

Seasonal variation in carbon dioxide exchange over a 200-year-old Chinese broad-leaved Korean pine mixed forest

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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 of Forest Ecosystem Open Research Station of Changbai Mountains (128°28'E and 42°24'N, Jilin Province, PR China), Chinese Academy of Sciences, since August 2002. This paper reports the result on (1) phase and amplitude of ecosystem CO₂ uptake and release and (2) sink/source status on the data obtained with open-path eddy-covariance system and CO₂ profile measurement system from August 2002 to August 2003. Corrections due to storage and friction velocity were applied to the eddy carbon flux. Behavior of pressure flux, neglected in common WPL correction, was analyzed to develop acceptable u^* range in dormant periods.

The ecosystem was a net sink of atmospheric CO₂ and sequestered $-308 \pm 116 \text{ g C m}^{-2}$ during the study period. The estimates of gross carbon gain and loss at this forest were -1432 ± 216 and $-1124 \pm 181 \text{ g C m}^{-2}$ separately. The seasonal trend of gross primary productivity (F_{GPP}) and respiration (R_{E}) followed closely the change in vegetation absorption index (V_{AI}) and temperature. The summer is the most significant season as far as ecosystem carbon balance is concerned. The net ecosystem exchange (F_{NEE}) during this period was about $-298.0 \pm 65.2 \text{ g C m}^{-2}$. The 90 days of summer contributed 67.0% of F_{GPP} , 58.9% of R_{E} of whole year. This study shows that old-growth forest can be strong net carbon sink of atmospheric CO₂.

There are uncertainties in estimate of annual carbon fluxes with eddy-covariance method. More work on advection and pressure fluxes is warranted.

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1. Introduction

Forests have been proposed as possible sinks of the 'missing' atmospheric carbon that is not accounted for by global carbon cycle models (Tans et al., 1990; Francey et al., 1995; Keeling et al., 1996; Fan et al., 1998). While young and recovering forest have obvious

potential as carbon sinks, forests older than approximately 100 years are thought to be in equilibrium between carbon uptake and total ecosystem respiration (TER), sequestering little and are generally considered to be insignificant carbon sinks (Jarvis, 1989; Melillo et al., 1996).

In contrast research by Carey et al. (2001) 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

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Nomenclature

Meteorological variables

| | |
|------------|---|
| L | MO length scale (m) |
| P_a | barometric pressure (kPa) |
| Q_{PPFD} | photosynthetic photon flux density ($\mu\text{mol m}^{-2} \text{s}^{-1}$) |
| T_a | air temperature ($^{\circ}\text{C}$) |
| T_s | soil temperature ($^{\circ}\text{C}$) |
| u | wind speed (m s^{-1}) |
| u_* | friction velocity (m s^{-1}) |
| V_{PD} | vapor pressure deficit (kPa) |

Flux variables

| | |
|------------------|--|
| F_{GPP} | gross primary production (g C m^{-2}) |
| F_{NEE} | net ecosystem exchange of CO_2 , calculated as the sum of the CO_2 flux determined by eddy-covariance and the CO_2 storage change in the canopy air layer (the sign convention of F_{NEE} is from the perspective of the atmosphere, i.e. a negative sign means the atmosphere is losing carbon) ($\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$ or $\text{g C m}^{-2} \text{yr}^{-1}$) |
| F_{NPP} | net primary production ($\text{g C m}^{-2} \text{yr}^{-1}$) |
| F_{RE} | ecosystem respiration ($\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$ or $\text{g C m}^{-2} \text{yr}^{-1}$) |
| $F_{RE,day}$ | ecosystem respiration during daytime ($\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$) |
| $F_{RE,night}$ | ecosystem respiration during nighttime ($\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$) |
| $F_{RE,T_{ref}}$ | F_{RE} at reference temperature T_{ref} ($\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$) |
| $F_{WPL,M\&L}$ | WPL correction term including pressure contribution (Massman and Lee, 2002) ($\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$) |
| R_s | soil respiration ($\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$ or g C m^{-2}) |
| γ_s | the contribution of soil surface efflux to ecosystem respiration |

