

DOI: 10.1007/s11430-006-8063-2

## Seasonal and annual variation of CO<sub>2</sub> flux above a broad-leaved Korean pine mixed forest

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Received October 27, 2005; accepted March 10, 2006

**Abstract** Long-term measurement of carbon metabolism of old-growth forests is critical to predict their behaviors and to reduce the uncertainties of carbon accounting under changing climate. Eddy covariance technology was applied to investigate the long-term carbon exchange over a 200 year-old Chinese broad-leaved Korean pine mixed forest in the Changbai Mountains (128°28'E and 42°24'N, Jilin Province, P. R. China) since August 2002. On the data obtained with open-path eddy covariance system and CO<sub>2</sub> profile measurement system from Jan. 2003 to Dec. 2004, this paper reports (i) annual and seasonal variation of  $F_{NEE}$ ,  $F_{GPP}$  and  $R_E$ ; (ii) regulation of environmental factors on phase and amplitude of ecosystem CO<sub>2</sub> uptake and release. Corrections due to storage and friction velocity were applied to the eddy carbon flux.

$L_{AI}$  and soil temperature determined the seasonal and annual dynamics of  $F_{GPP}$  and  $R_E$  separately.  $V_{PD}$  and air temperature regulated ecosystem photosynthesis at finer scales in growing seasons. Water condition at the root zone exerted a significant influence on ecosystem maintenance carbon metabolism of this forest in winter.

The forest was a net sink of atmospheric CO<sub>2</sub> and sequestered  $-449 \text{ g C} \cdot \text{m}^{-2}$  during the study period;  $-278$  and  $-171 \text{ g C} \cdot \text{m}^{-2}$  for 2003 and 2004 respectively.  $F_{GPP}$  and  $F_{RE}$  over 2003 and 2004 were  $-1332$ ,  $-1294 \text{ g C} \cdot \text{m}^{-2}$  and  $1054$ ,  $1124 \text{ g C} \cdot \text{m}^{-2}$  respectively. This study shows that old-growth forest can be a strong net carbon sink of atmospheric CO<sub>2</sub>.

There was significant seasonal and annual variation in carbon metabolism. In winter, there was weak photosynthesis while the ecosystem emitted CO<sub>2</sub>. Carbon exchanges were active in spring and fall but contributed little to carbon sequestration on an annual scale. The summer is the most significant season as far as ecosystem carbon balance is concerned. The 90 days of summer contributed 66.9, 68.9% of  $F_{GPP}$ , and 60.4, 62.1% of  $R_E$  of the entire year.

**Keywords:** old-growth forest; eddy-covariance; carbon metabolism; seasonal and annual dynamics

Forests have been proposed as possible sinks of the 'missing' atmospheric carbon that is not accounted for by global carbon models<sup>[1-4]</sup>. While young and recovering forests have obvious potential as carbon sinks,

forests older than 100 years are thought to be insignificant carbon sinks as they are generally in equilibrium between carbon uptake and total ecosystem respiration<sup>[5,6]</sup>.

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In contrast, research by Carey *et al.*<sup>[7]</sup> emphasized the need to account for multiple-aged, species-diverse, mature forests in models of terrestrial carbon dynamics to approximate the global carbon budget. Several recent process studies have indicated that some old forest ecosystems do not reach a steady state carbon flux and can continue to act as a net sink for atmospheric carbon dioxide over several decades or longer<sup>[8–11]</sup>. Long-term measurements of whole ecosystem carbon exchange are needed to determine the sink-source and budget status of ecosystems, and to analyze how carbon exchange varies with seasonal and interannual variation in environmental conditions. However, very few actual measurements of  $F_{NEE}$  in old forests have been conducted, and results varied depending on conditions<sup>[9, 11–16]</sup>. More actual measurements are needed to clarify the role of old-growth forests. Given the importance of the world's old-growth forests as a major terrestrial carbon store, this study of the dynamics of carbon stock capacity and carbon sink strength of old-growth forests will help to reduce the uncertainties in carbon accounting.

The Changbai Mountains lie in the northeast of China, on the boundary between China and North Korea. For special natural, historical and social causes this area, is the most complete and well-conserved natural ecosystems of China, even the world. Of these well conserved East Asian mountain forest ecosystems, the broadleaf Korean pine mixed forest is the typical zonal vegetation in Northeast China and is about 200 years old<sup>[17]</sup>. On the data obtained with open-path eddy covariance system and CO<sub>2</sub> profile measurement system from Jan. 2003 to Dec. 2004, This paper reports (i) annual and seasonal variation of  $F_{NEE}$ ,  $F_{GPP}$  and  $R_E$ ; (ii) regulation of environmental factors on phase and amplitude of ecosystem CO<sub>2</sub> uptake and release

## 1 Materials and methods

### 1.1 Study site description

The measurements were carried out in No. 1 Plot at the Forest Ecosystem Open Research Station of Changbai Mountains (128°28'E and 42°24'N, Jilin Province, P. R. China), Chinese Academy of Sciences, since August 2002. There are villages and towns, but

no industrial activities in the NE direction.

The annual mean temperature is 0.9–4.0°C, and the total precipitation is 693.9 mm·a<sup>-1</sup> (evaluated between 1982 and 2004). The site provides a maximum fetch of 60 km in the E-S-W direction and a minimum of 500 m in the NE direction. The area is covered by on average 200-year-old, multi-storied, uneven-aged, multi-species mixed forest consisting of Korean pine (*Pinus koraiensis*), *Tilia amurensis*, *Acer mono*, *Fraxinus mandshurica*, *Quercus mongolica*, etc. A dense understory, consisting of multi-species broad-leaved shrub, has coverage of 40%. The mean canopy height is 26 m. The peak leaf area index is about 6.1. The soil is classified as dark brown forest soil. The landscape is very flat. See ref. [18] for advanced detailed site information.

### 1.2 Instruments and measurements

Net ecosystem exchange (NEE, or  $F_{NEE}$ ) was determined from the measurements of eddy-covariance flux and CO<sub>2</sub> concentration profiles.

An open-path eddy covariance measurement system was installed at 40 m. The system consists of a Li7500 open-path sensor (IRGA, Li-Cor, USA) and a 3-D ultrasonic anemometer (CSAT3, Campbell Scientific, USA). Both instruments were sampled at 10 Hz. Half-hourly fluxes are calculated on-line and collected by a CR5000 data logger (Campbell Scientific, USA).

A 7-level CO<sub>2</sub> profile was measured by a CR10X (Campbell, USA) controlled multi-port system connected to a Li820 gas analyzer. Calibration of the IRGA against standard gases is done automatically every 2 hours.

Meteorological variables were sampled every 2 s and stored as half-hour statistics (CR23X, Campbell, USA). Meteorological measurements at 40 m include air temperature and relative humidity (HMP45C, Vaisala, Finland), wind speed (A100R, Vector, UK), downward/upward solar radiation and net radiation (CNR1, Kipp & Zonen, the Netherlands), and  $Q_{PPFD}$  (Li190SB, Li-Cor, USA). Precipitation (52203, Young, USA) is measured at 62.8 m. Two plates (HFP01 and HFP01SC, Hukseflux, the Netherlands) measure the heat flux at 5 cm under the soil surface. Soil water content is characterized by TDR probes (CS616, Campbell, USA).

