ACTA ECOLOGICA SINICA
Volume 27, Issue 3, March 2007
Online English edition of the Chinese language journal

Cite this article as: Acta Ecologica Sinica, 2007, 27(3), 846−854.

RESEARCH PAPER

Below-canopy CO_2 flux and its environmental response characteristics in a coniferous and broad-leaved mixed forest in Dinghushan, China

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Abstract: Accurate estimation of below-canopy CO_2 flux (*Fcb*) in typical forest ecosystems is of great importance to validate terrestrial carbon balance models. Continuous eddy covariance measurements of *Fcb* were conducted in a coniferous and broad-leaved mixed forest located in Dinghushan Nature Reserve of South China. Using year-round data, *Fcb* dynamics and its environmental response were analyzed, and the results mainly showed that: (1) *Fcb* decreased during daytime which indicated that the understory of the forest continued photosynthesis throughout the year; however, understory and soil acted as CO_2 source as a whole. (2) Using soil temperature (*Ts*) as a dependent variable, all of Van't Hoff equation, Arrhenius equation and Lloyd-Taylor equation can explain a considerable variation of *Fcb*. Among those three equations Lloyd-Taylor equation is the best to reflect the relationship between soil respiration and temperature for its ability in revealing the variation of Q_{10} with temperature. (3) *Fcb* derived from Lloyd-Taylor equation is utterly determined by *Ts*, while *Fcb* derived from the multiplicative model is driven by *Ts* and soil moisture (*Ms*). The multiplicative model can reflect the synthetic effect of *Ts* and *Ms*; therefore it explains more *Fcb* variations than Lloyd-Taylor equation does. (4)*Fcb* derived from the multiplicative model was higher than that from Lloyd-Taylor equation when *Ms* was relatively high; on the contrary, *Fcb* derived from the multiplicative model was lower than that from Lloyd-Taylor equation when *Ms* was low, indicating that *Ms* might be a main factor affecting *Fcb* when the ecosystem is stressed by low-moisture. (5) Annual *Fcb* of the forest in 2003 was estimated as (787.4±296.8) $gCm^{-2}a^{-1}$, which was 17% lower than soil respiration measured by statistic chamber method. CO_2 flux measured by eddy covariance is often underestimated, and further study therefore calls for emphasis on methods quantifying *Fcb* components of respiration of soil, as well as respiration and photosynthesis of understory vegetations.

Key Words: Dinghushan; below-canopy; CO_2 flux; eddy covariance

Forest is the largest terrestrial ecosystem on the earth; therefore fully understanding the carbon source/sink function of the forest ecosystem and the controlling factors is critical for evaluation of terrestrial ecosystem carbon budget and its variation[1]. Studies related to forest ecosystem and CO_2 flux observation have been carried out all over the world since 1970's. Studies in China are mainly focused on temperate forests[2], mid-subtropical woody plants[3] and tropical/subtropical forests[4–9], among which studies on Dinghushan forests is mainly focused on soil respiration mainly by static chamber[6–8] and alkali-lime absorption method[9]. In the last 10 years, flux measurement technique and methodology based on eddy covariance theory has been widely applied for flux measurement of carbon dioxide, water vapor and sensible heat in terrestrial ecosystem[10,11], and therefore, has become a standard method in FLUXNET[12]. Systematic observation and studies in the field in China, however, actually started when Chinese Terrestrial Ecosystem Flux Observation Research Network (ChinaFLUX) was established in 2002.

Measured at the interface between canopy and low-level

Received date: 2006-06-22; Accepted date: 2007-01-13

*Corresponding author. E-mail: gyzhou@scib.ac.cn vegetation, below-canopy CO_2 flux (*Fcb*) is composed of soil respiration, low-level vegetation respiration and photosynthesis. It is of great importance for terrestrial ecosystem carbon balance model validation to fully understand *Fcb* of typical forest ecosystem and the controlling factors. All of the four forest sites of ChinaFLUX have *Fcb* measurement; however, there is no public report about *Fcb* at present. Using year-round continuous eddy covariance measurements of *Fcb* of the coniferous and broad-leaved mixed forest in Dinghushan, *Fcb* dynamics and its environmental response were analyzed in this paper, which validates the reliability of the eddy measurement of *Fcb* over complex terrain, and also provides valid data for establishment and validation of ecosystem carbon balance model[1,13].

1 Site description

The Dinghushan Nature Reserve (hereafter referred to as DNR) is located in middle west part of Guangdong, China. Favored by the humid monsoon climate of southern subtropical zone, the DNR has abundant resources of radiation, rainfall and heat. Annual mean global radiation in DNR is 4665 MJ m^{-2} a^{-1}, and annual mean sunshine duration of 1433 h. Annual mean temperature is 21.0℃, with a mean minimum of 12.0℃ in January and a mean maximum of 28.0℃ in July. Annual average precipitation is 1956 mm, with a distinct pattern of wet season (from Apr. to Sep.), during which 76% of the rain occurs, and relative dry season (from Oct. through Mar.).

