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Annual variation of carbon flux and impact factors in the tropical seasonal rain forest of Xishuangbanna, SW China

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Abstract Two years of eddy covariance measurements of above- and below-canopy carbon fluxes and static opaque chamber and gas chromatography technique measurements of soil respiration for three treatments (bare soil, soil+litterfall, soil+litterfall+seedling) were carried out in a tropical seasonal rain forest. In addition, data of photosynthesis of dominant tree species and seedlings, leaf area index, litter production and decomposing speed, soil moisture, soil temperature and photosynthetic photon flux density within the forest were all measured concurrently. Data from January 2003 to December 2004 are used to present annual variability of carbon flux and relationships between carbon flux and impact factors. The results show that carbon flux of this forest presented unusual tendency of annual variation; above-canopy carbon fluxes were negative in the dry season (November—April) and mainly positive in the rainy season, but overall the forest is a carbon sink. Carbon flux has obviously diurnal variation in this tropical seasonal rain forest. Above-canopy carbon fluxes were negative in the daytime and absolute values were larger in the dry season than that in the rainy season, causing the forest to act as a carbon sink; at night, carbon fluxes were mainly positive, causing the forest to act as a carbon source. Dominant tree species have greater photosynthesis capability than that of seedlings, which have a great effect on above-canopy carbon flux. There was a significant correlation between above-canopy carbon flux and rate of photosynthesis of tree species. There was also a significant correlation between above-canopy carbon flux and rate of photosynthesis of seedlings; however, the below-canopy carbon flux was only significantly correlated with rate of photosynthesis of seedlings during the hot-dry season. Soil respiration of the three treatments displayed a markedly seasonal dynamic; in addition, above-canopy carbon fluxes correlated well with soil respiration, litterfall production, litterfall decomposition rate, precipitation, and soil moisture and temperature. A primary statistical result of this study showed that above-canopy carbon flux in this forest presented carbon source or sink effects in different seasons, and it is a carbon sink at the scale of a year.

Keywords: carbon flux, annual variation, impact factors, tropical seasonal rain forest, Xishuangbanna.

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The increasing concentration of carbon dioxide in the atmosphere since the industrial revolution is among the most significant human influences on the global environment. As a critical component of terrestrial ecosystems, forests play a major role in biosphere carbon uptake. The carbon dioxide concentration in the atmosphere is increasing due to fossil fuel combustion, land use/cover change, especially deforestation, which has a direct effect on global carbon cycle and balance[1−9]. Tropical rain forests account for 12% of global vegetation area[10,11]. This biome is characterized by abundant animal and plant species, complex structure and high productivity. A small perturbation in this biome could have a significant effect on the global carbon cycle and climate change; thus, determining whether tropical rain forests function as a sink or source of carbon to the atmosphere is an important problem. Houghton *et al.* and Saleska *et al.* believed that tropical forests are significant atmospheric carbon sources[12,13]; however, some studies found that tropical forests are carbon sinks[11,14−21]. So it is important to determine whether the tropical forest functions as C sink or source, which could provide vital insight into the future role of tropical forests in the global C cycle and climate change[22].

The tropical rain forest in China is mainly distributed in Hainan Province and south of Yunnan Province and characterized by abundant biodiversity and high production which have a significant effect on ecological environment at regional scales[23]. In recent years, several researches have studied CO_2 characteristics of tropical forests in Hainan Province and south of Yunnan Province by means of gradient observation and biomass models[24−30]. In this study, characteristics of CO_2 flux of a tropical seasonal rain forest in Xishuangbanna were analyzed by eddy covariance technique based on the observation data of 2003 and 2004.

1 Materials and methods

1.1 Site description

The tropical rain forest in Xishuangbanna is an important part of Indo-Malaysian tropical rain forest and is located on the northern edge of the tropical zone in South-East Asia[31]. A large proportion of the forest in this region is tropical seasonal rain forest and it is primarily formed in wet valleys, lowlands and on low hills below 900 m altitude[32]. To study and assess C sink or source characteristics and response to environmental changes of tropical seasonal rain forest in Xishuangbanna, instruments for CO_2, H_2O and energy fluxes were installed on a 70 m tower within the forest in 2002 for long-term, continuous measurement.

This study was conducted in a tropical seasonal rain forest (21°55′39″ N, 101°15′55″ E, elevation 750 m) in the Menglun Forest Reserve in Mengla County, Yunnan Province (Fig. 1). It is a permanent plot dedicated to long-term ecological research managed by the Xishuangbanna Tropical Rainforest Ecosystem Station, the Chinese Academy of Sciences. The forest structure at the study site can be divided into three general tree layers that are represented by different species. More than 70% of all individual trees occur in tree layer C (below 16 m), which is composed of small evergreen trees and juveniles of species from the upper tree layers (above 16 m). Tree layer B, between 16−30 m, consists of a mixture of evergreen and deciduous species, such as *Barringtonia macrostachya*, *Gironniera subaequalis*, and *Sloanea cheliensis*. Tree layer A, having a canopy height of over 30 m, is dominated by *Pometia tomentosa* and *Terminalia myriocarpa*. Many species of algae, lichens, mosses and ferns comprise the epiphyte communities. The woody climbers, such as *Byttneria integrifolia*, and *Gnetum montanum* are also common at the study site[33].

With direct impacts of the East Asian Monsoon, Xishuangbanna is dominated by warm-wet air masses from the Indian Ocean in summer and continental air masses of subtropical origin in winter, which results in two distinct seasons, each with distinctive characteristics[34]. A dry season occurs between November to April, which includes a cool sub-season from November to February and a hot sub-season from March to April. The cool-dry sub-season is characterized by the highest frequency of heavy radiation fog during the night and morning. The hot-dry sub-season is characterized by dry and hot weather during the afternoon with heavy radiation fog during the morning only. A rainy season occurs between May and October and is characterized by high rainfall, which is mainly brought