Leaf area index was measured with an LAI-2000 canopy analyzer (Li-Cor, USA). For a continuous record of canopy structure, a global vegetation absorption index ( $V_{AI}$ )<sup>[19]</sup> was deduced from  $Q_{PPFD}$  measurements above and below canopy (eqn (1)). Six  $Q_{PPFD}$  sensors (LQS70-10S, Apogee, USA) were installed below the forest canopy around the flux tower.

$$V_{AI} = -\frac{1}{k} \log \tau_c, \quad (1)$$

where  $k$  is the extinction coefficient for diffuse light.  $\tau_c$  is canopy transmittance and was estimated as the ratio of the averaged flux density measured below the canopy to that measured above canopy.

### 1.3 Flux calculation

#### 1.3.1 Calculation of $F_{NEE}$

At present, net ecosystem CO<sub>2</sub> exchange ( $F_{NEE}$ ) is assessed as the sum of eddy covariance measurements ( $F_c$ ) at height  $z_r$  and the storage of CO<sub>2</sub> ( $F_s$ ) in the underlying air (eq. (2)). However, many reports show that this may underestimate nocturnal respiration flux densities especially during stable nighttime conditions<sup>[20,21]</sup>. Several groups have recently addressed the advection terms by measurement or simulation<sup>[20, 22–27]</sup>. All these studies agree that the neglected advective processes are responsible for the underestimation of nighttime fluxes. Zhang *et al.* show that pressure-induced flux, which is always omitted, is the responsible reason for the negative nighttime  $F_{NEE}$  flux under strong wind in winter<sup>[28]</sup>. At present there are still methodological problems and potential deficits in the estimation of the advection and pressure-induced terms. Mass balance approaches are not

precise enough to allow reliable flux corrections. While waiting for a physically based correction, the  $u_*$  correction seems the best compromise<sup>[22, 25–27]</sup>.

In this study, net ecosystem exchange between forest and atmosphere was assessed with eq. (2).

$$F_{NEE} = \int_0^{\infty} \frac{\partial \bar{c}}{\partial t} dz + (\overline{w'c'})_r. \quad (2)$$

Here, the first term on the RHS is the storage term ( $F_s$ ), the second is the eddy CO<sub>2</sub> flux ( $F_c$ ) measured at height  $z_r$ . Subscript  $r$  denotes a quantity at eddy flux measurement height  $z_r$ . The storage term was calculated from CO<sub>2</sub> profile data in growth seasons and CO<sub>2</sub> series by IRGA of OPEC system in dormant seasons.

To avoid the underestimation of nighttime  $F_{NEE}$  under calm condition,  $u_*$  correction was applied to nighttime flux measurements.  $UU_*$  correction was applied to measurements in winter seasons. The storage corrected eddy flux is assumed to be independent of turbulence density, measured with  $u_*$ ; the threshold of  $u_*$  is 0.17 for growth period and 0.02 for dormant seasons.  $UU_*$  threshold is 0.37 (Fig. 1).

Calculations were made under R environment<sup>[29]</sup>. Post processing on eddy fluxes includes 3-D sonic anemometer tilt correction (coordinate rotation, Planar fit method), frequency response correction, sensors separation correction, humidity correction for temperature by ultrasonic anemometer, path correction, common WPL correction etc.

#### 1.3.2 Empirical formulas and gap-filling

Several strategies were used to fill the data gaps in order to get complete flux time series. (i) Data gaps of 2 hours or less were filled by direct interpolation. (ii) For longer gaps, empirical formulas describing rela-

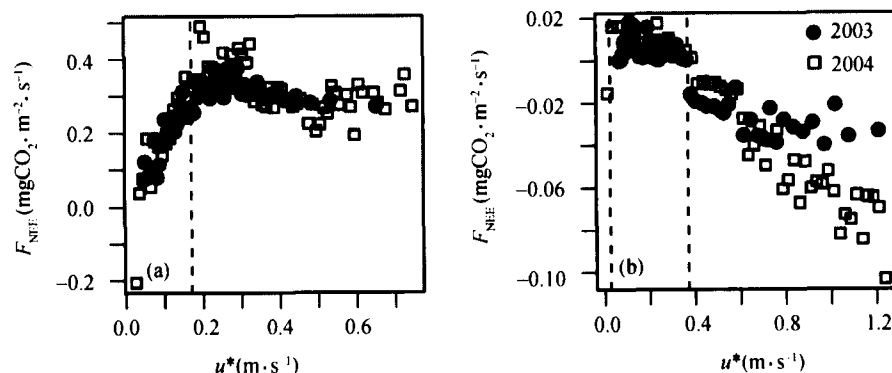


Fig. 1. Dependency of nighttime  $F_{NEE}$  on turbulence, expressed as friction velocity ( $u_*$ ). (a) from June to August and (b) from December to February. Data are bin averaged with an equal number of data points per bin.

tionships between  $Q_{PPFD}$ , soil temperature and net  $CO_2$  flux were applied separately for daytime (eq. (3)) and nighttime (eq. (4)). (iii) In cases where empirical relationships could not be developed as a result of missing meteorological data, mean diurnal variations were used to fill the missing data<sup>[30]</sup>. The time window is 1 month for winter and 1 week for the other seasons.

Daytime  $F_{NEE}$  measurements were fitted to a hyperbolic dependence on light ( $Q_{PPFD}$ ) according to the Michaelis – Menten equation<sup>[30]</sup>,

$$F_{NEE} = \frac{\alpha \cdot Q_{PPFD} \cdot F_{GPP, SAT}}{F_{GPP, SAT} + \alpha \cdot Q_{PPFD}} + R_D, \quad (3)$$

where  $\alpha$  is the ecosystem quantum yield ( $mg\ CO_2 \cdot m^{-2} \cdot s^{-1} / \mu mol\ photons \cdot m^{-2} \cdot s^{-1}$ ),  $F_{GPP, SAT}$  ( $mg\ CO_2 \cdot m^{-2} \cdot s^{-1}$ ) is the ecosystem gross primary productivity at “saturating” light, and  $R_D$  ( $mg\ CO_2 \cdot m^{-2} \cdot s^{-1}$ ) is the ecosystem respiration during the day.

To fill in nighttime data gaps and estimate daytime ecosystem respiration flux, nighttime valid  $F_{NEE}$  were modeled with the following Arrhenius type function<sup>[31]</sup>,

$$F_{NEE, night} = F_{R_E, T_{ref}} e^{[(E_a/R)(1/T_{ref} - 1/T_k)]}. \quad (4)$$

Here  $E_a$  is the activation energy in  $J\ mol^{-1}$ , and  $R$  is the gas constant ( $8.314\ J \cdot K^{-1} \cdot mol^{-1}$ ).  $T_{ref}$  is the reference temperature and was set to 283.15 K.  $F_{R_E, T_{ref}}$  is ecosystem respiration flux at reference temperature ( $mg\ CO_2 \cdot m^{-2} \cdot s^{-1}$ ).