Other variables

| | |
|----------|---|
| a_1 | parameter of Eq. (6) and may be interpreted as the maximum photosynthetic uptake ($\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$) |
| a_2 | parameter of Eq. (6) and may be interpreted as the light level (Q_{PPFD}) corresponding to half the maximum photosynthesis rate |
| D_{WG} | annual biomass dry weight growth ($\text{g m}^{-2} \text{yr}^{-1}$) |

| | |
|------------------|---|
| E_a | parameter of Eq. (7) and can be interpreted as the activation energy (J mol^{-1}) |
| I_C | carbon content (%) |
| k | the extinction coefficient for diffuse light |
| R | the gas constant ($8.314 \text{ J K}^{-1} \text{ mol}^{-1}$) |
| R_D | parameter of Eq. (6) and may be interpreted as the mean of daytime respiration |
| V_{AI} | vegetation absorption index, deduced from Q_{PPFD} measurements above and below canopy |
| z_r | the height where eddy-covariance systems installed (m) |
| γ_{wc} | ratio of pressure flux to eddy CO_2 flux |
| μ_v | the ratio of the molecular mass of dry air to the molecular mass of water vapor |
| $\bar{\rho}_c$ | the mean ambient CO_2 density (mg m^{-3}) |
| τ_c | the canopy transmittance, estimated as the ratio of the averaged flux density measured below the canopy to the flux density measured above canopy |
| $\bar{\chi}_v$ | the volumetric mixing ratio for water vapor |
| $\bar{\omega}_c$ | the mean mass mixing ratio for CO_2 |

state carbon flux and can continue to act as a net sink for atmospheric carbon dioxide over several decades or longer (Buchmann and Schulze, 1999; Hollinger et al., 1999; Janssens et al., 2001; Chen et al., 2002). 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 forest have been conducted, and results varied depending on conditions (Hollinger et al., 1999; Anthoni et al., 2002; Chen et al., 2002; Knohl et al., 2003; Kurpius et al., 2003; Law et al., 2003; Paw and Falk, 2003). 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, the study on 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 mountain mixed broad-leaved and Korean pine forest, which is the dominant vegetation type of north-east of China (Institute of Applied Ecology, Chinese Academy of Sciences, 1980), is about 200 years old (Yang et al., 1985). In this paper, we

use 1 year of eddy-covariance CO₂ fluxes over the canopy and supporting meteorological data since August 2002, as part of the ChinaFLUX project, to document: (1) phase and amplitude of ecosystem CO₂ uptake and release and (2) sink/source status of an old-growth, broad-leaved and Korean pine forest stand at Changbai.

2. Materials and methods

2.1. 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, PR China), Chinese Academy of Sciences, since August 2002. 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 dominant wind direction is SW. There are villages and towns, but no industrial activities in the NE direction. The influence of residential activities cannot be omitted. The flux data were treated as gaps when wind blew from this direction.

The annual mean temperature is 0.9–4.0 °C, total precipitation is 600–810 mm yr⁻¹ (evaluated over a period of 20 years). 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* and 135 other species. The mean canopy height is 26 m. A dense understory, consisting of multi-species broad-leaved shrub, has a height of 0.5–2 m. The peak leaf area index is about 6.1. The soil is classified as dark brown forest soil originating from volcanic ashes. The landscape is very flat. For advanced detailed site information see Wang (1980), Sun and Zhao (1995) and Dai et al. (2002).

2.2. Instruments and measurements

Net ecosystem exchange (NEE, or F_{NEE}) was determined from the measurements of eddy-covariance flux and CO₂ concentration profiles.

Two open-path eddy-covariance measurement systems were installed at 2.94 and 40 m separately on a 62.8 m tower. Fluctuations in CO₂/H₂O were measured by a Li7500 open-path sensor (IRGA, Li-Cor, USA) and a 3D ultrasonic anemometer (CSAT3, Campbell Scientific, USA) was used to measure wind velocities and temperature. Both instruments were sampled at

10 Hz. Half-hourly fluxes are calculated on-line and collected by CR5000 data logger (Campbell Scientific, USA).

Measurements with a close-path eddy-covariance system started in September 2003. Sample air is taken in at a rate of 26 l min⁻¹ near the ultrasonic anemometer at 40 m to an IRGA (Li7000, Li-Cor, USA). The 50 m long tubing is made of high-density polyethylene bonded to an overlapped aluminum tape having an ethylene copolymer coating (1/2 in. i.d.). Close-path and open-path systems are installed on the same tower and orientation. Calibration of the IRGA against standard gas is done automatically every 2 h.