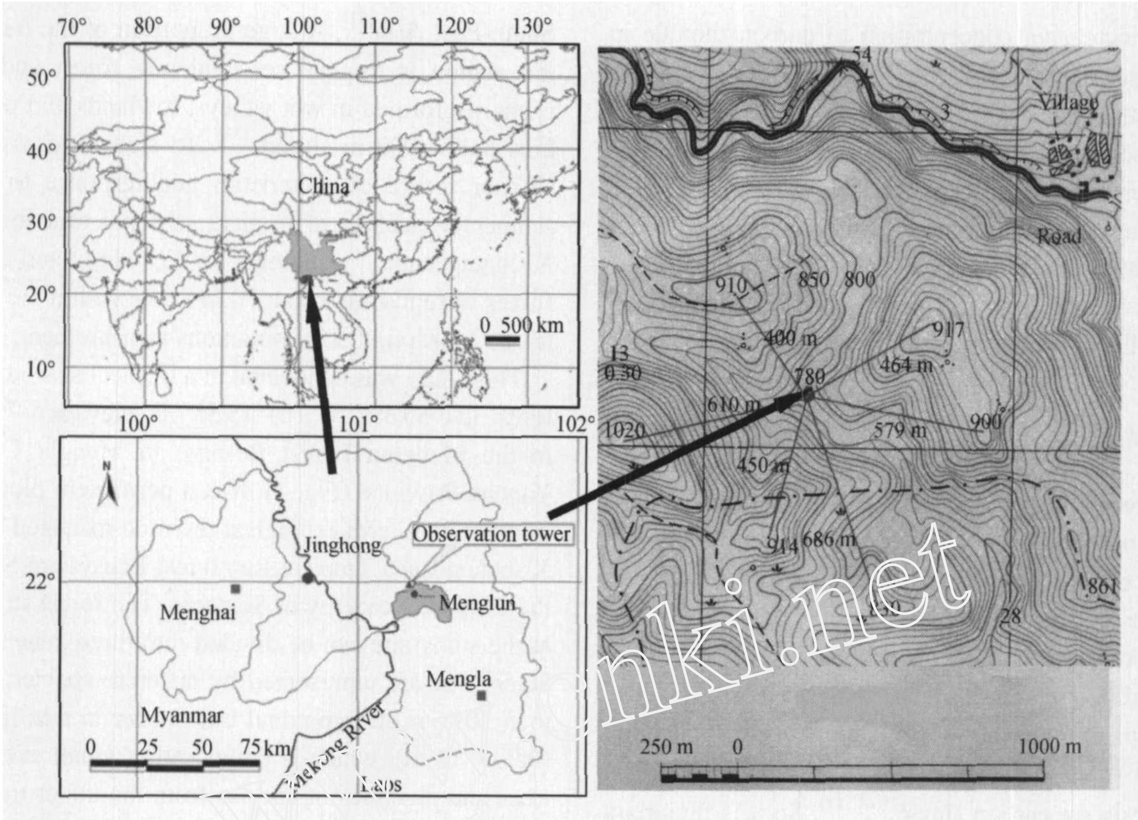

Fig. 1. The situation of observation tower.

by the southwestern summer monsoon.

Long-term climate records show that the mean annual air temperature is 21.7℃ with a maximum monthly temperature of 25.7℃ for the hottest month (June) and a minimum of 15.9℃ for the coldest month (January). The mean annual foggy days over the past 40 years are 186.4 d; the mean monthly foggy days in cool-dry sub-season are over 23 d, with a maximum monthly mean value of 26.1 d in January. Xishuangbanna is famous for its calm, with mean annual wind speed of 0.4 m s^{-1} and frequency of calm days of 75%.

1.2 Instruments and measurements

The fluxes of CO_2, water vapour and sensible heat were quantified using tower-based eddy covariance. The eddy covariance system utilized a fast response three-dimensional sonic anemometer-thermometer (CSAT3, CAMPBELL, USA) and a fast-response open-path infrared gas analyzer (LI-7500, LI-COR, Inc., Lincon, NE, USA) to measure the mean and fluctuating quantities of wind speed and temperature, and CO_2 and H_2O vapour, respectively. Eddy covariance sensors were mounted 48.8 m (about 15—16 m above the canopy) and 4.8 m above ground level and were oriented in the direction of the mean wind at the upwind side of the tower in order to minimize the potential for flow distortion from the tower[35]. All data were recorded at 10 Hz by two CR5000 data loggers (Model CR5000, Campbell Scientific) and 30 min mean values were calculated. In addition, affiliated meteorological variables above and within the forest, including wind speed, air temperature and humidity, photosynthetically active radiation, global radiation, net radiation, soil heat flux, soil temperature and soil moisture, were all measured simultaneously. These factors were sampled in 0.5 Hz and the data were stored in the data loggers. 30 min averages were also calculated by the data loggers and stored.

In order to eliminate the values of horizontal and vertical advection in the equation of conservation of mass, the raw 30 min flux data were transformed by three-dimension coordinate rotation that aligned the vertical velocity measurement normal to mean wind streamlines and brought the mean lateral and vertical velocity to zeros. The effect of fluctuation in air density on the flux data was also corrected by the WPL

(Webb, Pearman and Leuning correction) method. After the above corrections, CO_2 flux data with absolute values under 2.0 $mg \cdot m^{-2} \cdot s^{-1}$ were screened. Data gaps were not filled because (i) filling in missing data on a complex topography is very difficult, and (ii) this study was mainly focused on not sums but seasonal and inter-annual variation characteristics of CO_2 flux[36−38]. These measurements were started in November, 2002 and data of 2003 and 2004 are included in this paper.

1.3 *Soil respiration measurement*

The static opaque chamber technique was used to measure soil respiration in tropical seasonal rain forest in Xishuangbanna. Three treatments were applied with three replicates. In a square collar, litter was removed and seedlings were cleared (Treatment A), litter was not removed and seedlings were cleared (Treatment B), or neither litter nor seedlings were removed (Treatment C). Sampling was done on every Monday morning during 09: 00 to 11: 00 in every week. The process of samples collection and analysis is described in detail in Wang *et al.*[39,40].

1.4 *Photosynthesis measurement*

A Li-Cor 6400 portable photosynthesis system was used to measure light response curves of dominant canopy tree species (*Pometia tomentosa*) and underground seedlings (*Pometia tomentosa*, *Barringtonia macrostachya*, *Ardisia tenera* and *Drypetes indica*) in different light intensities and CO_2 concentrations in January (cool-dry sub-season), April (hot-dry sub-season), July (rainy season) and October (later rainy season), 2004. Photosynthetic diurnal variation of these samples was also measured concurrently.