Models were fitted by the modified Levenberg-Marquardt method and confidence ranges for parameter estimates were estimated with the bootstrap method<sup>[32]</sup>.

### 1.3.3 Decomposition of $F_{NEE}$ into $F_{GPP}$ and $R_E$

Eqs. (3)–(6) were applied to decompose  $F_{NEE}$  into  $R_E$  and  $F_{GPP}$ . Gross ecosystem exchange by primary photosynthesis (GPP or  $F_{GPP}$ ) can be defined as the difference between  $F_{NEE}$  and the total ecosystem respiration ( $R_E$ ):

$$F_{GPP} = F_{NEE} - R_E. \quad (5)$$

Daily ecosystem respiration  $R_E$  is composed of daytime respiration ( $R_{E, day}$ ) and nighttime respiration  $R_{E, night}$ ,

$$R_E = R_{E, night} + R_{E, day}. \quad (6)$$

Nighttime net exchange flux is always thought as nighttime ecosystem respiration. Temperature re-

sponse models obtained from nighttime net exchange fluxes ( $R_{E, night}$ ) were applied in daytime to estimate daytime ecosystem respiration ( $R_{E, day}$ ).

## 2 Results and discussion

### 2.1 Seasonal dynamics of meteorological variables and leaf area index

Dynamics of meteorological variables from 2003 to 2004 are shown in Fig. 2. The most significant difference between 2003 and 2004 was precipitation (Fig. 2(a)). The precipitation of 2004 was 707.3 mm and very close to 693.9 mm, the averaged value between 1982 and 2004, while the precipitation of 2003 was 538.4 mm. The precipitation between May and September of 2004 was 500 mm and very close to 547 mm, the averaged value of the corresponding period between 1982 and 2004, while that of the corresponding period of 2003 was 388 mm.  $Q_{PPFD}$  between June and September of 2004 was less than the corresponding period of 2003 (Fig. 2(c)) while soil moisture of 2004 was higher than that of 2003 (Fig. 2(b)).

There was significant difference in temperature between 2003 and 2004 (Fig. 2(d), (e)). This difference is especially obvious in ‘March–May’ and ‘June–September’. Atmospheric and soil temperature at 5 cm depth between June and September of 2004 were 0.7 and 0.5°C higher than that of 2003, respectively, while atmospheric and soil temperature at 5 cm depth between March and May of 2004 were 2.5 and 0.4°C lower than that of 2003, respectively.

$V_{PD}$  is determined by precipitation and air temperature. High precipitation and high temperature in 2004 and low temperature/poor precipitation in 2003 weakened the difference in  $V_{PD}$  of growth seasons between the 2 years (Fig. 2(f)).

Fig. 3 shows the clear seasonal course and significant inter-annual difference of  $L_{AI}$ . Bud burst occurred in early May.  $L_{AI}$  reached its maximum in August and decreased from September in 2003 while  $L_{AI}$  peaked in July and decreased from August in 2004. The averaged  $L_{AI}$  between June and September of 2003 was 0.3 higher than that of 2004.

### 2.2 Relationships between ecosystem carbon metabolism and environmental factors

Ecosystem photosynthesis was determined by  $L_{AI}$  at

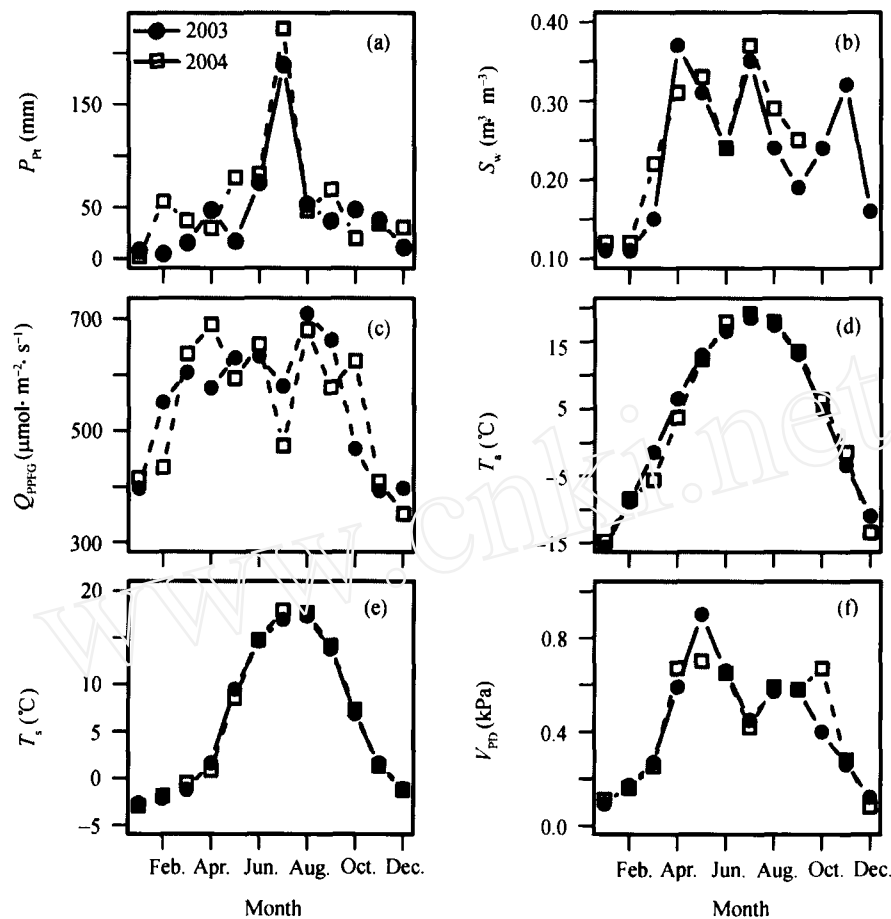


Fig. 2. Dynamics of meteorological variables between 2003 and 2004. (a) Monthly precipitation; (b) soil moisture at 10 cm; (c)  $Q_{PPFD}$ ; (d)  $T_s$  at 40 m; (e)  $T_s$  at 5 cm; (f)  $V_{PD}$  at 40 m

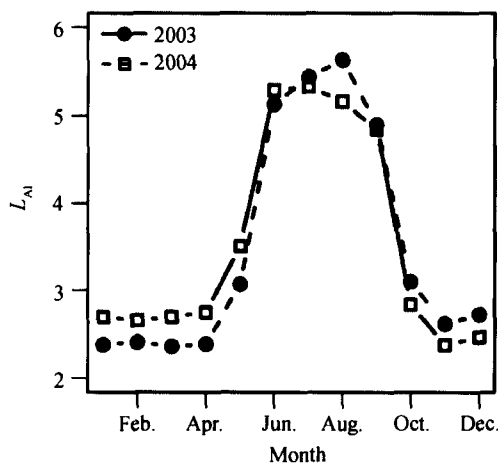


Fig. 3. Seasonal development of  $L_{AI}$  in 2003 and 2004.

a seasonal scale (Fig. 4(a)). For this mixed forest ecosystem, 94% and 93% of variance in  $F_{GPP}$  of 2003 and 2004 was explained by the variation of  $L_{AI}$ , respectively.  $F_{GPP}$  increased 23.3 and 20.8 g C·m<sup>-2</sup> per

week for each incremental increase in  $L_{AI}$  in 2003 and 2004. The close relationship between  $L_{AI}$  and  $F_{GPP}$  also appeared in other reports<sup>[33,34]</sup>.

