 13–23, 2003.

Table 1 Maximum CO₂ flux above canopy of coniferous and broad-leaved mixed forest in Dinghushan comparing with other forests in China and abroad

Forest type	Growing status	Maximum CO ₂ flux ($\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)	Ref
Subtropical coniferous and broad-leaved mixed forest	slowly growing season	-0.5–-0.8	this paper
Boreal aspen forest	growing season	-0.8–-1.2	[52]
Boreal pine forest	growing season	-0.4–-0.5	[34]
Subtropical coniferous plantation	slowly growing season	-0.29–-0.39	[29]
Subtropical coniferous plantation	growing season	-0.61–-0.67	[29]
Temperate broad-leaved forest	growing season	-0.7–-0.8	[34]
Temperate black spruce	growing season	-0.4–-0.8	[53]

CO₂ flux below the canopy has a similar, but smaller amplitude trend in daily variation to that above the canopy. Decreasing amplitude of CO₂ flux relates to the solar altitude angle, which is more distinct when solar altitude is high at noon compared with other day-time periods. When solar altitude angle was very low during sunrise and sunset, the levels of CO₂ flux measured above and below canopy were almost same. In terms of average value, CO₂ flux below the canopy was no more than 30% of that above the canopy, implying that CO₂ assimilation through photosynthesis of the canopy was the main cause of downward transfer of CO₂.

2.3 Response characteristic of daytime CO₂ flux to PAR

The relationship between daytime CO₂ flux above the canopy and PAR is shown in Fig. 4. CO₂ absorbed by the forest ecosystem increased with increasing PAR. Saturation radiation ranged from 600 to 1000 $\mu\text{molphotons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in winter and from 1000 to 1500 $\mu\text{molphotons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in summer, which was higher than that of the dominant species, *Schima superba*^[56]. Maximum CO₂ flux above the canopy was similar to that of a temperate spruce with lower saturation radiation (500–700 $\mu\text{molphotons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in winter)^[53].

Estimated by the Michaelis-Menten function (eq. (3)), the apparent quantum yield α ($\text{mgCO}_2 \cdot \mu\text{mol}^{-1}$ photons) ranged from 0.001–0.004 with an average value of 0.0027 ± 0.0011 ($\pm \text{std.}$) (Fig. 5), which was similar to a mixed forest of north Europe (which ranged from 0.0012 to 0.0020^[42] and 0.0025^[57]). Compared with the coniferous plantation of the Qianyanzhou site with similar latitude in the subtropical region, α of the mixed forest in Dinghushan was lower and there was no distinct seasonal variation. The asymptotic value of the gross primary production A_{max} ($\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), averaged 1.102 ± 0.288 (Fig. 6), similar to a mixed forest of north Europe (ranging from 0.88 to 1.14^[42]) and the broad-leaved Korean pine forest in the Changbai Mountains (ranging from 0.717 to 1.423^[16]). Annual variation in A_{max} was low and there was no distinct seasonal variation, which was different from a northern pine forest^[16].

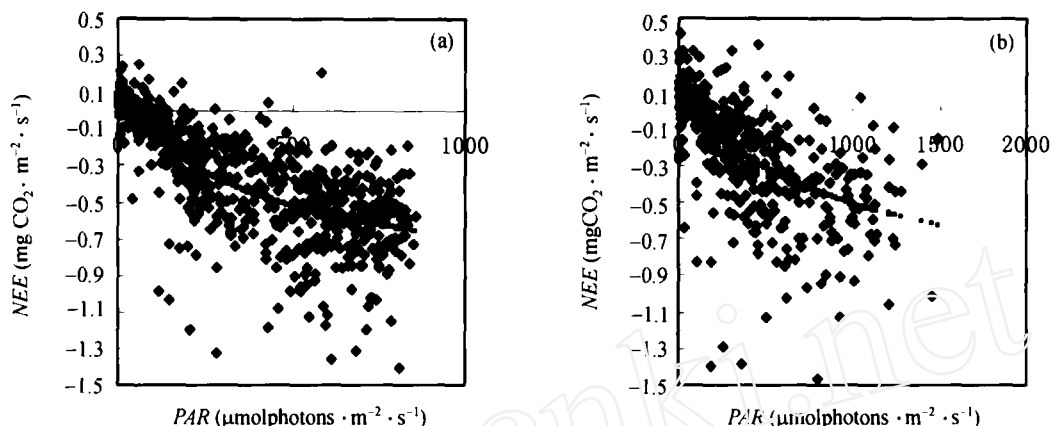


Fig. 4. NEE vs. PAR in the mixed forest of Dinghushan for winter (a) and summer (b) respectively. Lines represent the best fits of Michaelis-Menten equation (eq. (3)) to data. The y-intercept of the line is interpreted as an estimate of ecosystem respiration, $Reco$ in eq. (3). PAR was measured at 21 m high (on the fourth platform of the tower), a threshold PAR of $1.0 \mu\text{mol photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ is used to discriminate daytime data. (a) for winter season, using data of Dec. 2003, where parameters of eq. (3) are: $\alpha = 0.00281$, $A_{max} = 1.0871$, $Reco = 0.09303$, $n = 685$, $R^2 = 0.54$; (b) for summer season, using data of Aug. 2003, where parameters of eq. (3) are: $\alpha = -0.00111$, $A_{max} = 1.1854$, $Reco = 0.06585$, $R^2 = 0.223$, $n = 423$.