1.5 *Leaf area index measurement*

Vertical profiles of Leaf area index were measured using a *LAI*-2000 (Li-Cor, Lincoln, Nebraska, USA) every month from December 2003 onward.

1.6 *Litterfall and litter decomposition rate measurement*

Forty litter traps (caliber: 0.2 m^2) were placed randomly within the research plot. Litter was collected at monthly intervals from the traps. All litterfall collections were weighed fresh and sorted into leaves, branches, bark, flowers and fruits, epiphytic materials and "mixed matter", then oven-dried to a constant weight at 85℃. Samples of 26.5 g for dried litterfall collections were placed in 0.71 mm mesh nylon bags. Litter decomposition rate was calculated by embedding 60 litterbags simultaneously on April when forest shed more leaves in this period than other months and removing five bags at one month intervals to get fresh and dry weight.

Net or gross "exchange" of CO_2 into the forest is considered negative, and "exchange" out of the forest positive. However, we discuss "photosynthesis" as processes with positive signs, and "respiration" negative signs.

2 Results and analyses

2.1 *Annual, seasonal and daily changes in carbon flux*

A distinct seasonality in daily averaged CO_2 flux between the tropical seasonal rain forest and atmosphere characteristics was observed in 2003 and 2004 in Xishuangbanna (Fig. 2). The results showed that above-canopy CO_2 flux was negative in dry season (November—April) when the forest acts as a C sink, and mainly positive in rainy season (May—October), when the forest acts as a weak C source (Fig. 2(a)). Maximum and minimum monthly averaged CO_2 flux were 0.0467 and –0.0800 $mg \cdot m^{-2} \cdot s^{-1}$, respectively. Seasonal changes in daytime and nighttime averaged CO_2 flux were also significant in this forest (Fig. 2(b)). Diurnal above-canopy CO_2 fluxes were almost negative, which indicate that forest uptakes C in the daytime. Absolute values of diurnal CO_2 fluxes were larger in the dry season and smaller in the rainy season and the monthly maximum and minimum uptake values were –0.0247 and –0.1732 $mg \cdot m^{-2} \cdot s^{-1}$ from January 2003 to December 2004, respectively. Nighttime CO_2 fluxes were mainly positive which suggests that this forest served as a C source during the night. Nighttime CO_2 fluxes were smaller in the dry season and larger in the rainy season, with monthly maximum and minimum values of 0.1524 and –0.0125 $mg \cdot m^{-2} \cdot s^{-1}$ during the period from January 2003 to December

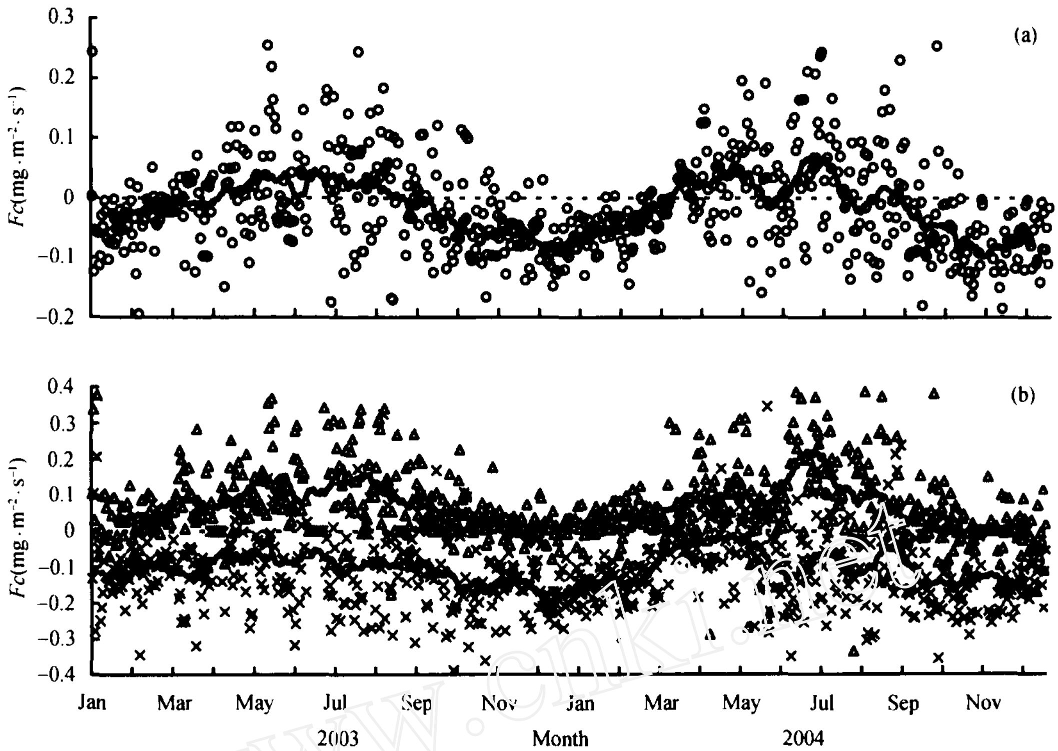

Fig. 2. Annual variation of daily average of above-canopy carbon flux in tropical seasonal rain forest. (a) Daily average; (b) daytime (furcation) and nighttime average (triangle).

2004, respectively. In addition, the annual pattern of nighttime CO_2 flux was more variable than that of the daytime.

2.2 *Impact factors*

2.2.1 Photosynthesis

Diurnal variations in the photosynthetic rate of dominant canopy tree species (*Pometia tomentosa*) were all significant in cool-dry (January), hot-dry (April), rainy (July) and the later rainy season (October) (Fig. 3(a)), with greater and lower photosynthetic rate in later rainy season and hot-dry sub-season, respectively. However, there were differences in the time of the day when the maximum photosynthetic rate occurred between seasons. The maximum value of photosynthetic rate of *Pometia tomentosa* occurred at 12: 00, 16: 00 and 11: 00 local time in January, August and October, respectively. As for hot-dry sub-season, the values of photosynthetic rate were higher in forenoon than that in the afternoon.