Variation in radiation can explain 31% of residual variance in  $F_{GPP}$  of spring/autumn seasons and contributed almost nothing to that of summer (Fig. 4(b)).

Parameters  $\alpha$  and  $F_{GPP, SAT}$  in eq. (3) can be used to explore the relationships between  $F_{GPP}$  and environmental factors (with the exception of radiation). Multiple environmental variables jointly control CO<sub>2</sub> exchange of the ecosystem and strong interactions among these variables make it difficult to discern their individual effects. To minimize the confounding among variables, partial correlation analysis was applied to separate the influence of individual factors.

$L_{AI}$  determined dynamics of  $\alpha$  and  $F_{GPP, SAT}$  at a seasonal scale.  $F_{GPP, SAT}$  and  $\alpha$  significantly increased in magnitude with  $L_{AI}$  (Fig. 5 and Table 1). To analyze

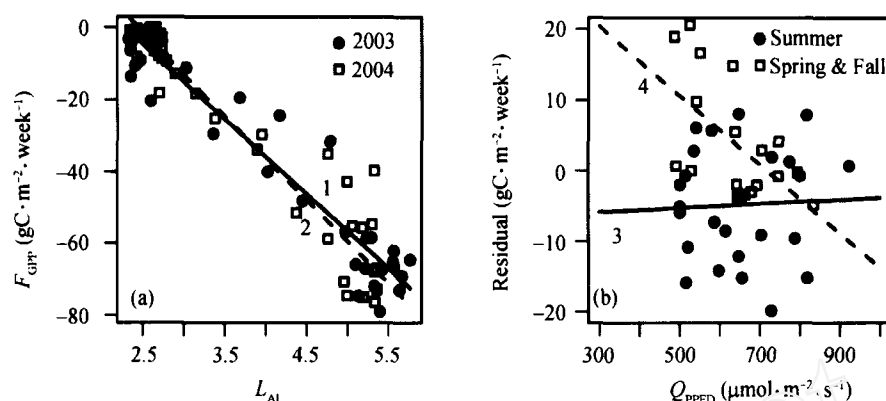


Fig. 4. Dependency of  $F_{GPP}$  on  $L_{AI}$  (a) and  $Q_{PPFD}$  (b). 1 (solid line): Fitted function for 2003,  $F_{GPP} = 47.4 - 25.8 \times L_{AI}$ ,  $A-R^2 = 0.94$ ; 2 (dashed line): Fitted function for 2004,  $F_{GPP} = 57.1 - 23.3 \times L_{AI}$ ,  $A-R^2 = 0.93$ ; 3 (solid line): fitted function for summer seasons,  $F_{GPP} \text{ residual} = -6.75 + 0.003 \times Q_{PPFD}$ ,  $A-R^2 = 0.04$ ; 4 (dashed line): fitted function for spring and fall seasons,  $F_{GPP} \text{ residual} = 35.1 - 0.049 \times Q_{PPFD}$ ,  $A-R^2 = 0.31$

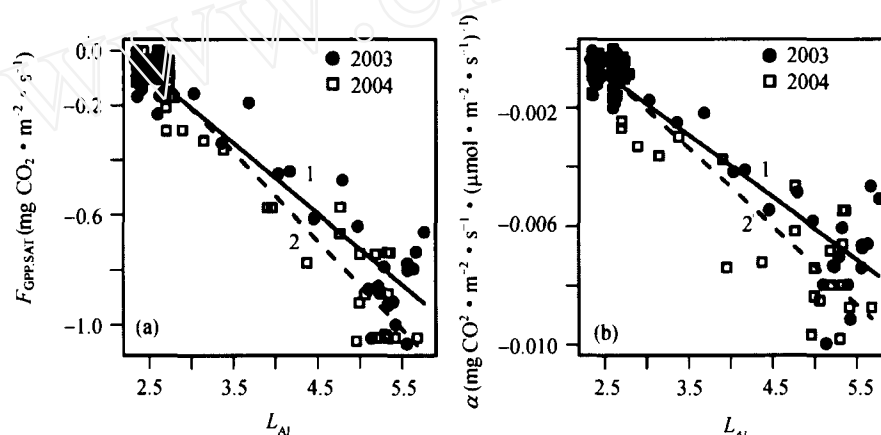


Fig. 5. Dependency of  $F_{GPP,SAT}$  and  $\alpha$  on  $L_{AI}$ . See table 1 for fitted function.

the influence on  $F_{GPP}$  by other factors, we calculated partial correlation coefficients between residuals of  $\alpha$  and  $F_{GPP,SAT}$  ( $\alpha$  and  $F_{GPP,SAT}$  minus predications by Equations shown in Table 1) and environmental factors (Table 2).

In summer, soil moisture was not a controlling factor for photosynthesis of this ecosystem because of the abundant precipitation.  $F_{GPP,SAT}$  was controlled by  $V_{PD}$  and air temperature while  $\alpha$  was only correlative with  $V_{PD}$ .  $T_a$  and  $V_{PD}$  significantly influenced ecosystem photosynthesis via  $\alpha$  and  $F_{GPP,SAT}$  in spring.  $\alpha$  significantly correlated with water condition in the roots zone in the cold and dry winter. This shows that there was maintenance photosynthesis in winter and validated the Freeland's report on photosynthesis by some conifers below  $-6^\circ\text{C}$  even down to  $-40^\circ\text{C}$ <sup>[35]</sup>.

The parameter  $R_D$  in eq. (3) is the mean daytime

Table 1 Fitted function for the dependency of  $F_{GPP,SAT}$  and  $\alpha$  on  $L_{AI}$

Year	Functions	$A-R^2$
2003	$F_{GPP,SAT} = 0.58 - 0.26 \times L_{AI}$	0.92
	$\alpha = 0.0047 - 0.0022 \times L_{AI}$	0.90
2004	$F_{GPP,SAT} = 0.76 - 0.32 \times L_{AI}$	0.94
	$\alpha = 0.0059 - 0.0026 \times L_{AI}$	0.89

ecosystem respiration of each time window and can be applied to analyze the relationship between ecosystem respiration and environmental variables. Soil temperature was the only factor that controlled respiration at a seasonal scale. The relationship can be described with the exponential function (Fig. 6). To analyze the influence on ecosystem respiration by other factors, we calculated partial correlation coefficients between residuals of  $R_D$  ( $R_D$  minus predications by Equations shown in Fig. 6) and environmental factors (Table 2). This shows that soil temperature was the only significant driver for ecosystem respiration when surface soil