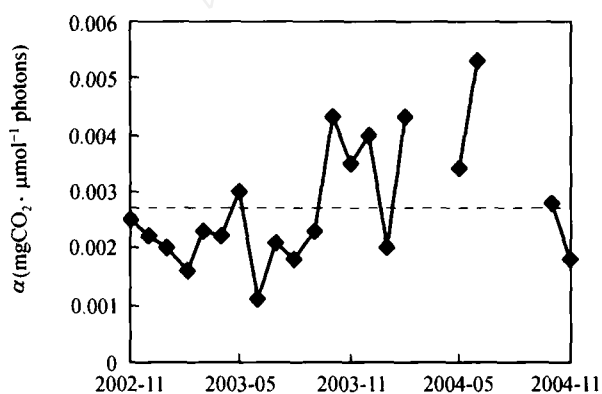


Fig. 5. Monthly apparent quantum yield α of Dinghushan mixed forest. α was constrained through the Michaelis-Menten-type function (eq. (3)) monthly, using daytime NEE during windy conditions ($u^* > 0.2 \text{ m/s}$) and PAR measured at 21 m high (on the fourth platform of the tower), with a threshold PAR of $1.0 \mu\text{mol photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ to discriminate daytime.

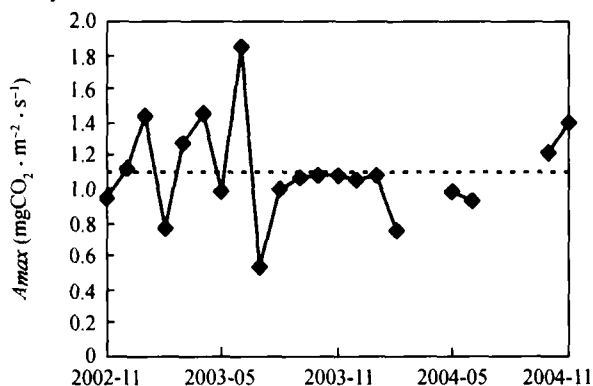


Fig. 6. Monthly asymptotic value of the gross primary production, A_{max} , of Dinghushan mixed forest. A_{max} was constrained through Michaelis-Menten-type function (eq. (3)) monthly, using daytime NEE under sufficient turbulent condition ($u^* > 0.2 \text{ m/s}$) and PAR measured at 21 m high (on the fourth platform of the tower), with a threshold PAR of $1.0 \mu\text{mol photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ to discriminate daytime.

Parameters of the Michaelis-Menten-type function (eq. (3)), including α and A_{max} , were derived by data of wet and dry seasons respectively. Seasonal differences of parameters are not statistically significant, implying that the ecosystem is free from dry and low temperature even in relatively dry season of winter (see Fig. 1(b)), which is consistent with: 1) the climatic characteristic of subtropical region with plenty resources of radiation, heat and water; 2) lesser seasonal variation of the Leaf area index (LAI) and environmental elements in the forest in Dinghushan.

Annual mean $Reco$ of 2003 derived from eq. (3) was $0.13 \pm 0.06 \text{ mgCO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, which was comparable with the annual mean soil respiration of $0.13 \text{ mgCO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ measured by Yi *et al.*^[30], and CO_2 efflux of the ground surface ranged from 0.136 to $0.159 \text{ mgCO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ (averaged of $0.111 \pm 0.008 \text{ mgCO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) measured by Zhou *et al.*^[31–33]. In the light of the result that soil respiration accounts for 69% of $Reco$ derived from the forest sites of EuroFLUX^[58], $Reco$ of the Dinghushan mixed forest estimated as above based on eq. (3) was about 30% lower than that measured with other routine methods^[30–33].

As shown by the Michaelis-Menten lines (eq. (3)) plotted in Fig. 4, there was a trend of overestimation of NEE during the early morning and evening, which could be one of the causes of the underestimation of $Reco$.