Significant diurnal variations of photosynthetic rate of seedlings were also observed in every season, characterized by lower photosynthetic rate in the morning

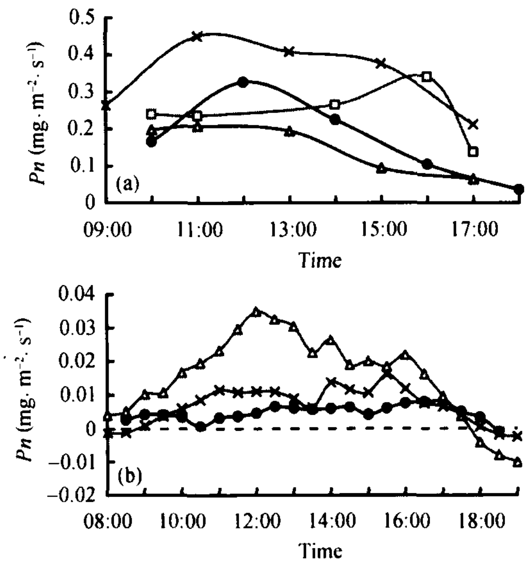

Fig. 3. Diurnal variation of photosynthetic rate of dominant tree species (a) and seedlings (b) in cool-dry (circle), hot-dry (triangle), rainy (square) and later rainy seasons (furcation).

and dusk and higher values in the daytime (Fig. 3(b)). There were also differences in the time of the day when the maximum photosynthetic rate of seedlings appearing in different seasons. Photosynthetic rate of seedlings in the hot-dry sub-season (April) and cool-dry sub-season were the highest and lowest in a year, respectively.

Significant correlations ($P<0.001$) between diurnal above-canopy CO_2 fluxes and photosynthetic rate of *Pometia tomentosa* were observed in the dry and rainy season (Fig. 4). The absolute values of above-canopy CO_2 flux increased with increasing photosynthetic rate of *Pometia tomentosa*, suggesting that photosynthetic rate of dominant tree species plays a substantial role in diurnal above-canopy CO_2 fluxes. The regression equations were $Fc = -1.4516Pn + 0.0886$ in the dry season and ($R^2 = 0.8305$, $P < 0.001$) and $Fc = -1.8896Pn + 0.4292$ in the rainy season ($R^2 = 0.9044$, $P < 0.001$), respectively. The intercept of the dry season equation ($0.0886\ mg \cdot m^{-2} \cdot s^{-1}$) was much lower than that of the rainy season ($0.4292\ mg \cdot m^{-2} \cdot s^{-1}$), indicating that there are other factors have influence on above-canopy CO_2 flux besides photosynthetic rate of dominated tree species. Moreover, the effects of other impress factors would have a greater effects on above-canopy CO_2 flux in the rainy season than in the dry season.

Above-canopy CO_2 fluxes in every season were significantly correlated with the mean photosynthetic rate of seedlings (Fig. 5); moreover, the correlation coefficient was lowest in cool-hot season ($R^2 = 0.1324$, $P < 0.05$) and highest in the dry-hot season ($R^2 = 0.5605$, $P < 0.01$). In addition, the intercept of the correlation equation was negative in the cool-dry sub-season and positive in the hot-dry sub-season and rainy season, suggesting that other factors rather than plant photosynthesis influenced the above-canopy CO_2 flux.

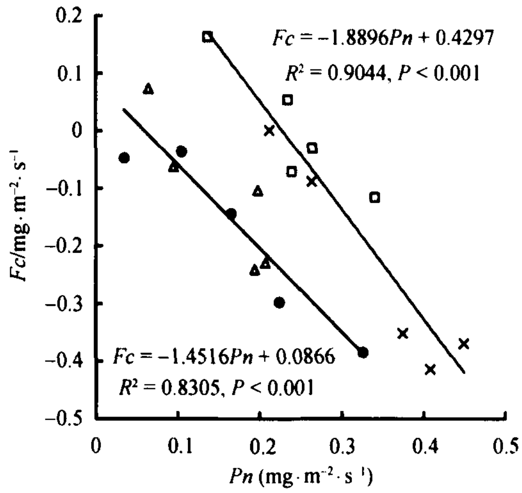

Fig. 4. The relationships between above-canopy carbon flux and photosynthetic rate of dominant tree species. Circle, cool-dry; triangle, hot-dry; square, rainy; furcation, later rain.

Dark respiration of plants has an important effect on nighttime CO_2 flux of tropical seasonal rain forests. Both monthly average values and daily mean values of nighttime above-canopy CO_2 flux are lower than dark respiration of dominated tree species and seedlings in the cool-dry sub-season. However, nighttime above-canopy CO_2 flux was higher in the dry-hot sub-season and rainy season (Table 1).

2.2.2 Leaf area index

A substantial proportion of tree species in this forest are deciduous and they shed more leaves in later dry season induced by its location on the region characterized by northern edge of the tropical zone and high-latitude, and climate traits of distinct dry and rainy season, which conduced that a distinctly sea-

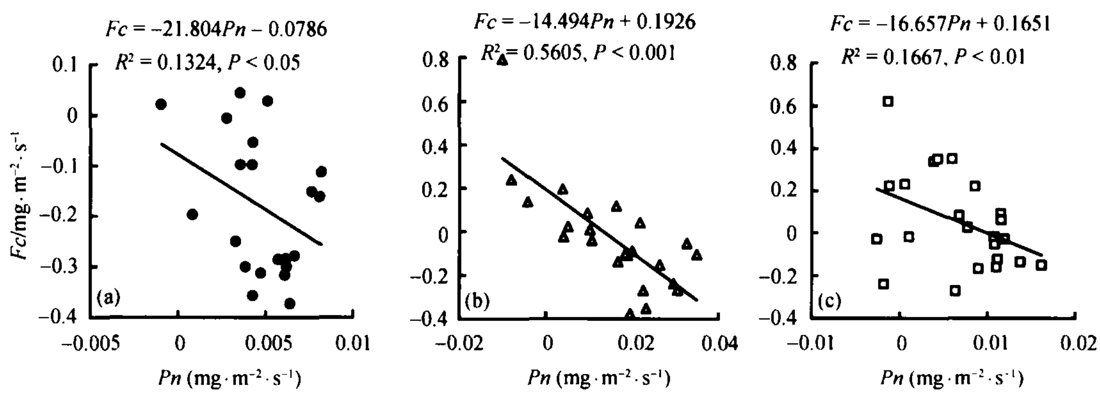

Fig. 5. The relationship between above-canopy CO_2 flux and photosynthetic rate of seedlings. (a) Cool-dry season; (b) hot-dry season; (c) rainy season.