A 7-level CO₂ profile is 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 h.

Meteorological and soil sensors are 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) along a 200 m transect in southwest direction from the tower weekly since May 2003. For a continuous record of canopy structure, a global vegetation absorption index (V_{AI} , Aubinet et al., 2002) was deduced from Q_{PPFD} measurements above and below canopy. Six Q_{PPFD} sensors (LQS70-10S, Apogee, USA) were installed below the forest canopy around the flux tower. The canopy transmittance (τ_c) was estimated as the ratio of the averaged flux density measured below the canopy to the flux density measured above canopy. Only measurements taken between 10:00 and 14:00 under diffuse radiation conditions were considered. The V_{AI} was deduced as

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

where k is the extinction coefficient for diffuse light (Goudriaan and Van Laar, 1994). A full list of symbols is given in Nomenclature.

2.3. Flux calculation

2.3.1. Long-term CO₂ flux measurement theory

At present, net ecosystem CO₂ exchange (F_{NEE}) is assessed, by members of the meteorological community, as the sum of eddy-covariance measurements (F_c) at height z_r and the storage of CO₂ (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 (Baldocchi et al., 2000; Massman and Lee, 2002).

Several groups have recently addressed the advection terms by measurement or simulation (Lee, 1998; Finnigan, 1999; Baldocchi et al., 2000; Paw et al., 2000; Finnigan et al., 2003; Aubinet et al., 2003; Feigenwinter et al., 2004; Staebler and Fitzjarrald, 2004). All these studies agree that the neglected advective processes are responsible for the underestimation of nighttime fluxes, rather than instrumental or eddy flux measurements errors. The contribution of advection to the mass budget is highly variable and site-dependent.

At present there are still methodological problems and potential deficits in the estimation of the advection terms (Lee, 1998; Aubinet et al., 2003; Feigenwinter et al., 2004). Mass balance approaches are not precise enough to allow reliable flux corrections. In waiting for a physically based correction, the u_* correction seems the best compromise.

In this study, net ecosystem exchange between forest and atmosphere was assessed with the following equation:

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

Here, the first term on the RHS is the storage term (F_s), the second is the eddy CO₂ 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 CO₂ profile data. Due to a failure of the CO₂ profile system, the storage term from October 2002 to late March 2003 was evaluated only based on the two point CO₂ concentrations from the open-path IRGA of the eddy-covariance systems.

Standard micrometeorological software was applied to the post-processing of the flux data. The 3D sonic anemometer tilt correction (coordinate rotation) was carried out monthly with the planar fit (PFT) method (Paw et al., 2000; Wilczak et al., 2001; Finnigan, 2004). The approach of Massman (2000) and Moore (1986)

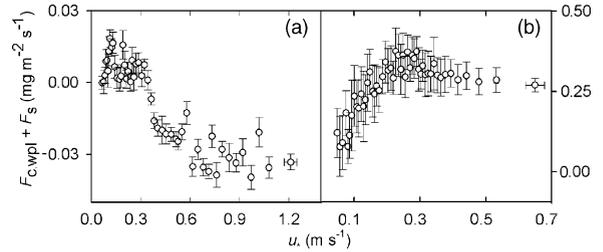


Fig. 1. Dependency of nighttime F_{NEE} on turbulence, expressed as friction velocity (u_*): (a) in peak dormant seasons (from day 330 of year 2002 to day 65 of year 2003) and (b) in peak growth seasons (from day 165 to day 215 of year 2003). Data are bin averaged with an equal number of data points per bin. Error bars are estimated confidence interval of the average.

were applied to the eddy fluxes from close-path and open-path systems separately to correct the frequency losses. Webb–Pearman–Leuning corrections (Webb et al., 1980) were applied to the eddy flux from the open-path system.