The study site (23°10′N, 112°32′E, altitude: 240m) is located in the investigation plot of the evergreen coniferous and broad-leaved mixed forest, in the kernel area of the DNR. The slope of the plot is about 10° facing southeast, and the terrain is nearly flat especially at the northeast, which is the prevailing wind direction of the site. Dominant species in canopy layers are *Schima superba*, *Castanopisis chinensis, Pinus massoniana* and so forth. The mean canopy height is about 17m. The stand age of the forest is about 100a 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 mainly consists of lateritic red-earth with a varied depth of 30–60cm. Surface litter covers 80%–90% of the ground with a thickness of 1–3cm and pH value of 3.9.

2 Material and methods

2.1 Flux measurement and data processing

Open Path Eddy Covariance (OPEC) flux measurement was fixed on a mast with a height of 2 m. Three component wind speed and virtual temperature were measured with a three-dimensional sonic anemometer (Model CSAT3, Campbell Scientific Inc., USA(CSI)), and fluctuations of carbon dioxide and water vapor concentration in the air were measured with a fast response infrared gas analyzer (IRGA; Model Li-7500, LiCor Inc., USA) using the open-path approach running at 10 Hz. The 10 Hz raw measurements were stored online by a CR5000 data logger (Compbell Scientific Inc., USA), and half-hourly flux of CO_2 (*Fcb*) were computed considering correction of cross-wind contamination of virtual temperature[14] and air density fluctuations[15].

Influences from tilt of terrain or sensors were not considered on-line; therefore, two-dimensional coordinate rotation[37,38] was employed to normalize the vertical velocity to the mean wind streamlines following the local terrain (i.e., bringing the mean lateral and vertical velocity components to zero) in the article. In the following sections, CO_2 flux, latent heat and sensible heat flux are presented as positive if directed away from the surface. With respect to flux measurement analysis, eddy covariance theory and its technical limitation, a data-screening procedure was applied to remove problematic 30 min records with (i) rainfall; (ii) signals exceed specified instrumentation limits; (iii) weak turbulence condition ($u^* < 0.05$ ms^{-1}); (iv) valid samples in a run less than 15000; (v) excessive spikes in the sonic and IRGA data. Normally the threshold value for u^*-correction is 0.15–0.2 ms^{-1}. Analysis of this station showed that *Fcb* did not change much with increasing u^* when u^* was more than 0.05 ms^{-1}, while valid samples decrease rapidly; therefore, 0.05 ms^{-1} was selected as u^*-correction threshold to avoid more uncertainty because of deficient samples. Further analysis showed that, probably caused by local terrain, daily variation of wind direction below canopy existed in the site, and *Fcb* during south wind was lower than other directions. In order to avoid systematic underestimation of *Fcb* owing to terrain reasons, flux data during wind direction of 120–200° was discarded.

Routine Meteorology (RMET) measurements, such as air temperature, soil temperature and soil moisture etc., running at 0.5 Hz, were calculated on-line and stored half hourly by 4 dataloggers (model CR23X-TD/CR10X-TD, CSI). Data period used in this article were 2003-4-13–2004-6-10.

2.2 Respiration evaluation model

Temperature condition is usually regarded as the main controlling environmental factors of ecosystem respiration. The response of ecosystem respiration (R_{eco}) to temperature is commonly described using Van't Hoff (eq.(1)), Arrhenius (eq.(2)), Lloyd-Taylor (eq.(3)) and exponential equation (eq. (4))[17]:

$$R_{eco} = R_{eco,ref}\exp(B(T_m - T_{ref}) \tag{1}$$

$$R_{eco} = R_{eco,ref}\exp\left(\frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T_m}\right)\right) \tag{2}$$

$$R_{eco} = R_{eco,ref}\exp\left(E_0\left(\frac{1}{T_{ref} - T_0} - \frac{1}{T_m - T_0}\right)\right) \tag{3}$$

$$R_{eco} = a\exp(bT_m) \tag{4}$$

Where $R_{eco,ref}$ in eqs. (1–3) is the ecosystem respiration at reference temperature (T_{ref}); $R_{eco,ref}$ and B in eq.(1), activation energy Ea(J/mol) in eq.(2), T_0 in eq.(3) and parameters a and b in eq.(4) are all fitted site-specific parameters; T_m is soil temperature in K; R is the gas constant (8.134 $\mathrm{J \cdot K^{-1} mol^{-1}}$); in application, E_0 is set to be 309K.