Table 2 Partial correlation coefficients between environmental variables and residuals of parameters in eq. (3)<sup>a)</sup>

Season	Residual of $F_{GPP, SAT}$			Residual of $\alpha$			Residual of $R_D$			
	$V_{PD}$	$S_{W, 50cm}$	$T_{a, 40m}$	$V_{PD}$	$S_{W, 50cm}$	$T_{a, 40m}$	$V_{PD}$	$S_{W, 10cm}$	$S_{W, 50cm}$	$T_{a, 40m}$
Summer	0.54***	0.11	0.36*	0.51**	-0.11	0.1	-0.20	-0.1	0.17	-0.14
Winter	-0.01	-0.14	0.08	-0.02	0.36***	-0.09	-0.05	0.18	0.44***	0.022
Spring&Fall	0.58***	-0.20	-0.78***	-0.48*	-0.14	-0.75***	-0.29	0.22	0.17	0.09

a)  $V_{PD}$ , Vapor pressure defect (kPa) measured at 40m;  $S_{W, 10cm}$ , soil moisture measured at depth of 10cm;  $S_{W, 50cm}$ , soil moisture measured at depth of 50cm;  $T_{a, 40m}$ , air temperature measured at 40m. Season definition: Summer, June to August; winter, October to April; Spring & Fall, May and September. Significance levels: 0.001 \*\*\*, 0.01 \*\*, 0.05 \*.

water content was abundant in summer and temperature exhibited high amplitude fluctuations in spring and autumn. In winter, the soil surface was dry and soil respiration was very weak and water condition in the roots zone significantly regulated ecosystem maintenance metabolism as demonstrated by the close relationship between soil moisture at 50 cm and  $\alpha$  and  $R_D$  (Table 2).

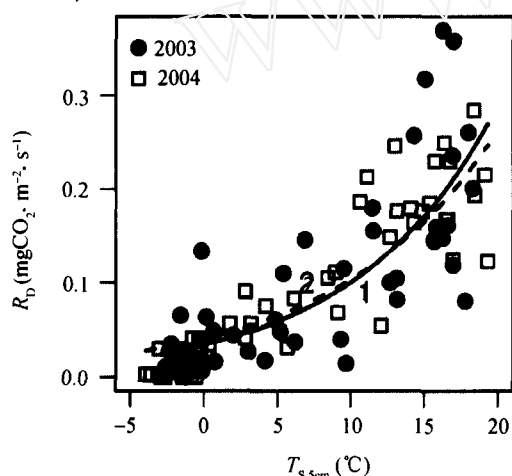


Fig. 6. Dependency of  $R_D$  on soil temperature  $T_{s,5cm}$  (solid line): fitted function for 2003,  $R_D = 0.035 \exp(0.106 \times T_{s,5cm})$ ,  $A-R^2 = 0.46$ ; 2 (dashed line): fitted function for 2004,  $R_D = 0.041 \exp(0.094 \times T_{s,5cm})$ ,  $A-R^2 = 0.42$ .

### 2.3 Annual carbon budget and seasonal dynamics

Table 3 shows monthly and annual carbon budgets of broadleaved Korean pine mixed forest in Changbai Mountain from 2003 to 2004.  $F_{NEE}$ ,  $F_{GPP}$ ,  $R_E$  were -278, -1332 and 1054 g C·m<sup>-2</sup> in 2003 and -171, -1294 and 1124 g C·m<sup>-2</sup> in 2004, respectively. This old-growth forest ecosystem was a carbon sink during the research time periods.

Annual dry mass weight growth of this forest, esti-

mated by Zhao (2005)<sup>1)</sup> with a dendrometry method, were 2100.3, 2056.2 g·m<sup>-2</sup>·a<sup>-1</sup> in 2003 and 2004, respectively. As carbon content varies from 0.4 to 0.5 in different plant parts<sup>[36]</sup>, the annual  $F_{NPP}$  were  $945.1 \pm 105$  and  $925 \pm 102$  g C·m<sup>-2</sup>·a<sup>-1</sup> in 2003 and 2004, respectively.

Table 3 Monthly and annual carbon budget from 2003–2004 (unit: g C·m<sup>-2</sup>)

Season	Month	2003			2004		
		$F_{NEE}$	$R_E$	$F_{GPP}$	$F_{NEE}$	$R_E$	$F_{GPP}$
Winter	10	12.8	52.1	-39.3	29.6	72.0	-42.4
	11	8.5	19.4	-10.9	5.6	11.5	-5.9
	12	1.6	8.3	-6.7	3.0	9.3	-6.3
	1	1.1	8.7	-7.6	0.6	5.7	-5.2
	2	0.6	9.9	-9.3	0.2	4.8	-4.5
	3	3.0	17.6	-14.5	3.3	14.1	-10.8
	4	1.1	36.7	-35.5	5.0	35.1	-30.1
Spring	SUM	28.8	152.6	-123.9	47.3	152.4	-105.1
	5	-30.4	108.2	-138.6	-23.8	116.6	-140.3
Summer	SUM	-30.4	108.2	-138.6	-23.8	116.6	-140.3
	6	-97.0	184.2	-281.2	-73.0	208.5	-281.5
Autumn	7	-96.3	214.9	-311.2	-78.2	229.9	-308.1
	8	-62.2	237.3	-299.5	-42.1	259.4	-301.4
	SUM	-255.4	636.5	-891.9	-193.3	697.8	-891.0
	9	-20.8	157.0	-177.8	-0.8	156.9	-157.7
	SUM	-20.8	157.0	-177.8	-0.8	156.9	-157.7
	SUM	-278	1054	-1332	-171	1124	-1294

Eddy covariance data do not provide values of  $F_{NPP}$ . We adopted a ratio  $F_{NPP}/F_{GPP}$  of  $0.47 \pm 0.04$ <sup>[37]</sup> to estimate the annual ' $F_{NPP}$ ' from the eddy-covariance  $F_{GPP}$ .  $F_{NPP}$  on eddy covariance data were  $945.1 \pm 105$  and  $925 \pm 102$  g C·m<sup>-2</sup>·a<sup>-1</sup> in 2003 and 2004, respectively. Considering the stochastic error, uncertainties of experiential formulas and gap-filling of eddy-covariance data, the  $F_{NPP}$  estimated by eddy covariance and dendrometry method can be deemed same.

1) Zhao X S, Estimation of net ecosystem productivity by eddy covariance and biometry in the mixed forest of broad-leaved and Korean-pine in Changbai Mountain. Master Thesis, Chinese Academy of Sciences, China, 2005

Soil respiration in 2003 and 2004, estimated with the temperature response function by Wang *et al.* in an eddy-covariance field with the chamber method<sup>[38]</sup>, were 514.5 and 527.4 g C·m<sup>-2</sup>·a<sup>-1</sup>, respectively. Soil respiration accounted for 49% of ecosystem respiration<sup>[39]</sup>. Ecosystem respiration in 2003 and 2004 were 1050 and 1076.3 g C·m<sup>-2</sup>·a<sup>-1</sup>, respectively; these values were very close to those estimated with the eddy-covariance method.