2.4 Annual variation of $Reco$ and NEE

$Reco$ includes autotrophic respiration (R_a) and het-

erogeneous respiration (R_h). R_a is influenced by vegetation metabolism while R_h is associated with activity of microbes in the soil; both R_a and R_h response closely to temperature in the same manner^[51]. In this paper, $Reco$ was derived from eq. (3) using daytime data first, then the exponential type equation between $Reco$ and $Ts05$ was constrained as follows (see Fig. 7):

$$Reco = 0.0479 \exp(0.049Ts05). \quad (4)$$

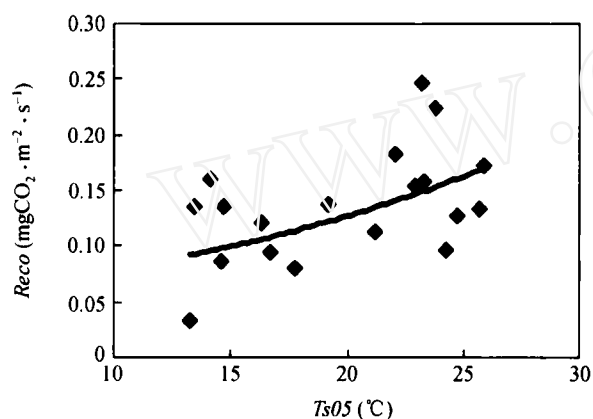


Fig. 7. $Reco$ vs. $Ts05$. $Reco$ was constrained through Michaelis-Menten-type function (eq. (3)) monthly, using daytime NEE under sufficient turbulent condition ($u^* > 0.2$ m/s) and PAR measured at 21 m high. The exponential line is: $Reco = 0.0479 \exp(0.049Ts05)$, $R^2 = 0.2559$, $n = 19$.

$Reco$ of both nighttime and daytime was calculated by eq. (4), NEE of the daytime was deduced with eq. (3), and GPP was calculated by eq. (1) ($GPP = NEE - Reco$). Monthly accumulated $Reco$, NEE and GPP are shown in Fig. 8.

Monthly accumulated $Reco$ (from Nov. 2002 to Dec. 2004) ranged from 65.4 to 131.0 $gC \cdot m^{-2}$ with an average of 95.3 ± 21.1 (\pm std.) $gC \cdot m^{-2}$ (Fig. 8). With a

maximum occurring in July to August and a minimum occurring in January to February, the seasonal variation trend of $Reco$ was similar to that of soil temperature ($Ts05$) (Fig. 1(a)), while no apparent relationship was observed between $Reco$ and soil water content (SWC) (Fig. 1 (c)) and vapor pressure deficit (VPD) in the canopy (Fig. 1 (d)). This confirms the previously mentioned result that no distinct water deficiency in the forest even in such years of relatively lesser precipitation.

Monthly accumulated NEE of the Dinghushan mixed forest ranged from 10.6 to $-89.6 gC \cdot m^{-2}$, with mean NEE of $-43.2 \pm 29.6 gC \cdot m^{-2}$. In contrast to most northern forest ecosystems^[16] that feature with a maximum carbon sequestration ability in seasons with best climate resources, Dinghushan mixed forest had a relatively higher ability to sequester carbon during the autumn-winter season (from September to November). During the period from July to August, $Reco$ was increased while carbon absorption ability GPP was depressed due to high temperature (Fig. 8), therefore NEE of this period was not very high compare to winter season. Most monthly values of accumulated NEE of the site were negative, implying that the forest acts as a carbon sink all year without a seasonal period of efflux.

Annual accumulated NEE was -563 and $-441.2 gC \cdot m^{-2} \cdot a^{-1}$ for 2003 and 2004, respectively, which was comparable to the results of other forests with similar latitude in the country and abroad. For example, the annual NEE of 2003 of the subtropical coniferous plantation^[29] was estimated as -553 and $-645 gC \cdot m^{-2} \cdot a^{-1}$ for two layers of 39 and 23 m, respectively; NEE of the mixed forest in Belgian Ardennes^[42] was estimated as $-600 gC \cdot m^{-2} \cdot a^{-1}$, which was similar to the

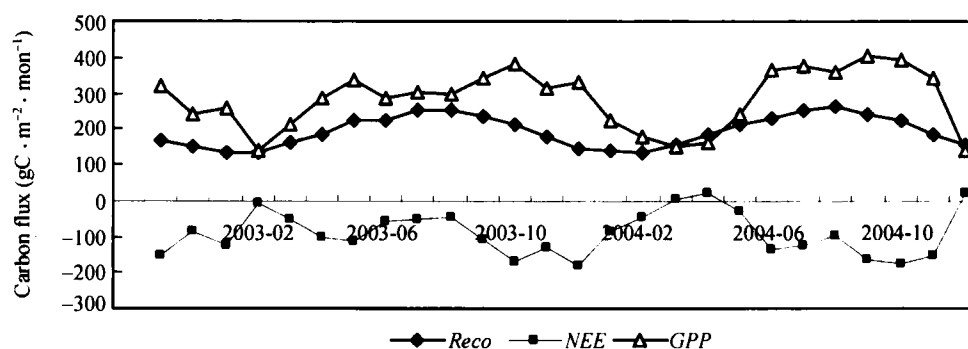


Fig. 8. $Reco$, NEE and GPP . $Reco$ was calculated by eq. (4), NEE by eq. (3) combining with eq. (4).