Water factors, especially soil moisture, are also important factors controlling ecosystem respiration. Taken as a predictor, soil moisture (*Ms*) is often coupled with temperature factors to construct an ecosystem respiration model. At present, multiplicative model and Q_{10} model are frequently used. Multiplicative model[18] was selected in this study:

$$R_{eco} = R_{eco,ref} \exp\left(E_0 \left(\frac{1}{T_{ref} - T_0} - \frac{1}{T_m - T_0} \right) \right) \cdot \exp(cMs + dM_s^2) \qquad (5)$$

Where temperature response equation of R_{eco} in eq.(5) is exactly the Lloyd-Taylor equation (eq.(3)), and soil moisture response equation of R_{eco} is a two-order polynomial of M_s. The reference temperature T_{ref} in eq.(5) was set to be 283.16K. $R_{eco,ref}$, T_0 , c and d were fitted site-specific parameters. T_m and *Ms* were input variables.

3 Results and analysis

3.1 Daily variation of *Fcb*

Fcb were positive all day long, indicating that understory vegetation and soil acted as CO_2 source as a whole (Fig.1). During daytime CO_2 concentration and *Fcb* decreased owing to photosynthesis of understory vegetation, suggesting that photosynthesis of understory absorbed more CO_2 than that released by understory and soil, which is caused by increasing temperature in daytime. Daily variation extent of *Fcb* in summer was more than that in winter season, implying that understory assimilates more CO_2 in summer in winter. Eddy covariance method of flux measurement was based on the assumption of homogeneous terrain, and the above analysis showed that the method has the ability to reveal daily variation of *Fcb* over such a relatively complex terrain of Dinghushan flux site.

3.2 Response of *Fcb* to temperature factors

In order to avoid disturbance of photosynthesis, nighttime (*PAR*<1 μmol photons·$\mathrm{m^{-2} \cdot s^{-1}}$) flux data are selected to study relationship between *Fcb* and environmental factors. All the temperature factors, which are statistically significant, relate to *Fcb* (Table 1), and soil temperature has more significant relation with *Fcb* than other temperature factors. From R^2 of the fitted equation, canopy temperature (at 0.5 m above ground) relates with *Fcb* more significantly than air temperature, indicating that understory respiration contributes directly to *Fcb*. Between 0–20cm, the significance of relationship between soil temperature and *Fcb* increases with increasing depth of soil temperature with maximum peak at 20 cm .

Q_{10} is temperature sensitivity index of ecosystem respiration, representing relative increase of R_{eco} when temperature increases by 10℃ within feasible range. Q_{10} of Van't Hoff equation doesn't change with temperature, whereas Q_{10} of Arrhenius equation and Lloyd-Taylor equation decreases with rising temperature. Especially, Q_{10} of Lloyd-Taylor equation is more sensitive to temperature than that in Arrhenius equation. Considering Lloyd-Taylor equation with input variable of soil temperature at 5cm (*Ts*) for instance, Q_{10} is 2.32 when temperature is 20℃, and Q_{10} is 1.86 when temperature is 30℃. The value of Q_{10} is consistent with that in the study of Yu *et al*[19], indicating that Lloyd-Taylor equation performs better than the other two to describe response of *Fcb* to temperature factors.

Using exponential equation (eq.(4)), relationship between nighttime *Fcb* and *Ts* was derived for winter and summer, respectively (Fig.2). Q_{10} was 2.7 and 1.08 for winter and summer seasons, respectively, suggesting that sensitivity of *Fcb* to

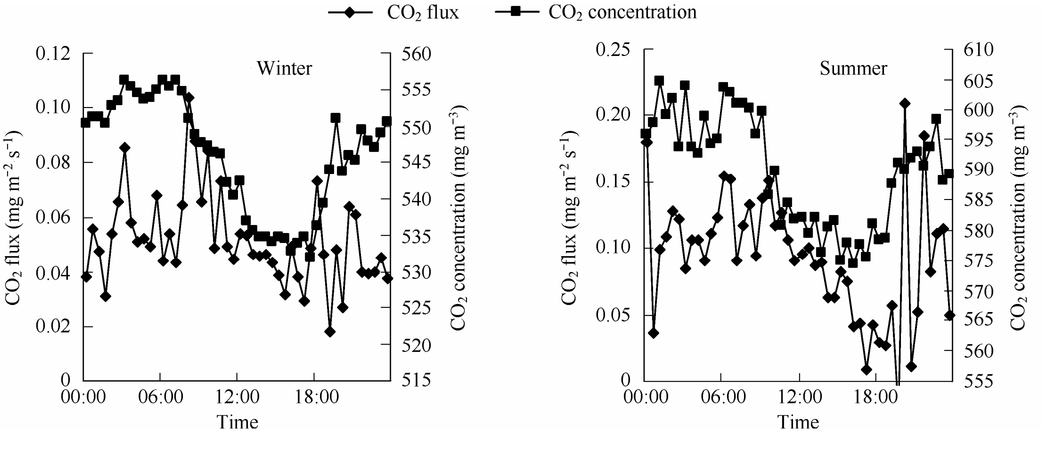

Fig.1 Daily variation of below-canopy CO_2 flux

Winter data shown were averaged over October 2003 to March 2004; Summer data shown were averaged over April to September 2004