To assess the status of ecosystem carbon balance, Falge *et al.* (2001) defined an index  $z$ ,

$$z = |F_{\text{NEE}}/R_E| + 1 = F_{\text{GPP}}/R_E. \quad (7)$$

When  $z > 1$  the system is storing carbon, and when  $z = 1$  the system is in carbon balance and  $R_H$  equals  $F_{\text{NPP}}$ . In general,  $z$  varies between 1 and 2 in growth seasons and is less than 1 in dormant seasons. Our  $z$  values were consistent with the theoretical ranges (Fig. 7(g), (h)). The  $z$  values of 2003 and 2004, 1.26 and 1.15, were very close to that of Harvard forest (42°32'N, 72°11', MA, USA) in 1993 and 1994<sup>[30]</sup>.

Daily integrated  $F_{\text{NEE}}$  and calculated  $F_{\text{GPP}}$  and  $R_E$  of 2003 and 2004 are shown in Fig. 7. Seasonal dynamics in these 2 years were similar. The years can be divided into four characteristic periods in terms of  $F_{\text{NEE}}$ . On

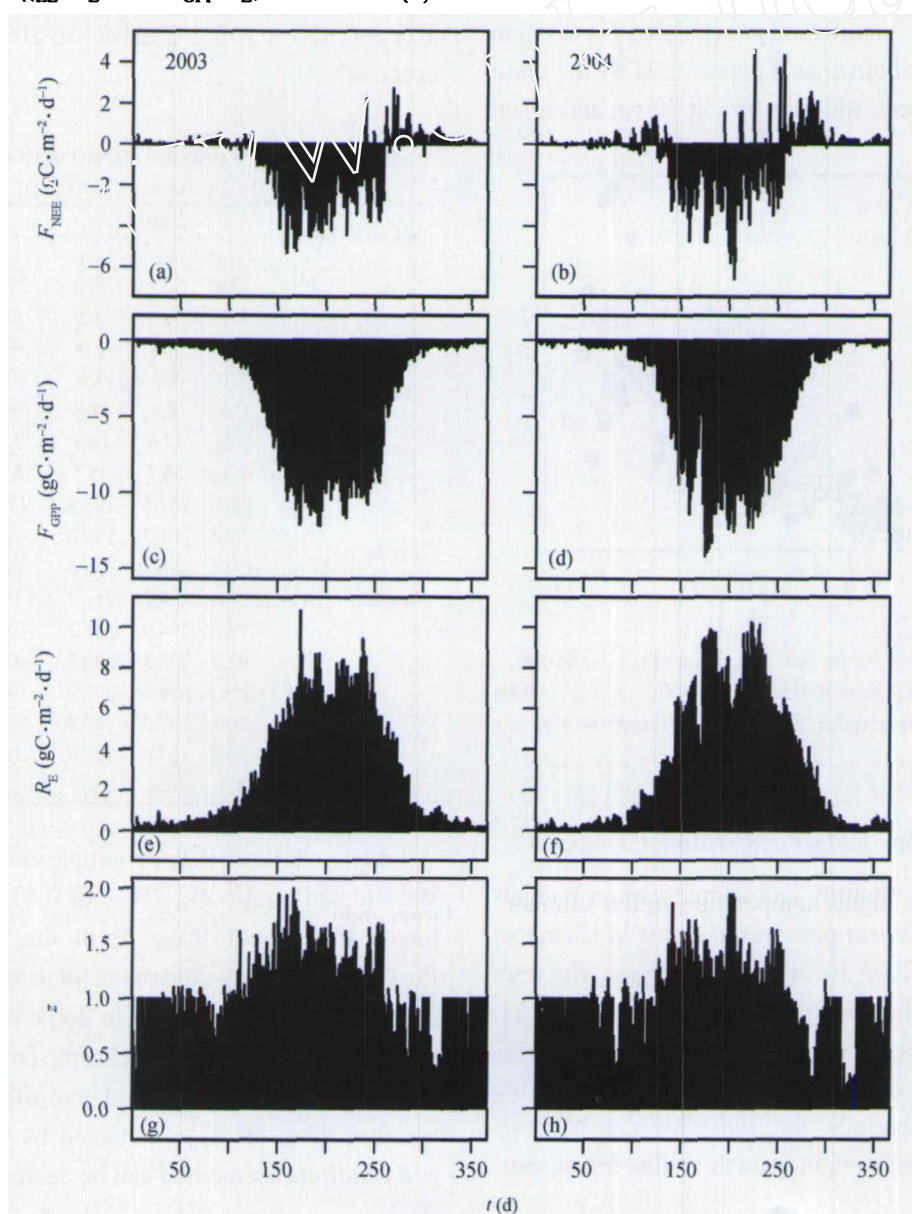


Fig. 7. Seasonal and annual dynamics of  $F_{\text{NEE}}$  ((a), (b)),  $F_{\text{GPP}}$  ((c), (d)),  $R_E$  ((e), (f)) and  $Z$  ((g), (h)).



the whole, they correspond to the meteorological seasons.

In winter, from early October to later April, low soil surface moisture seriously constrained the activities of microbes and soil respiration was very weak even though thick snow cover kept soil temperature above  $-5^{\circ}\text{C}$ . In general, the ecosystem emitted CO<sub>2</sub> while there was weak photosynthesis supported by an abundant water supply in the roots zone. The 210 days of winter accounted for 14.5% and 13.5% of  $R_E$  and 9.3% and 8.1% of  $F_{GPP}$  in 2003 and 2004, respectively.  $R_E$  and  $F_{GPP}$  in the winter of 2004 were less than that of 2003 except for October. This may have been caused by lower winter soil temperature in 2004 (Fig. 2(e)).

In spring, from late April to late May, ecosystem carbon metabolism rapidly increased in magnitude which was consistent with the quick increase in  $L_{AI}$  and temperature. This ecosystem was carbon source during this period.

Summer, from June to August, exerts the most influence on the ecosystem carbon balance. There was a significant difference in carbon metabolism between the two years of the study. Summer  $F_{NEE}$  was  $-255.4$  and  $193.3 \text{ g C}\cdot\text{m}^{-2}$  in 2003 and 2004, respectively. The 90 days of summer accounted for 66.9% and 68.9% of  $F_{GPP}$  and 60.4% and 62.1% of  $R_E$  in 2003 and 2004, respectively.

The peak of daily integrated  $F_{GPP}$  in 2004 ( $14.5 \text{ g C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ) was higher than that of 2003 ( $12.4 \text{ g C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ).  $V_{PD}$  and temperature were the controlling factors for ecosystem production efficiency while  $L_{AI}$  changed very little during growth periods. Compensation between temperature and precipitation caused the difference in  $V_{PD}$  to be non-significant between these 2 growth seasons (Fig. 2(f)). The cause for the higher production efficiency in 2004 (Figs. 4 and 5) may have been the higher temperature in the summer of 2004.