results of most forest sites of EuroFLUX^[55]. However, those forests with higher latitude acted as a much weaker carbon sink than Dinghushan mixed forest. For example, *NEE* of 2003 of the temperate pine forest in Changbaishan^[16] was $-184 \text{ gC}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$, *NEE* of pine forest in semidry area^[59] was $-320 \text{ gC}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$, and *NEE* of the mixed forest in Canada^[50] was $-190 \text{ gC}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$; all of these values were much lower than that of Dinghushan mixed forest, suggesting that the forest had rather strong carbon sequestration ability.

3 Discussion and conclusion

Under insufficient turbulent conditions, especially during calm and stable nighttime, CO_2 flux measured by the eddy covariance technique is often underestimated^[47,50,54]. Malhi^[51] and Lee^[60] also pointed out that for high vegetation with a high vertical CO_2 concentration gradient the eddy covariance method tends to underestimate CO_2 flux. In this study, ecosystem respiration of nighttime measured by OPEC was lower than the soil respiration measured by chamber method^[31–33] and alkali lime absorption method^[30]. Energy balance analysis indicated that the energy balance ratio (*EBR*) increased with increasing u^* , suggesting that insufficient turbulent condition is one of the main reason caused underestimation of eddy flux, especially during nighttime.

Possible reasons for nighttime underestimation of eddy flux are: (1) Due to insufficient turbulence, CO_2 released by soil and vegetation is suspected to leave the control volume, and thus undetected by the eddy covariance sensors; (2) daily variation of wind direction was observed due to unfavorable terrain of the observation site, possibly leading to CO_2 leak in the nighttime; (3) the surface of the canopy in the mixed forest is not flat and fails to meet the assumption of horizontal homogeneity of the forest canopy.

Therefore, this paper didn't use the widely adopted engineering-type approach to deal with what is often referred to as the "night time problem"; that is, to replace *NEE* measurements during calm conditions (and missing values) with *NEE* simulated by a exponential function of temperature constrained with measurements during windy conditions, when the eddy covariance system is supposed to capture the "true" bio-

logical flux^[50–52]. Alternatively, *Reco* was derived from daytime eddy covariance data by extrapolating the relationship between daytime *NEE* and *PAR*, the so-called Michaelis-Menten-type function^[53,54], to zero irradiance. Sequentially, the exponential function between *Reco* and soil temperature at 5 cm depth was applied to calculate ecosystem respiration of both night and daytime. Soil respiration is often used as a reference to check *Reco* since most of *Reco* is accounted for by soil respiration^[52]. Estimated by the method mentioned above, *Reco* of the Dinghushan mixed forest averages $0.13 \pm 0.06 \text{ mgCO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, which is comparable to the CO_2 efflux of ground surface of the site measured by alkali-lime absorption^[30] and static-chamber-gas-chromatogram method^[31–33]. Considering that the ratio of soil respiration to *Reco* was estimated as 69% for forests of EuroFLUX^[58], *Reco* estimated in this paper was possibly 30% underestimated. On the other hand, *Reco* accounts for 80% of *GPP* in forests of EuroFLUX^[58], while the ratio of *Reco* to *GPP* calculated in this paper for 2003–2004 was only 69%, implying about 15% underestimation of *Reco*. In conclusion, *Reco* estimated in this paper was possibly 15%–30% underestimated.

At present, ecosystem-scale *NEE* for forests with latitudes of 20° – 30°N is rare in the literature. *NEE* of the mixed forest in Dinghushan was estimated as -563 and $-441.2 \text{ gC}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$ for 2003 and 2004, respectively, which was comparable to *NEE* measured in subtropical coniferous plantation^[29] and most forests of EuroFLUX. *NEE* in this study is higher than that in northern forests in China^[16] and North America^[60,61], which is consistent with the decreasing trend of *NEE* with increasing latitude^[54]. *NEE* of the forest was possibly overestimated to some extent due to underestimation of *Reco*.

Further studies should explore: (i) correction methods of eddy covariance fluxes of nighttime over complex terrain; (ii) gap filling methods specific for a given site, for the purpose of accumulating 30 min measurements to annual *NEE*; (iii) the effect of severe rainfall on carbon flux measurements using the eddy covariance technique. Studies^[53] show that soil respiration increases sharply when soil moisture increase during the course of rainfall. This so-called respiration pulse could have a significant effect on soil respiration

as well as *Reco* and *NEE* of forests in subtropical regions with frequent rainfall. Also, physiological response mechanisms of soil microbes to sudden increases in soil moisture need to be better understood^[62].

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