Table 1 Relationship between soil respiration and soil temperature measured at different depths fitted with Van’t Hoff equation, Arrhenius equation and Lloyd-Taylor equation, respectively (n=2137)

Item	$R_{eco,ref}$ (283.16K)	$B/Ea/T_0$	Q_{10}			R^2
			10℃	20℃	30℃	
Van’t Hoff equation						
Air temperature at 4m	0.0467	0.0486	1.63	1.63	1.63	0.014
Canopy temperature at 0.5m	0.0442	0.0549	1.73	1.73	1.73	0.017
Soil temperature at 0cm	0.0271	0.0971	2.64	2.64	2.64	0.032
Soil temperature at 5cm	0.0262	0.0996	2.71	2.71	2.71	0.032
Soil temperature at 10cm	0.0243	0.1052	2.86	2.86	2.86	0.034
Soil temperature at 15cm	0.0230	0.1096	2.99	2.99	2.99	0.035
20cm Soil temperature at 20cm	0.0220	0.1133	3.10	3.10	3.10	0.035
40cm Soil temperature at 40cm	0.0192	0.1240	3.46	3.46	3.46	0.034
Arrhenius equation						
Air temperature at 4m	0.0465	33399	1.64	1.59	1.54	0.014
Canopy temperature at 0.5m	0.0439	37776	1.75	1.69	1.63	0.017
Soil temperature at 0cm	0.0263	67898	2.73	2.56	2.41	0.032
Soil temperature at 5cm	0.0254	69626	2.80	2.62	2.46	0.032
Soil temperature at 10cm	0.0235	73671	2.98	2.77	2.60	0.034
Soil temperature at 15cm	0.0222	76743	3.12	2.89	2.70	0.035
20cm Soil temperature at 20cm	0.0212	79363	3.24	3.00	2.79	0.035
40cm Soil temperature at 40cm	0.0184	86896	3.62	3.33	3.08	0.034
Lloyd-Taylor equation						
Air temperature at 4m	0.0460	210.5	1.67	1.50	1.38	0.014
Canopy temperature at 0.5m	0.0433	215.3	1.79	1.57	1.43	0.017
Soil temperature at 0cm	0.0228	236.5	3.22	2.27	1.83	0.032
Soil temperature at 5cm	0.0218	237.3	3.34	2.32	1.86	0.032
Soil temperature at 10cm	0.0197	239.0	3.64	2.43	1.91	0.034
Soil temperature at 15cm	0.0183	240.2	3.89	2.53	1.96	0.035
20cm Soil temperature at 20cm	0.0171	241.1	4.10	2.60	2.00	0.035
40cm Soil temperature at 40cm	0.0142	243.5	4.80	2.84	2.10	0.034

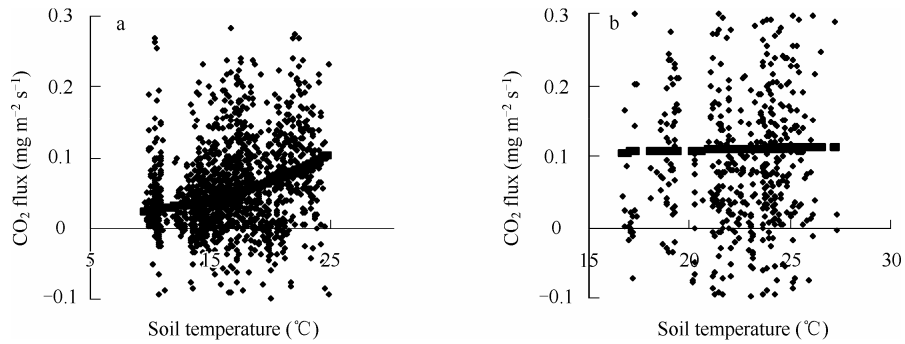

Fig.2 Relationship between nighttime below-canopy CO_2 flux (y) and soil temperature of 5cm depth (x) for winter (a) and summer (b) respectively

(a) the fitted curve for winter (October 2003 to March 2004); y=0.00887exp(0.0987x), n=1592, R^2=0.023, Q_{10}=2.7; (b) the fitted curve for summer (April to September 2004): y= 0.0927exp(0.0069x), n=545, R^2=0.0004, Q_{10}=1.08)

temperature factors decreases with increasing temperature, which is consistent with the analysis based on Lloyd-Taylor equation.