2.3.2. Friction velocity (u_*) correction

A common phenomenon at long-term flux sites is that turbulent CO₂ flux approaches zero as the level of turbulence, measured by the friction velocity, drops to zero (Goulden et al., 1996). Wofsy et al. (1993) and Goulden et al. (1996) suggest that biological source strength of CO₂ is not a function of air movement, implying that the storage corrected eddy flux should be independent of u_* , if the 1D approach accurately approximates the surface layer mass balance. Our data (Fig. 1a and b) and numerous other observations show however that storage correction does not bring the flux to the same level as observed at high wind conditions (Massman and Lee, 2002).

To determine turbulence conditions that would lead to acceptable nighttime flux data, the curve of nighttime respiration flux vs. measurement of turbulence (u_* , friction velocity) was analyzed as shown in Fig. 1. Data were selected from the peak non-growth period (day 330 of year 2002 to day 65 of year 2003) and growth period (days 165–235 of year 2003) to minimize the effects from other variables on respiration (such as temperature, etc.). The nighttime respiration fluxes increase with u_* , reach a plateau, and then decrease with the increasing friction velocity, even become negative in the non-growth period.

In the non-growth period, a u_* threshold around 0.05 m s^{-1} (Fig. 1a) by Moving Point Test (MPT) technology (Gu et al., 2004), an automated statistical method to determine the friction velocity (u_*) thresholds in nighttime eddy flux filtering, can be applied to correct

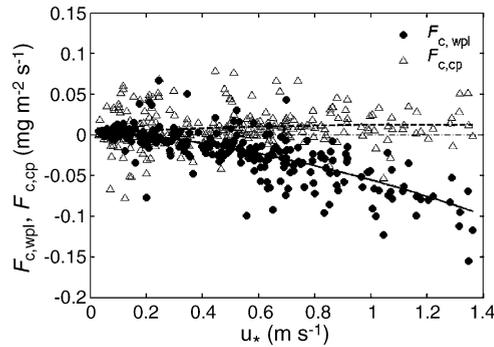


Fig. 2. Difference between the influence of friction velocity on nighttime carbon fluxes by open-path system ($F_{c,WPL}$) and close-path system ($F_{c,CP}$) in December 2003.

the underestimation of night respiration by low turbulent exchange. This threshold is $<0.17 \text{ m s}^{-1}$ for the peak growth period (Fig. 1b).

There are several causes for the decline of nighttime respiration flux under strong wind, such as 3D airflow and pressure variation etc (Massman and Lee, 2002). The big difference of performance between the WPL-corrected CO_2 eddy flux from the open-path system ($F_{c,WPL}$) and CO_2 eddy flux from the close-path system ($F_{c,CP}$) with friction velocity (Fig. 2) imply other important causes for the negative night flux besides the 3D airflow in wintertime.

Measurements and simulations show that pressure fluctuations are extremely important in the budgets of turbulent kinetic and shear stress (McBean and Elliott, 1975; Wilczak et al., 1999; Gotoh and Nakano, 2003; Miles et al., 2004), and the magnitude of pressure fluctuations increase with increasing wind velocity (McBean and Elliott, 1975; Sigmon et al., 1983). Observations in southern Wyoming USA at a height of 27.1 m above the ground over a forest of approximately 18 m height showed that pressure flux contributes significantly to the WPL term for CO_2 or any other trace gas under very turbulent atmospheric conditions (Massman and Lee, 2002), although it was always

neglected (Webb et al., 1980; Fuehrer and Friehe, 2002).

Massman and Lee (2002) deduced a new WPL correction function including the pressure flux term:

$$F_{WPL,M\&L} = \bar{\rho}_c (1 + \bar{\chi}_v) \left[\frac{\overline{w'T'_a}}{\bar{T}_a} - \frac{\overline{w'p'_a}}{\bar{p}_a} \right] + \bar{\omega}_c \mu_v \overline{w'\rho'_v} \quad (3)$$

where $\bar{\rho}_c$ is the mean ambient CO_2 density; \bar{p}_a the mean ambient pressure; μ_v the ratio of the molecular mass of dry air to the molecular mass of water vapor; \bar{T}_a the mean ambient atmosphere temperature; $\bar{\chi}_v$ the volumetric mixing ratio for water vapor; and $\bar{\omega}_c$ is the mean mass mixing ratio for CO_2 .