Table 1 Nighttime averaged carbon flux in clear days ($mg \cdot m^{-2} \cdot s^{-1}$)

	Fc-upm	*Fc-up*	*Re-up*	*Re-down*
Cool-dry sub-season	0.0188	0.0144	0.0332	0.0074
Hot-dry sub-season	0.0836	0.0502	0.0482	0.0349
Rainy season	0.0762	0.0751	0.0319	0.0226

sonal variability in leaf area index was observed in this forest; furthermore, annual variability in *LAI* of tree layer A was opposite to that of tree layer C (Fig. 6). *LAI* of tree layer A was lowest in April and peaked in July. In contrast, tree layer C achieved the maximum *LAI* in May when leaves of small evergreen trees and juveniles grew quickly because tree layer A was shedding leaves, increasing the light available to tree layer C. Similarly, the lowest *LAI* of tree layer C in July was the lowest because leaves of tree species in the upper layers developed rapidly during this period and inhibited growth of the seedlings in tree layer C.

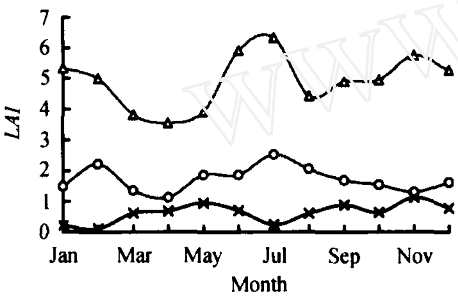

Fig. 6. Annual variation of leaf area index in tropical seasonal rain forest. Triangle, tree layer A; circle, tree layer C; furcation, whole tree layer.

Leaf area index of this forest ecosystem presented two peaks (July and November) and two troughs (April and August) in a year, with a maximum value of 6.34 in July and minimum value of 3.56 in April (Fig. 7).

Daily mean above-canopy CO_2 flux was negative and absolute values were greater from September to February when *LAI* was higher; however, above-canopy CO_2 flux was mostly positive and absolute values were lower during the time when *LAI* was lower (March—April) and monthly variability (May—August) in *LAI* was greater. The results suggest that above-canopy CO_2 flux is positively correlated with *LAI*.

2.2.3 Photosynthetically active radiation

Plant photosynthesis was strongly correlated with photosynthetically active radiation (*PAR*). Annual variation of daily mean *PAR* and above-canopy CO_2 flux during clear days is illustrated by Fig. 8, showing that average *PAR* changed seasonally, with the yearly maximum in the dry rather than the rainy season. Moreover, above-canopy CO_2 flux was correlated with *PAR*.

2.2.4 Litterfall production

A substantial proportion of tree species in this forest are deciduous, shedding more leaves in the later dry season, which induce that litterfall are almost composed by large numbers of leaves and have a yield peak during this period, with a maximum value of 136.1 $g \cdot m^{-2}$ in March (Fig. 9(a)). Flowers and fruits

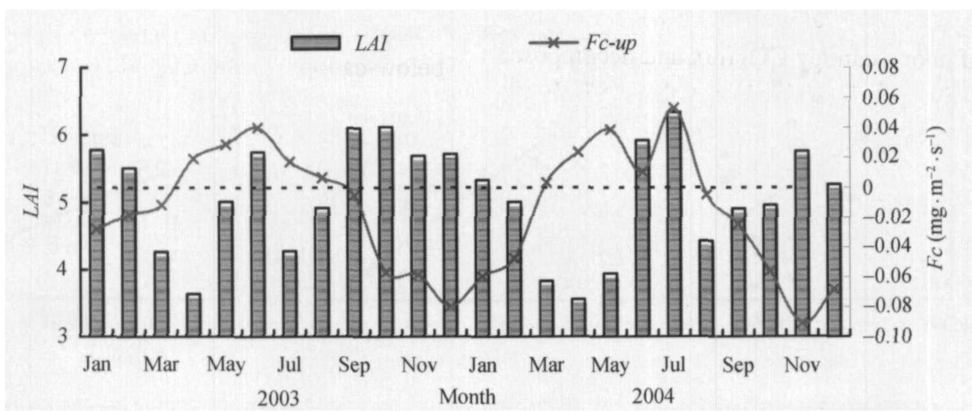

Fig. 7. Annual variation of monthly average above-canopy CO_2 flux and leaf area index of forest ecosystem.

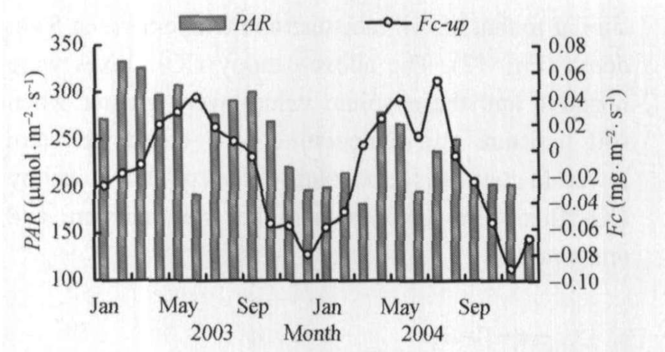

Fig. 8. Annual variation of monthly average above-canopy CO_2 flux and *PAR*.