In order to reduce random error, daily and monthly average of nighttime *Fcb* and *Ts* was conducted using the exponential equation derived (Fig.3). R^2 of the equation derived by daily and monthly averaged data is higher than that fitted by 30 min data (Table 1), showing that average processing can reduce variability of eddy covariance measurement of flux significantly[20]. Meanwhile, Q_{10} of the exponential equation was 3.0 and 3.14 for daily and monthly averaged data, respectively, which was higher than Q_{10} (2.71) of Van’t Hoff equation in Table 1, indicating that in general Q_{10} increases with length of data average processing.

3.3 Response of *Fcb* to soil moisture

Daily average soil moisture at 5cm depth (*Ms*) in the conif-

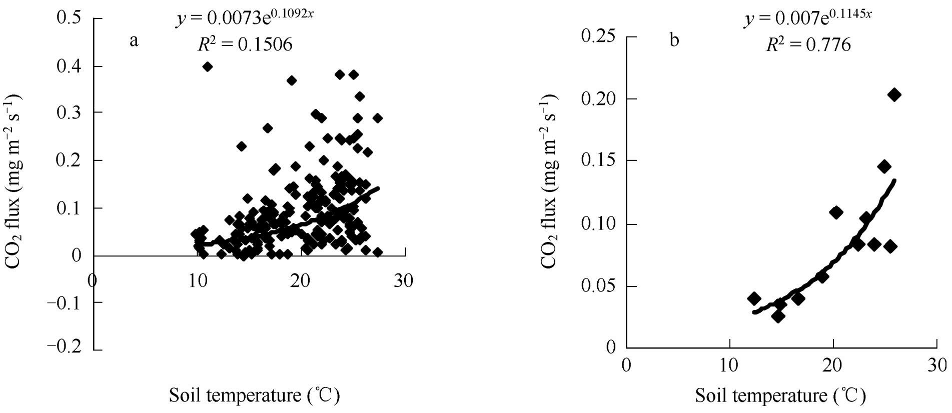

Fig.3 Relationship between nighttime below-canopy CO_2 flux (y) and soil temperature at 5cm depth (x) at daily (a) and monthly (b) steps, respectively

(a) fitted model: y=0.0073exp(0.1092x), n=211, R^2=0.1506, Q_{10}=3.0; (b) fitted model: y=0.007exp(0.145x), n=12, R^2=0.776, Q_{10}=3.14

erous and broad-leaved mixed forest in Dinghushan was (0.21 ±0.05) m^{3}m^{-3} for 2003–2004, during which Ms was continuously below 0.15 m^{3}m^{-3} in winter season (from October to March) with a minimum peak of 0.12 m^{3}m^{-3} (Fig.4). Driven by Ts and Ms, multiplicative model was fitted as:

$$Fcb = 0.0193\exp\left(309\cdot\left(\frac{1}{283.16-225.9}-\frac{1}{(Ts\_05+273.16)-225.9}\right)\right)\cdot \exp(0.899Ms+8.158Ms^2)$$
$$R^2 = 0.039, n = 2137 \qquad (6)$$

Where in eq.(6), parameters of Ms were positive, and R^2 was higher than that in Table 1 fitted by soil temperature only, indicating that introducing moisture factor was helpful to increase the significance of the respiration equation.

Daily accumulated Fcb estimated by Lloyd-Taylor equation and multiplicative model, respectively, showed similar annual variation (Fig.5), which is higher in summer than in winter, and which were consistent with annual variation of air temperature. Estimated by multiplicative model, Fcb was more sensitive to variation in Ms, and it had more distinct diurnal variation than Fcb estimated by Lloyd-Taylor equation. When Ms was relatively higher, Fcb estimated by multiplicative was higher than Fcb that was estimated by Lloyd-Taylor equation; on the contrary, it was lower than Fcb derived by Lloyd-Taylor equation during dry period. The difference between the two models mentioned above was more distinct in summer season during which both Ms and Ts was high. In conclusion, Fcb estimated by Lloyd-Taylor equation is utterly affected by Ts, while Fcb estimated by multiplicative model is driven by Ts and Ms, which have the ability to reflect the synthetic influence of water and heat condition; therefore it performs better to simulate Fcb.