For $\overline{w'p'_a} \leq 0$, the nighttime flux will be underestimated, and the daytime flux will be overestimated under strong wind conditions without the consideration of pressure-induced flux. However, high frequency pressure variation measurements are not available in our station. To minimize the influence of pressure fluctuation, the behavior of pressure flux with increasing wind speed is to be analyzed and acceptable u_* ranges will be developed to filter flux data in the following discussion.

The measurement within and just above a wave boundary layer (WBL) by Wilczak et al. (1999) show that the non-dimensionalized pressure flux is a function of atmospheric stability expressed as z/L and that the non-dimensionalized pressure flux at wave surface is the same order as that just above WBL. The response of non-dimensionalized flux to z/L could be site-specific and it is impossible to be tested in our site and most long-term flux sites, but the agreement between Wilczak et al. (1999) and Massman and Lee (2002) indicates that we have at least an estimate for the order of magnitude of pressure effects in the roughness sublayer over rough surfaces.

It can be ignored that the influence of seasonal foliage development on the pressure fluctuation variance (Sigmon et al., 1983), vertical velocity fluctuation variance (Fig. 3b) and relationships between

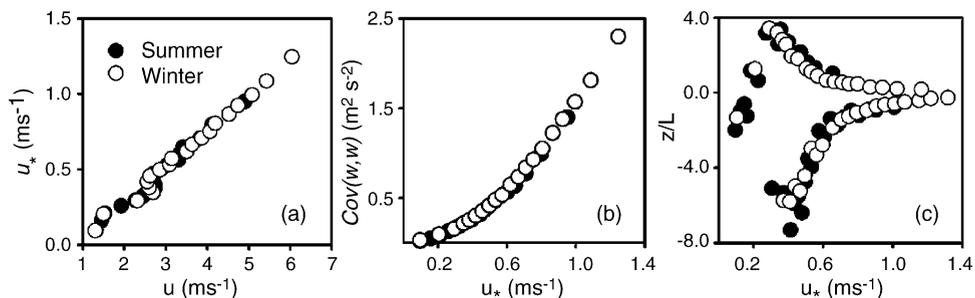


Fig. 3. Relationships between (a) mean wind speed (u) and friction velocity (u_*); (b) friction velocity (u_*) and vertical velocity variance; (c) friction velocity (u_*) and z/L in peak dormant periods and peak growth periods. Data are bin averaged with an equal number of data points per bin.

u_* and z/L (Fig. 3c), u and u_* (Fig. 3a). So Eq. (4) adopted from Fig. 6.2 of Wilczak et al. (1999) can be applied in different seasons:

$$\frac{\overline{w'_a p'_a}}{\rho_a u_*^3} = \xi\left(\frac{z}{L}\right) = \begin{cases} -6.0 & -1 < \frac{z}{L} \leq -0.5 \\ -4.41\left(\frac{z}{L}\right)^2 + 5.67\left(\frac{z}{L}\right) - 1.87 & -0.5 < \frac{z}{L} \leq 0 \\ -1.9 & 0 < \frac{z}{L} \leq 0.5 \end{cases}$$

The influence of pressure fluctuation on $\overline{w'T'_a}$ and $\overline{w'\rho'_v}$, estimated by Eqs. (1) and (2) in Massman and Lee (2002) and Eq. (4), are negligible (<1%). We define the ratio of pressure flux to eddy CO₂ flux (corrected with common WPL terms):

$$\gamma_{wc} = \left| -\frac{\bar{\rho}_c(1 + \bar{\chi}_v)(\overline{w'p'_a}/\bar{p}_a)}{\overline{w'\rho'_c}} \right| = \left| -\frac{\bar{\rho}_a \bar{\rho}_c u_*^3 (1 + \bar{\chi}_v) \xi(z/L)}{\bar{p}_a \overline{w'\rho'_c}} \right| \quad (5)$$