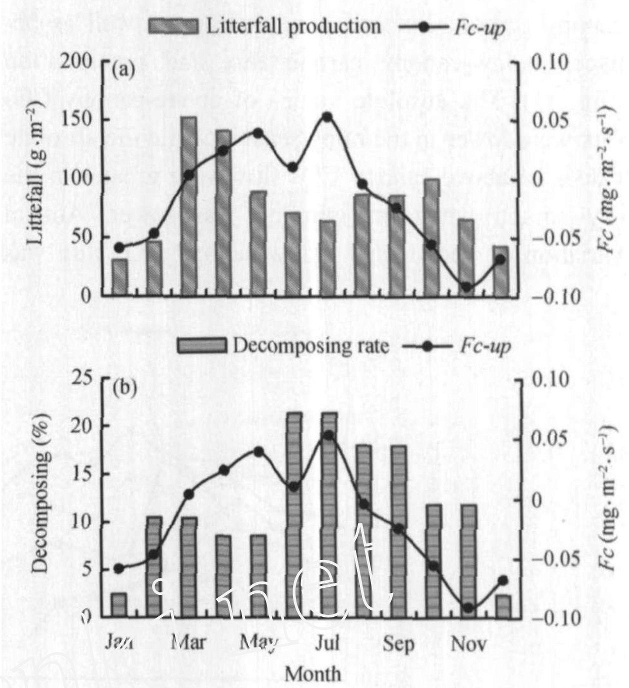

Fig. 9. Annual variation of monthly average above-canopy CO_2 flux, litterfall production and decomposing rate.

are the dominant components of litterfall from September to October, with a peak of 58.0 $g \cdot m^{-2}$ in October. Seasonal variation of other kinds of litterfall are smaller and litter production is generally less than 20 $g \cdot m^{-2}$, causing two peaks and two troughs of litterfall per year (Fig. 9(b)). The annual dynamics of litter production and relative decomposition rate are illustrated in Fig 9. It is very easy for litter to decompose during periods of high temperature and high precipitation in tropical rain forest. So, decomposed production and relative decomposition rate increased rapidly in May during the rainy season, which is characterized by high temperature and soil water content caused by high rainfall. The decomposed production and relative decomposition rate reach the peak in June and July at 21.4%. In the subsequent 5 months decomposed production and relative decomposition rate decreased; the lowest values of 2.4% occurred in December and January, respectively, when temperature and moisture were low.

There existed a definite correlation relationship between the absolute values of above-canopy CO_2 flux and litterfall production, as well as between the absolute values of above-canopy CO_2 flux and decomposed production (Fig. 9). The absolute values of above-canopy CO_2 flux are smaller when litterfall production is higher. On the contrary, the higher absolute values of above-canopy CO_2 flux coincided with lower litterfall production. Moreover, variations of above-canopy CO_2 flux were similar to those of decomposition rate. So, above-canopy CO_2 flux was mainly influenced by Leaf area index.

Shedding of leaves induced higher litterfall production and lower photosynthetic rate, causing the absolute value of above-canopy CO_2 flux to decrease; on the contrary, a higher leaf area index corresponds with lower litterfall production and greater photosynthetic rate, causing absolute values of above-canopy CO_2 flux to increase.

2.2.5 Annual patterns of above-, below-canopy carbon flux and soil respiration

Soil respiration is one of the key processes in the forest ecosystem carbon cycle. Annual patterns in above-canopy (*Fc-up*), below-canopy (*Fc-down*) mean CO_2 flux and soil respiration for different treatments (A bare soil, B soil + litter) were similar (Fig. 10). Values of soil respiration and below-canopy mean CO_2 flux were positive but lower in the dry season; while below-canopy mean CO_2 flux was mainly negative; moreover, the absolute values of them are great. In contrast, values of soil respiration and below-canopy mean CO_2 flux increased in the rainy season; absolute values of above-canopy mean CO_2 flux decreased, but above-canopy mean CO_2 flux remained positive during this period.

2.2.6 Relationship between carbon flux and environment factors

There existed correlation relationship between above-canopy carbon flux and precipitation, as well as between below-canopy carbon flux and precipitation (Fig. 11). The absolute values of above-canopy CO_2 flux were lower in the rainy season, while the absolute values of above-canopy CO_2 flux were greater in the dry season when precipitation was lower. Annual variation of above- and below-canopy CO_2 flux was similar to that of soil moisture and temperature at 5 cm depth (Fig. 12). The above-canopy CO_2 fluxes were negative and the absolute values were greater when soil moisture and temperature at 5 cm depth were lower. In contrast, the absolute values of above-canopy CO_2 flux were lower with higher soil moisture and temperature.

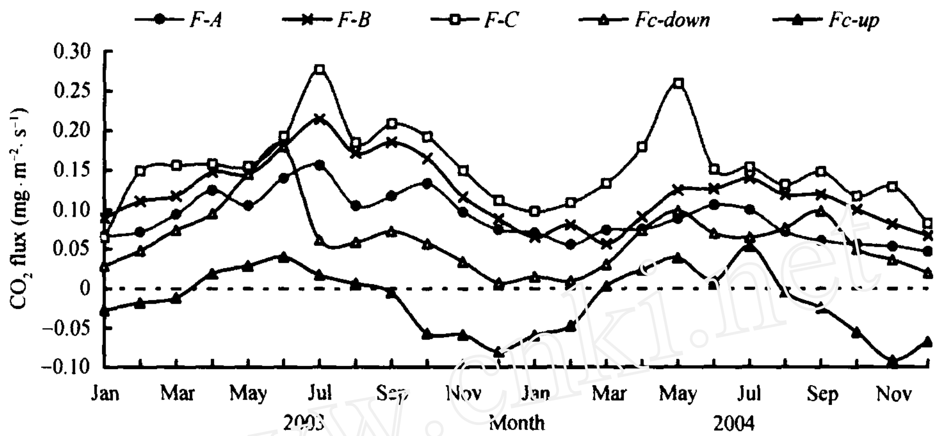

Fig. 10 Annual variation of monthly mean carbon flux in tropical seasonal rain forest.

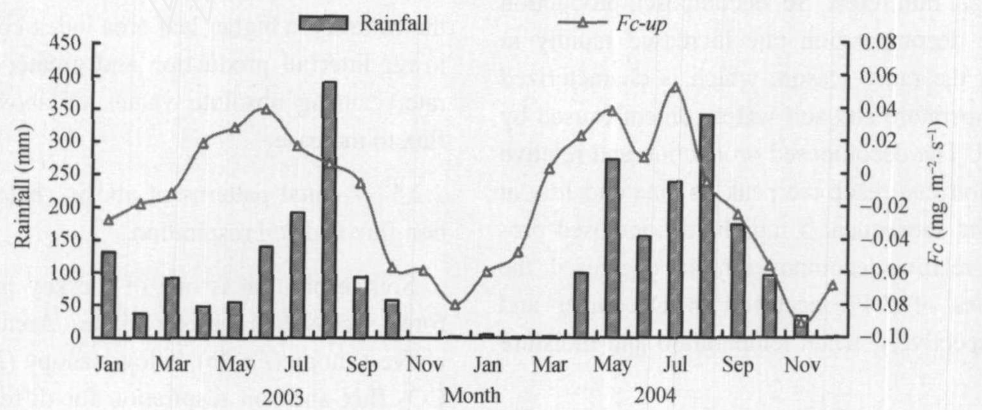

Fig. 11. Annual variation of above-canopy CO_2 flux and rainfall.