3.4 Annual accumulated *Fcb*

Years 2003 and 2004 had higher precipitation and higher air temperature than normal average. Precipitation in the years

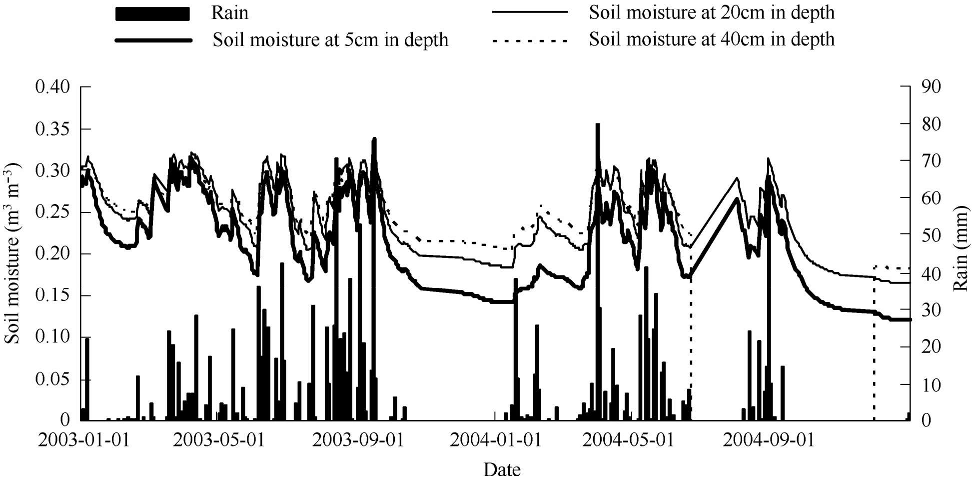

Fig.4 Annual variation of daily mean soil moisture at 5, 20cm and 40cm in depth and for rain from 2003 to 2004

2003 and 2004 were 25.1% and 17.4% less than normal, respectively, and annual mean air temperature are 0.6 and 0.3℃ higher than normal average, respectively. Annual mean *Fcb* of 2003 derived by multiplicative model ((0.092±0.024) $\mathrm{mgCO_2\ m^{-2}s^{-1}}$) was higher than that derived by Lloyd-Taylor equation ((0.082±0.037) $\mathrm{mgCO_2m^{-2}s^{-1}}$) (Table 2) , whereas annual mean *Fcb* of 2004 derived by multiplicative model ((0.075±0.034) $\mathrm{mgCO_2m^{-2}s^{-1}}$) was lower than that by Lloyd-Taylor equation ((0.077±0.034) $\mathrm{mgCO_2m^{-2}s^{-1}}$). Difference of *Fcb* between the two models was determined by *Ms*; in the year of higher *Ms*, *Fcb* derived by multiplicative model was higher than that by Lloyd-Taylor equation. On the contrary, in year of lower *Ms* *Fcb* derived by multiplicative model was lower than that by Lloyd-Taylor equation. The results show that soil moisture can become a leading factor affecting *Fcb* when there exists low-water limitation in the ecosystem, which is consistent with the study of Yu *et al* [19]. *Fcb* of 2003 was higher than that of 2004 because of the fact that both *Ts* and *Ms* of 2003 were higher than those of 2004, respectively.

Compared with soil respiration in the coniferous and broad-leaved mixed forest in Dighushan, *Fcb* of 2003 estimated by multiplicative model was 17% lower than the soil respiration observed by chamber method[8] (Table 2), but between the results of evergreen broad-leaved forest[7,9] and coniferous forest[7], indicating that *Fcb* measured by eddy covariance method was comparable with that by traditional methods of cham- ber[7,8] and alkali-absorbing method[9]. Compared with domestic study, *Fcb* of the site in Dinhushan estimated in this article was between that of rain season forest [6] and northern broad- leaved forest[21] (Table 3), which was consistent with the variation trend of ecosystem respiration with latitude and forest type.

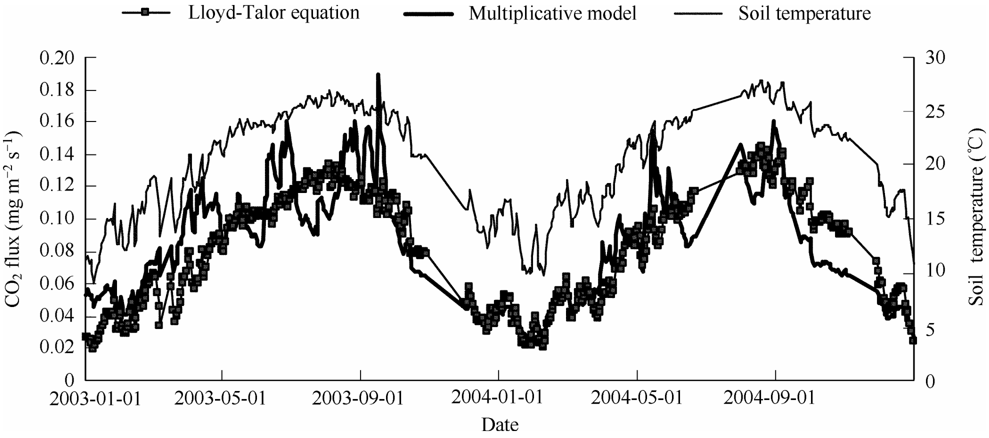

Fig.5 Annual variations of daily mean below-canopy CO_2 flux simulated by Lloyd-Taylor equation and multiplicative model, respectively