Fig. 4a shows the monthly averaged γ_{wc} between September 2002 and August 2003. The value of γ_{wc} is controlled by the balance between pressure flux and ecosystem activity. The seasonal course of γ_{wc} is very clear, the low ecosystem activity and high pressure flux produced high γ_{wc} in the non-growth period (October–April). The contribution of pressure variation to CO₂ flux is very significant and cannot be neglected, and the $\gamma_{wc} \sim u_*$ curve can be used to determine the u_* correction threshold value in the non-growth period (Fig. 4b). The u_* at breakpoint, determined with 1D continuous wavelet analysis (Coif 4, Mathworks), of nighttime $\gamma_{wc} \sim u_*$ curve is 0.36, in good agreement

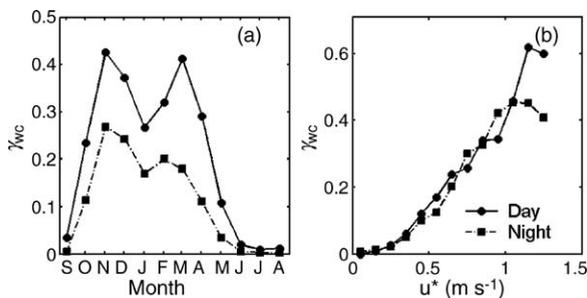


Fig. 4. (a) Year-long course of γ_{wc} and (b) influence of turbulence (expressed as friction velocity (u_*) on γ_{wc} in peak dormant periods (day 330 of year 2002 to day 65 of year 2003). Eqs. (4) and (5) were applied for $-1.0 \leq z/L \leq 0.5$ for whole day and $u_* > 0.05$ at night.

with the right edge of $(F_c + F_s) \sim u_*$ plateau in Fig. 1a. This u_* value can be used as threshold to filter influence of pressure fluctuations under strong windy circumstances. It appears that the dependence of γ_{wc} on u_* at daytime is similar to that at night and the u_* threshold for daytime is 0.37.

In the growth period, night storage-corrected respiration fluxes for $u_* > 0.4$ were lower than that for $0.17 < u_* \leq 0.4$, but still fell into the latter's variation range. This decrease may due to variation of wind direction. We chose to accept all data for $u_* > 0.17$.

The nighttime CO₂ flux F_c and other terms lying in the acceptable turbulence ranges developed in above discussions, $0.05 \leq u_* \leq 0.36$ for dormant periods and $u_* > 0.17$ for growth periods, were reserved for further analysis. Daytime flux terms for $u_* > 0.37$ in dormant periods were filtered out to minimize the influence of pressure fluctuations.

As shown in Fig. 5, the u_* correction corrected the nighttime 'problem' of negative F_{NEE} under strong wind and made the estimates of dormant periods more ecologically reasonable. The very close daily course pattern between u_* -corrected F_{NEE} from open-path system and that from closed-path system proves that our u_* correction is reliable.

2.4. Empirical formulas and gap filling

Missing and rejected data were filled for annual integration and to provide a complete database for other usage. Several strategies were used. Data gaps of 2 h or less were filled by direct interpolation. For longer gaps, empirical formulas describing relationships between Q_{PPFD} , soil temperature and net CO₂ flux were applied

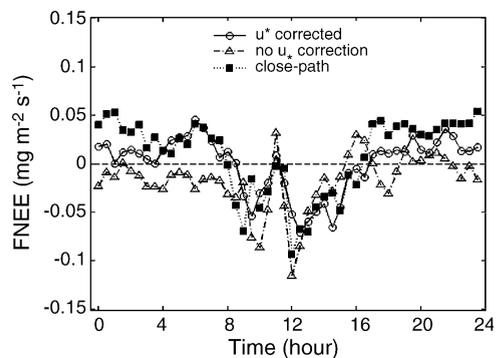


Fig. 5. Monthly averaged daily course of F_{NEE} in December 2003. u_* range for night F_{NEE} from closed-path system was $u_* \geq 0.05$; u_* correction range for night and daytime F_{NEE} from open-path system was $0.05 \leq u_* \leq 0.36$ and $u_* \leq 0.37$ separately.

separately for daytime (Eq. (6)) and nighttime (Eq. (7)). In cases where empirical relationships could not be developed as a result of missing meteorological data, weekly mean diurnal variations were used to fill the missing data (Falge et al., 2001).