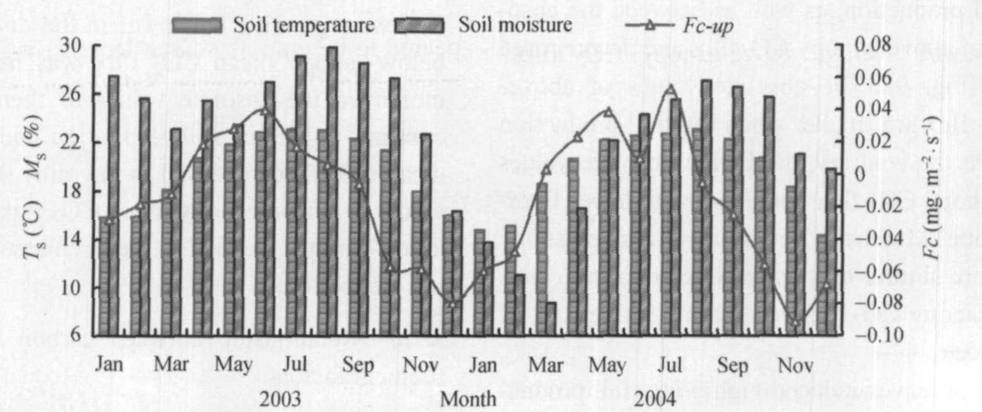

Fig. 12. Annual variation of above-canopy CO_2 flux, soil moisture and soil temperature.

Table 2 Carbon flux and leaf area index

	Fc-upm	*Pn-up*	*Pn-down*	*F-A*	*F-B*	*F-B-A*	*LAI-c*	*LAI-all*
Daytime								
Cool-dry sub-season	−0.1355	0.1710	0.0048	0.0784	0.1006	0.0247	1.73	5.51
Hot-dry sub-season	−0.0673	0.1515	0.0154	0.0737	0.0911	0.0175	1.25	3.83
Rainy season	−0.0950	0.2922	0.0068	0.1038	0.1466	0.0423	1.93	5.22
Nighttime								
	Fc-upm	*Re-up*	*Re-down*	*F-A*	*F-B*	*F-C-B*	*LAI-c*	*LAI-all*
Cool-dry sub-season	0.0215	0.0332	0.0074	0.0784	0.1006	0.0202	1.73	5.51
Hot-dry sub-season	0.0779	0.0482	0.0349	0.0737	0.0911	0.0454	1.25	3.83
Rainy season	0.0975	0.0319	0.0226	0.1038	0.1466	0.0320	1.93	5.22

2.3 Comparisons among seasonal mean values of CO_2

Diurnal average above-canopy CO_2 fluxes (*Fc-upm*) were all negative in every season, with absolute values always lower than mean photosynthetic rate of dominant canopy tree species (*Pn-up*) (Table 2); furthermore, differences between the above-canopy CO_2 fluxes and photosynthetic rate were smaller in the cool-dry season, but greater in the rainy season. Although photosynthetic rate of dominant canopy tree species was small in the cool-dry season, soil respiration (Treatment B: soil+litterfall) was also lower, resulting in higher absolute values of diurnal mean above-canopy CO_2 flux. As for the rainy season, higher mean photosynthetic rate and higher soil respiration and below-canopy CO_2 flux resulted in lower diurnal mean above-canopy CO_2 flux. Absolute values of diurnal mean above-canopy CO_2 flux were lower in the hot-dry season due to lower daytime average photosynthetic rate and soil respiration.

Nighttime average above-canopy CO_2 flux (*Fc-upm*) was positive in every season (Table 2); moreover, it was higher than dark respiration of dominant canopy tree species (*Re-up*), but lower than the sum of dark respiration and soil respiration in the hot-dry and rainy season. Nighttime average above-canopy CO_2 flux was lower than dark respiration of canopy trees in the cool-dry season, and was much lower than sum of dark respiration and soil respiration (*F-B*). The results indicate that CO_2 discharged by plant respiration was difficult to spread upward because this seasonal rain forest is characterized by heavy radiation fog and steady atmospheric stratification; however, the forest served as a carbon sink through gravitational effects. Similarly, soil respiration was also unable to spread outside of the canopy, which induced smaller above-canopy CO_2 flux. It will require further analysis to determine how high soil respiration impacts above-canopy CO_2 flux of a tropical seasonal rain forest with a canopy height over 30 m.

3 Discussion and conclusion

3.1 Discussion

A small perturbation in a tropical rain forest ecosystem could have a significant effect on the global carbon cycle and climate change; thus, it is important to determine whether tropical rain forests serve as a carbon source or a carbon sink. Recent research suggests that tropical rain forests are carbon sinks. For example, results of a simulation experiment by Tian *et al.* show that tropical forests act as a C sink to the atmospheric in Brazil[14]. Measurements by Fan *et al.* also indicated that Amazonian tropical rain forests were C sinks at least during the experimental period[15]; moreover, other studies imply Amazonian tropical rain forests function as C sinks throughout the year[11,16,17]. Long-term experiments in Amazonian tropical forests confirm that the forests are a sink for atmospheric C[18]. A short-term study in a Malaysian tropical rain forest drew similar conclusions; the forest under study appeared to be a net C sink at least during the measurement period[19]. However, Saleska *et al.* measured net ecosystem exchange of carbon dioxide for 3 years in two old-growth Amazonian forests in Brazil and found that carbon was lost in the wet season and gained in the dry season[13]. Houghton *et al.* confirm that the source of carbon dioxide was convincingly ascribed to the forest degradation and plantation abandonment during 1989—1998 in Amazonian, and they calculated the value of CO_2 emission due to forest deforestation and fire in tropical region, which showed that tropical forests are significant carbon source[12]. In our study, a tropical seasonal rain forest serves as a C sink at the scale of a year; however, above-canopy CO_2 flux was positive in the rainy season and negative in the dry season, similar to the results of the study by Saleska *et al.*[13].