Table 2 Annual respiration of 2003–2004 estimated by Lloyd-Taylor equation and Multiplicative model, respectively

Year	Model	Average respiration ($\mathrm{mg\ CO_2\ m^{-2}s^{-1}}$)	Accumulated respiration ($\mathrm{gC\ m^{-2}a^{-1}}$)	Soil temperature (℃)	Soil moisture ($\mathrm{m^3m^{-3}}$)
2003	Lloyd-Taylor equation	0.082±0.037	708.6±290.2	20.6±4.8	0.230±0.048
	Multiplicative model	0.092±0.024	787.4±296.8		
2004	Lloyd-Taylor equation	0.077±0.034	663.4±295.9	19.9±4.9	0.189±0.050
	Multiplicative model	0.075±0.034	643.5±292.2		

Table 3 Comparison of the below-canopy CO_2 flux in different forest ecosystems

Location	Vegetation	Period	Method	Soil respiration ($\mathrm{mg\ CO_2m^{-2}s^{-1}}$)	Reference
Dinghushan	Mixed forest	Annual (2003)	EC	0.092	This paper
Dinghushan	Mixed forest	Annual (2003)	Static chamber	0.111	[7,8]
Dinghushan	Evergreen forest	Annual (2003)	Static chamber	0.132	[7]
Dinghushan	Evergreen forest	Annual (2003)	Alkali-lime absorption	0.13	[9]
Dinghushan	Pine forest	Annual (2003)	Static chamber	0.070	[7]
Xishuangbannan	Tropical rain forest	Annual (2003)	Static chamber	0.169	[6]
Hawaii	Evergreen forest	Annual	Static chamber	0.084	[21]

4 Discussion and conclusion

(1) Understory vegetation in the mixed forest in Dinghushan has photosynthesis ability throughout year, which is different from that in temperate pine forest[22], which has photosynthesis only in growing season. *Fcb* of the mixed forest in Dinghushan has positive sign, indicating that the understory vegetation and soil of the forest acts as carbon dioxide source as a whole.

(2) A variety of temperature and soil moisture factors have fairly good relationship with *Fcb*. Soil temperature at 20cm depth relates to best *Fcb*, instead of soil moisture at 5cm depth where microbe is most active, indicating that there exists complex nonlinear relationship between respiration and environmental factors such as moisture and temperature.

(3) All of Van't Hoff equation, Arrhenius equation and Lloyd-Taylor equation can explain considerably the variation of *Fcb*. Among those three equations Lloyd-Taylor equation is the best to reflect the relationship between soil respiration and temperature because of its ability to reveal the variation of Q_{10} with temperature. When Q_{10} between different stations was compared, respiration model, temperature measuring position, temperature range, as well as average length of flux data should be identical.

(4) *Fcb* derived from Lloyd-Taylor equation is utterly determined by *Ts*, while *Fcb* derived from the multiplicative model is driven by *Ts* and *Ms*. The multiplicative model can reflect the synthetic effect of *Ts* and *Ms*; therefore it explains more *Fcb* variations than Lloyd-Taylor equation does. *Fcb* derived from multiplicative model was higher than that from Lloyd-Taylor equation when *Ms* was relatively high. On the contrary, *Fcb* derived from multiplicative model was lower than that from Lloyd-Taylor equation when *Ms* was low, indicating that *Ms* might be a main factor affecting *Fcb* when the ecosystem is under stress because of low-moisture. Study[23] showed that multiplicative model possibly overestimated the response of ecosystem respiration to temperature, and the model could also systematically underestimate ecosystem respiration response to water condition, especially under drought condition[19]. According to the study in this article, multiplicative model performs better than Lloyd-Taylor function when used to simulate dynamics of *Fcb*. Considering water factor is of significant importance to avoid systematically underestimation of *Fcb* in summer season.

(5) Compared with soil respiration measured by statistic chamber method, *Fcb* of the forest in 2003 ((0.092±0.024) mg $CO_2m^{-2}s^{-1}$) was 17% lower but still between those of evergreen forest and coniferous forest, and the *Fcb* value which was consistent with the respiration changed the orderliness between different development stages of a forest ecosystem. Eddy covariance measurement *Fcb* was comparable with that measured by traditional methods such as chamber and alkali-absorbing methods. CO_2 flux measured by eddy covariance is often underestimated, and further study therefore calls for emphasis on methods quantifying *Fcb* components of respiration of soil, as well as respiration and photosynthesis of understory vegetations.

Acknowledgements

The project was financially supported by the National Key fundamental research development layout project (No. 2002 CB412501); two knowledge innovation funds of Chinese Academy of Sciences (Nos. KZCX1-SW-01-01A and KSCX2-SW-120); Natural Science Foundation of Guangdong Province, China (No. 010567).