Daytime F_{NEE} measurements were subjected to a further criterion of non-precipitating conditions, grouped by hybrid time windows, and fitted to a hyperbolic dependence on light (P_{PPFD}) according to

$$F_{NEE} = \frac{a_1 Q_{PPFD}}{a_2 + Q_{PPFD}} + R_D \quad (6)$$

with fitted parameters a_1 , a_2 and R_D . The value of F_{NEE} at no light ($Q_{PPFD} = 0$) is estimated as R_D , and may be interpreted as the mean of daytime respiration of the time window. The maximum photosynthetic uptake is estimated as a_1 , and the light level (Q_{PPFD}) corresponding to half the maximum photosynthesis rate as a_2 .

To fill in missing data and estimate daytime ecosystem respiration, nighttime valid F_{NEE} were modeled with the following Arrhenius type function (Lloyd and Taylor, 1994):

$$F_{NEE,night} = F_{R_E, T_{ref}} e^{(E_a/R)(1/T_{ref} - 1/T_K)} \quad (7)$$

Here F_{R_E} , T_{ref} and E_a are the fitted parameters, E_a the activation energy in $J mol^{-1}$, and R is the gas constant ($8.314 J K^{-1} mol^{-1}$). T_{ref} is reference temperature and was set to 283.15 K.

Models were fitted by the modified Levenberg–Marquardt method and parameters confidence ranges were estimated with the Monte Carlo method (Matlab, Mathworks).

2.5. Decomposition of F_{NEE} into F_{GPP} and R_E

The F_{NEE} time series were decomposed into R_E and F_{GPP} by Eqs. (6)–(9). 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):

$$F_{GPP} = F_{NEE} - R_E \quad (8)$$

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

$$R_E = R_{E,night} + R_{E,day} \quad (9)$$

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

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

3. Result and discussion

3.1. Seasonal trends in meteorological variables and canopy architecture

The annual course of dominant meteorological variables is given in Fig. 6. Half-hourly averaged T_a reached $25^\circ C$ in summer and lay between 0 and $-20^\circ C$ in winter between late October and early April, with peak minima to $-25^\circ C$. Due to the deep snow-cover, the soil temperature at 5 cm depth varied between 0 and $-3^\circ C$ in the whole winter with several peaks close to $-4^\circ C$, far warmer than air temperature. Soil temperature reached freezing temperature about 1 month later than air temperature, but returned to above $0^\circ C$ simultaneously with the latter.

It seems that there is no water limitation during the whole growth season. Soil water content at the depth of 50 cm was larger than the field capacity (26.9%) all year around. The surface soil (10 and 20 cm) water contents were less than wilting point (12%) only in January and February 2003. Due to the deep snow-cover, surface soil water content kept almost constant during the whole winter. The thaw in late March provided enough water for quick growth of the forest.

Daily maximum of half an hour averaged Q_{PPFD} reached $1800 \mu mol m^{-2} s^{-1}$ in summertime and $800 \mu mol m^{-2} s^{-1}$ in winter.

The global vegetation absorption index (V_{AI}) showed a clear seasonal trend (Fig. 7). Bud burst occurred in early May and LAI reached the maximum in mid July, and began to decrease until late October.

3.2. Response of carbon flux to environmental factors

Photosynthesis is driven by light but there were marked differences in the light response curve among seasons for the evolution of the forest canopy. Fig. 8 presents four curves representative for the seasons. At all times of the year, upward fluxes dominate at low light levels, but with increasing light give way to downward fluxes. The magnitudes of radiation, temperature and F_{NEE} are highest during summer (Fig. 8c), moderate in the spring (Fig. 8b) and autumn (Fig. 8d), and smallest in winter (Fig. 8a).