The peak of daily integrated  $R_E$  in 2004 ( $10.3 \text{ g C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ) was higher than that of 2003 ( $9.5 \text{ g C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ). Possible explanations include (i) soil temperature is the controlling factor for summer total ecosystem respiration and summer soil temperature in 2004 was higher than that of 2003; (ii) Litter fall in 2003,  $440 \text{ kg}\cdot\text{ha}^{-1}$ , was higher than that of 2002, 400

$\text{kg}\cdot\text{ha}^{-1}$ . This means that, and material for decomposition in 2004 was greater than in 2003; (iii) summer precipitation in 2004 (353.3 mm) was higher than in 2003 (314.8 mm) and the number of days without rain in the summer of 2004 (28 days) was higher than in 2003 (25 days). It is possible that stronger precipitation intensity in 2004 pumped more CO<sub>2</sub> from the soil<sup>[33,34]</sup>.

From September onward,  $F_{GPP}$  and  $R_E$  gradually declined with air temperature and  $L_{AI}$ . There was not a significant difference in total ecosystem respiration between 2003 and 2004. Stronger  $Q_{PPFD}$  and higher  $L_{AI}$  may explain why  $F_{GPP}$  was higher in 2003 than in 2004. This significant difference in  $F_{GPP}$  caused the ecosystem to be carbon source in September 2003 and a sink in the corresponding period of 2004.

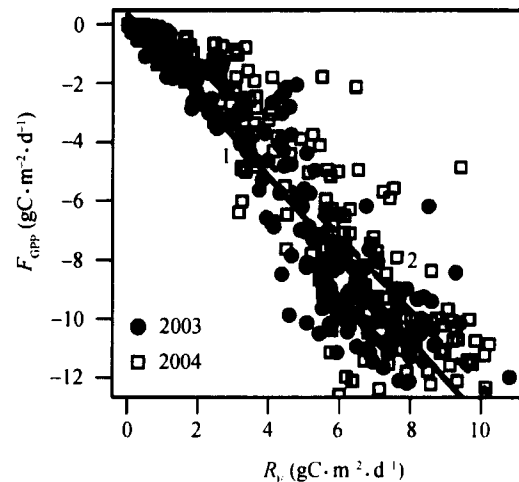


Fig. 8. Relationship between  $F_{GPP}$  and  $R_E$ . 1(solid line): fitted function for 2003,  $F_{GPP} = 0.33 - 1.38 \times R_E$ ,  $A-R^2 = 0.93$ ; 2(dashed line): fitted function for 2004,  $F_{GPP} = 0.32 - 1.25 \times R_E$ ,  $A-R^2 = 0.91$ .

Evidences to estimate  $R_E$  with  $F_{GPP}$  did exist although there were only a few reports<sup>[34, 40]</sup>. Fig. 8 shows the significant relationship between  $F_{GPP}$  and  $R_E$  in this forest ecosystem. The significance is even larger than that between  $R_E$  and soil temperature (Fig. 6). The peak daily values of  $R_E$  did not correspond to days with the highest  $F_{GPP}$  values. Rather, the days with highest  $R_E$  occurred later than that of  $F_{GPP}$ , consistent with other reports<sup>[33,34, 41]</sup>. This delay may be caused by the lag between metabolism processes of photosynthesis and plant respiration<sup>[42]</sup> which accounted for 60.7% of total ecosystem respiration<sup>[1][43]</sup>.

1) Liu Y. Study on soil carbon efflux in the typical forest ecosystems of Changbai Mountains. Ph.D. Thesis, Chinese Academy of Sciences, P.R.China, 2005

### 3 Conclusions

This paper reports the carbon exchange measurement above a 200 year-old Chinese broad-leaved Korean pine mixed forest in Changbai Mountains with eddy-covariance technique from 2003 to 2004. Given the importance of the world's old-growth forests as a major terrestrial carbon store, this study will help to reduce the uncertainties in carbon accounting.

$L_{AI}$  and soil temperature determined the seasonal and annual dynamics of  $F_{GPP}$  and  $R_E$ , respectively.  $V_{PD}$  and air temperature regulated ecosystem photosynthesis at finer scales during growing seasons. Water condition at the root zone exerted a significant influence on ecosystem maintenance carbon metabolism in winter.

The forest was a net sink of atmospheric  $CO_2$  and sequestered  $-449 \text{ g C}\cdot\text{m}^{-2}$  during the study period,  $-278$  and  $-171 \text{ g C}\cdot\text{m}^{-2}$  for 2003 and 2004, respectively.  $F_{GPP}$  and  $F_{RE}$  over 2003 and 2004 were  $-1332$ ,  $-1294 \text{ g C}\cdot\text{m}^{-2}$  and  $1054$ ,  $1124 \text{ g C}\cdot\text{m}^{-2}$ , respectively. This study shows that old-growth forests can be strong net carbon sinks of atmospheric  $CO_2$ .

There was significant seasonal and annual variation in carbon metabolism for the regulation of environmental factors. In winter, there was weak photosynthesis and the ecosystem emitted  $CO_2$  on average. Carbon exchanges were active in spring and fall but contributed little to carbon sequestration of the entire year; the ecosystem captured and emitted almost same amount of  $CO_2$  during these periods. The summer is the most significant season as far as ecosystem carbon balance is concerned. The 90 days of summer accounted for 66.9, 68.9% of  $F_{GPP}$  and 60.4, 62.1% of  $R_E$  of the entire year.

**Acknowledgements** This study was supported by the State Key Basic Research Project (Grant No. 2002CB412502), the Innovation Study Key Project of the Chinese Academy of Sciences (Grant No. KZCX1-SW-01-01), the Young Scientist Project of National Natural Sciences Foundation (Grant No. 30500079) and the Key Project of National Natural Sciences Foundation (Grant No. 90411020).