References

[1] Yu G R, Zhang L M, Sun X M, *et al*. Advances in carbon flux observation and research in Asia. Science in China Ser D. Earth Sciences, 2004, 34(Supp Ⅱ): 15–29.

[2] Liu S H, Fang J Y, Makoto K. Soil respiration of mountainous temperate forests in Beijing, China. Acta Phyhytoecologica Sinica, 1998, 22(2): 119–126.

[3] Huang C C, Ge Y, Chang J, *et al*. Studies on the soil respiration of three woody plant communities in the east mid subtropical zone, China. Acta Ecologica Sinica, 1999, 19(3): 324–328.

[4] Wu Z M, Zeng Q B, Li Y D, *et al.* A preliminary research on the carbon storage and CO_2 release of the tropical forest soils in Jianfengling, Hainan Island, China. Acta Phytoecologica Sinica, 1997, 21(5): 416–423.

[5] Luo S S, Chen B F, Li Y D. Litter and soil respiration in a tropical mountain rain forest in Jianfengling, Hainan Island. Acta Ecologica Sinica, 2001, 21(12): 2013–2016.

[6] Sha L Q, Zheng Z, Tang J W, *et al*. Soil respiration in tropical seasonal rain forest in Xishuangbanna, SW China. Science in China (Ser D). Earth Sciences, 2004, 34(Supp. Ⅱ): 167–174.

[7] Zhou C Y, Zhou G Y, Wang Y H, *et al*. CO_2 efflux from different forest soils and impact factors in Dinghu Mountain, China. Science in China (Ser D). Earth Sciences, 2004, 34 (supp. Ⅱ): 175–182.

[8] Zhou C Y, Zhang D Q, Qang Y S, *et al*. Diurnal variations of fluxes of the greenhouse gases from a coniferous and broad-leaved mixed forest soil in Dinghushan, Acta Ecologica Sinica, 2004, 24(8): 1738–1741.

[9] Yi Z G, Yi W M, Zhou G Y, *et al*. Soil carbon effluxes of three major vegetation types in Dinghushan Biosphere Reserve. Acta Ecologica Sinica, 2003, 23(8):1673–1678.

[10] Baldocchi D D. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rate of ecosystem: past, present and future. Global Change Biol, 2003, 9: 479–492.

[11] Valentini R, Angelis P D, Matteucci G, *et al*. Seasonal net carbon exchange of a beech forest with the atmosphere. Global Change Biology, 1996, 2: 197–207.

[12] Baldocchi D D, Falge E, Gu L H, *et al.* Fluxnet: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull. Am. Meteorol. Soc., 2001, 82(11): 2415–2434.

[13] Law B E, Falge E, Gu L, *et al*. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agricultural and Forest Meteorology, 2002, 113: 97–120.

[14] Schotanus P H, Nieuwstadt F T M, de Bruin H A R. Temperature measurements with a sonic anemometer and its application to heat and moisture fluxes. Boundary-Layer Meteorol, 1983, 26, 81–93.

[15] Webb E K, Pearman G I, Leuning R. Correction of flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorological Society, 1980, 106: 85–100.

[16] Wilczak J M, Oncley S P, Stage S A. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol, 2001, 99(1): 127–150.

[17] Falge E, Baldocchi D D, Olson R J, *et al*. Gapfilling strategies for defensible annual sums of net ecosystem exchange. Agric -ultural and Forest Meteorology, 2001, 107, 43–69.

[18] Fang C, Moncrieff J B. A model for soil CO_2 production and transport 1: model development. Agricultural and Forest Meteorology, 1999, 95: 225–236.

[19] Yu G R, Wen X F, Li Q K, *et al*. Seasonal patterns and environmental control of ecosystem respiration in subtropical and temperate forests in China. Science in China (Ser D). Earth Sciences, 2004, 34 (SuppⅡ): 84–94.

[20] Griffis T J, Black T A, Morgenstern K, *et al*. Ecophysiological controls on the carbon balances of three southern boreal forests. Agricultural and Forest Meteorology, 2003, 117: 53–71.

[21] Townsend A R, Vitousek P M, Trumbore S E. Soil organic matter dynamics along gradients in temperature and land use on the island of Hawaii. Ecology, 1995, 76: 721–733.

[22] Law B E, Baldocchi D D, Anthoni P M. Below-canopy and soil CO_2 fluxes in a ponderosa pine forest. Agricultural and Forest Meteorology, 1999, 94, 171–188.

[23] Reichstein M, Tenhunen J D, Roupsard O, *et al*. Ecosystem respiration in two Mediterranean evergreen Holm Oak forests: drought effects and decomposition dynamics. Functional Ecology, 2002, 16: 27–39.