Forest ecosystem CO_2 was impacted by many environment factors, and furthermore, tropical seasonal rain forests in Xishuangbanna are mainly distributed across rugged topography, leading to complex patterns of CO_2 flux. Above-canopy CO_2 flux was mostly influenced by *LAI*; low *LAI* coincident with high litterfall production resulted in low photosynthetic rate, decreasing above-canopy CO_2 flux. On the contrary, low litterfall production co-occurred with high *LAI*, causing greater photosynthetic rate and increasing above-canopy CO_2 flux. Below-canopy CO_2 flux was correlated with litter decomposition. Higher litter decomposition produced greater CO_2 causing below-canopy CO_2 flux to increase; this is similar to the results of a study by George *et al.* and Michael *et al.* in Amazonian tropical forests[20,21]. As illustrated in Fig. 4, the intercept of the equation for the dry season ($0.0886\ mg \cdot m^{-2} \cdot s^{-1}$) was much lower than that of the rainy season ($0.4292\ mg \cdot m^{-2} \cdot s^{-1}$), indicating that factors other than photosynthetic rate of dominant tree species affected diurnal above-canopy CO_2 flux; that is, when photosynthetic rate was zero, CO_2 flux remained positive at $0.0886\ mg \cdot m^{-2} \cdot s^{-1}$ and $0.4292\ mg \cdot m^{-2} \cdot s^{-1}$ in the dry and rainy season, respectively. The effects of factors other than photosynthetic rate are greatest in the rainy season, perhaps partially explaining why the forest serves as a C source during the rainy season.

Soil respiration for different treatments had a significant effect on above-canopy CO_2 flux with the effects differing across seasons and treatments. For example, values of above-canopy CO_2 flux was negative when soil respiration for bare soil (*F-A*) was under $0.10\ mg \cdot m^{-2} \cdot s^{-1}$; while, positive values of above-canopy CO_2 flux coincided with soil respiration for treatment A (*F-A*) over $0.10\ mg \cdot m^{-2} \cdot s^{-1}$, or soil respiration for treatment B (*F-B*) over $0.15\ mg \cdot m^{-2} \cdot s^{-1}$. The results suggest that above-canopy CO_2 flux was mainly affected by plant photosynthesis when soil respiration was low, and by soil respiration when soil respiration was high. Such different contribution during different periods could explain the present unusual variation of above-canopy CO_2 flux.

The results of this study show that diurnal above-canopy CO_2 flux was negative in the dry season (November—April) when the forest acted as a C sink, while it was mainly positive in the rainy season (May—October when the forest acted as a weak C source. In the cool-dry sub-season, environmental conditions were characterized by high *LAI*, greater *PAR* and photosynthetic rate, low litterfall production, decomposition rate, soil respiration and plant dark respiration caused the tropical seasonal rain forest to act as a sink of CO_2 to the atmosphere.

In the hot-dry sub-season, the tropical seasonal rain forest ecosystem was near a state of carbon balance. The low above-canopy CO_2 flux was consistent with low soil respiration when litterfall and decomposed production are low, due to low rainfall, soil moisture and temperature.

Decomposed production and relative decomposition rate increased rapidly in May during the rainy season characterized by high temperature and high soil water content; these conditions caused soil respiration to increase and further counteracted the C uptake effect of photosynthesis. So, absolute values of above-canopy CO_2 flux decreased in the rainy season. Above-canopy CO_2 flux was positive during the night when plant photosynthesis stopped and respiration strengthened, which made forest ecosystem act as a C source. Thus it can be seen soil respiration was another important factor to affect above-canopy CO_2 flux other than photosynthesis.

3.2 *Conclusions*

(1) The CO_2 flux of the tropical seasonal rain forest ecosystem was low in Xishuangbanna, similar to measurments from Amazonian and Malaysian tropical rain forests. The findings demonstrate a seasonal pattern of CO_2 flux; uptake of carbon in the dry season caused the forest to act as a C sink, while in the rainy season it acted as a C source. The results were similar to those obtained by Saleska *et al.* (2003)[13]. This forest acted as a C sink at the scale of a year.

(2) Dominant tree species have high photosynthesis capability, and thus have a large effect on above-canopy carbon flux. Above-canopy carbon flux was

significantly correlated with the rate of photosynthesis of dominant tree species and seedlings.

(3) Soil respiration of three treatments possessed a markedly seasonal dynamic. In addition, soil respiration was correlated with above-canopy carbon fluxes and played a significant role in annual variation of CO_2 flux.

(4) This research showed that carbon flux was impacted by many factors in this forest. Moreover, carbon fluxes of this forest have are correlated with litterfall production, litterfall decomposition rate, precipitation, and soil moisture and temperature.

Due to its unique geographical location, climatic features, plant physiological traits and soil environmental characteristics of Xishuangbanna all differed in other places. It needs to further analyze how plant physiological actives and soil environment how to impact annual variation of carbon flux in this tropical seasonal rain forest.

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Appendix

Parameter	Meanings and measurement methods	Parameter	Meanings and measurement methods
F	soil respiration (the static opaque chamber technique)	*LAI*	leaf area index (*LAI*-2000)
F-A	soil respiration (bare soil)	*LAI-c*	*LAI* for tree layer A
F-B	soil respiration (bare soil+litter)	*LAI-all*	*LAI* for above 3.8 m
F-C	soil respiration (bare soil+litter+seedling)	*Pn*	photosynthetic rate (LI-6400)
F-B-A	differences between soil respiration for F-B and F-A	*Pn-up*	photosynthetic rate for dominated tree species
F-C-B	differences between soil respiration for F-C and F-B	*Pn-down*	photosynthetic rate for seedlings
Fc	CO_2 flux of forest ecosystem (eddy covariance)	*Re*	dark respiration
Fc-up	above-canopy CO_2 flux (48.8 m)	*Re-up*	dark respiration for dominated tree species
Fc-upm	monthly averaged above-canopy CO_2 flux in clear days	*Re-down*	dark respiration for seedlings
Fc-down	below-canopy CO_2 flux (4.8 m)	*PAR*	photosynthetically active radiation

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