### References

- 1 Tans P P, Fung I Y, Takahashi T. Observational constraints on the global atmospheric  $CO_2$  budget. *Science*, 1990, 247 : 1431 — 1438
- 2 Francey R J, Tans P P, Allison C E, et al. Changes in oceanic and terrestrial carbon uptake since 1982. *Nature*, 1995, 373: 326 — 330
- 3 Keeling R F, Piper S C, Heimann M. Global and hemispheric  $CO_2$  sinks deduced from changes in atmospheric  $CO_2$  concentration. *Nature*, 1996, 381: 218 — 221
- 4 Fan S, Gloor M, Mahlman J, et al. A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models. *Science*, 1998, 282: 442 — 446
- 5 Jarvis P G. Atmospheric carbon dioxide and forests. *Philosophical Transactions of the Royal Society of London, Series B*, 1989, 324: 369 — 392
- 6 McIlroy J M, Prentice I C, Farquhar G D, et al. Terrestrial biotic responses to environmental change and feedbacks to climate. In: Houghton J T, et al., eds. *Climate Change 1995: The Science of Climate Change*. New York: Cambridge University Press, 1996. 444 — 481
- 7 Carey E V, Sala A, Keane R, et al. Are old forests underestimated as global carbon sinks? *Global Change Biology*, 2001, 7: 339 — 344
- 8 Buchmann N, Schulze E D. Net  $CO_2$  and  $H_2O$  fluxes of terrestrial ecosystems. *Global Biogeochemical Cycles in the Climate System*, 1999, 13/3: 751 — 760
- 9 Hollinger D Y, Goltz S M, Davidson E A, et al. Seasonal patterns and environmental control of carbon dioxide and water vapour exchange in an ecotonal boreal forest. *Global Change Biology*, 1999, 5: 891 — 902
- 10 Janssens I A, Lankreijer H, Matteucci G, et al. Productivity overshadows temperature in determining soil and ecosystem respiration across European forests. *Global Change Biology*, 2001, 7: 269 — 278
- 11 Chen J Q, Falk M, Euskirchen E, et al. Biophysical controls of carbon flows in three successional Douglas-fir stands based on eddy-covariance measurements. *Tree Physiology*, 2002, 22: 169 — 177
- 12 Anthoni P M, Unsworth M H, Law B E, et al. Seasonal differences in carbon and water vapor exchange in young and old-growth ponderosa pine ecosystems. *Agricultural and Forest Meteorology*, 2002, 111: 203 — 222
- 13 Knohl A, Schulze E D, Kolle O, et al. Large carbon uptake by an unmanaged 250 year-old deciduous forest in Central Germany. *Agricultural and Forest Meteorology*, 2003, 118: 151 — 167
- 14 Kurpius M R, Irvine J, Law B E, et al. The influence of stand development on annual carbon exchange in ponderosa pine in eastern Oregon. *Eos Trans. AGU*, 2003, 84 (46), Fall Meet. Suppl. Abstract B21H-02
- 15 Law B E, Thornton P E, Irvine J, et al. Carbon storage and fluxes in ponderosa pine forests at different developmental stages. *Global Change Biology*, 2001, 7: 755 — 777
- 16 Paw U K T, Falk M. Carbon flux partitioning in an old-growth forest: Study of seasonal and interannual variation. *Eos Trans.*

- AGU, 2003, 84 (46): Fall Meet. Suppl, Abstract B51D-0989
- 17 Yang H X, Wang B N, Han J X. Quantitative classification of plant species in broad-leaved Korean pine mixed forest on northern slope of Changbai Mountains. *Research of Forest Ecosystem*, 1985, 5: 15 — 30
  - 18 Wang Z. Main forest types and characteristics of community structure on the northern slope of Changbai Mountains. *Research of Forest Ecosystem*, 1980, 1: 1 — 8
  - 19 Aubinet M, Heinesch B, Longdoz B. Estimation of the carbon sequestration by a heterogeneous forest: Night flux corrections, heterogeneity of the site and inter-annual variability. *Global Change Biology*, 2002, 8: 1053 — 1071
  - 20 Baldocchi D D, Finnigan J, Wilson K, et al. On measuring net ecosystem carbon exchange over tall vegetation on complex terrain. *Boundary-Layer Meteorology*, 2000, 96: 257 — 291
  - 21 Massman W J, Lee X H. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. *Agricultural and Forest Meteorology*, 2002, 113: 121 — 144
  - 22 Lee X H. On micrometeorological observations of surface-air exchange over tall vegetation. *Agricultural and Forest Meteorology*, 1998, 91: 39 — 49
  - 23 Finnigan J J. A comment on the paper by Lee (1988): "On micrometeorological observations of surface-air exchange over tall vegetation". *Agricultural and Forest Meteorology*, 1999, 97: 55 — 64
  - 24 Paw U K T, Baldocchi D D, Meyers T P, et al. Correction of eddy-covariance measurements incorporating both advective effects and density fluxes. *Boundary-Layer Meteorology*, 2000, 97: 487 — 511
  - 25 Aubinet M, Heinesch B, Yernaux M. Horizontal and vertical CO<sub>2</sub> advection in a sloping forest. *Boundary-Layer Meteorology*, 2003, 108: 397 — 417
  - 26 Feigenwinter C, Bernhofer C, Vogt R. The influence of advection on the short term CO<sub>2</sub> - budget in and above a forest canopy. *Boundary-Layer Meteorology*, 2004, 113: 201 — 224
  - 27 Staebler R M, Fitzjarrald D R. Observing subcanopy CO<sub>2</sub> advection. *Agricultural and Forest Meteorology*, 2004, 122: 139 — 156
  - 28 Zhang J H, Han S J, Sun X M, et al. UU<sub>z</sub> filtering of nighttime net ecosystem CO<sub>2</sub> exchange flux over forest canopy under strong wind in wintertime. *Sci China Ser D-Earth Sci*, 2004, 34(Suppl. II): 77 — 83
  - 29 R Development Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, 2005, URL <http://www.R-project.org>
  - 30 Falge E, Baldocchi D, Olson R, et al. Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology*, 2001, 107: 43 — 69
  - 31 Lloyd J, Taylor J A. On the temperature dependence of soil respiration. *Function Ecology*, 1994, 8: 315 — 323
  - 32 Timur V E. Minpack.lm: R interface for MINPACK least squares optimization library. R package version 1.0 - 5, 2005
  - 33 Flanagan L B, Wever L A, Carson P J. Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate grassland. *Global Change Biology*, 2002, 8: 599 — 615
  - 34 Xu L K, Baldocchi D D. Seasonal variations in carbon dioxide exchange over a Mediterranean annual grassland in California. *Agricultural and Forest Meteorology*, 2004, 123: 79 — 96
  - 35 Freeland R O. Apparent photosynthesis in some conifers during winter. *Plant Physiology*, 1944, 19: 179 — 185
  - 36 Cheng B R, Xu G S, Ding G F, et al. Litter fall and biological cycling intensity in Coniferous forest and broad leaved Korean pine forest on the northern slope of Changbai Mountains. *Research of Forest Ecosystem*, 1984, 4: 19 — 24
  - 37 Waring R H, Landsberg J J, Williams M. Net primary production of forests: A constant fraction of gross primary production? *Tree Physiology*, 1998, 18: 129 — 134
  - 38 Wang M, Han S J, Wang Y S. Important factors controlling rate of soil respiration in Korean pine broad leaved mixed forest. *Chinese Journal of Ecology*, 2004, 23: 24 — 29
  - 39 Guan D, Wu J, Zhao X, et al. CO<sub>2</sub> flux over an old, temperate mixed forest in North-eastern China. *Agricultural and Forest Meteorology*, 2006, 137: 138 — 149.
  - 40 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
  - 41 Bowling D R, McDowell N, Bond B, et al. <sup>13</sup>C content of ecosystem respiration is linked to precipitation and vapor pressure deficit. *Oecologia*, 2002, 131: 113 — 124
  - 42 Tang J, Baldocchi D D, Xu L. Tree photosynthesis modulates soil respiration on a diurnal time scale. *Global Change Biology*, 2005, 11: 1298 — 1304
  - 43 Wang M, Guan D, Wang Y, et al. Estimate of productivity in ecosystem of the broadleaved -Korean pine mixed forest in Changbai Mountain. *Sci China Ser D-Earth Sci*, 2006, 49(Suppl I): 74 — 88