The dependence of daytime carbon exchange on light was simulated with Eq. (6) for different time

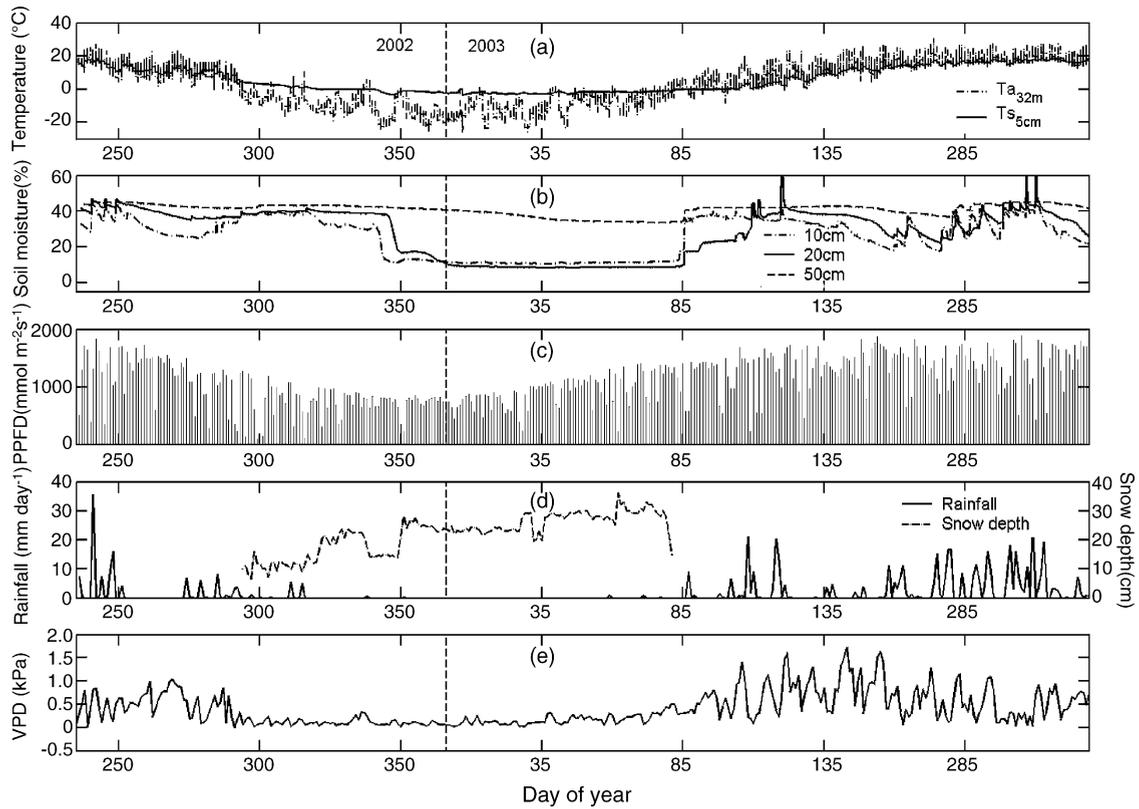


Fig. 6. Year-long course of: (a) air and soil temperature; (b) soil volume water content; (c) Q_{PPFD} ; (d) rainfall and snow depth; (e) V_{PD} .

windows to minimize the confounding effects of soil water content, temperature and forest phenology (Davidson et al., 1998; Luo et al., 1996; Flanagan et al., 2002). The time window is 1 month for winter (November 2002 to March 2003), and 1 week for the rest of the time.

The a_1 in Eq. (6), which can be explained as F_{GPP} at light saturation, separated the influence of other physical variables on ecosystem CO_2 uptake from that

of irradiance and is a good means to analyze the potential relationship between ecosystem carbon uptake and other physical variables. Multiple environmental variables jointly control CO_2 exchange of the ecosystem and strong interactions among these variables result in some difficulty in discerning their individual effects. To minimize the confounding among variables, partial correlation analysis was applied to separate the influence of single factors.

At seasonal scale, the variations in ecosystem CO_2 uptake were highly correlated with the variations in V_{AI} ($p < 0.0001$). The highest rate of F_{GPP} occurred during the period of greatest V_{AI} , and F_{GPP} declined as V_{AI} declined (Fig. 9). The strong correlation between F_{GPP} and V_{AI} has also been reported by others (Flanagan et al., 2002; Xu and Baldocchi, 2004). Partial correlation analysis between the residuals (a_1 minus a_1 predicted from the linear function driven by V_{AI}) and physical variables, including rooting zone soil water content, air and soil temperature and V_{PD} showed that rooting zone soil water content controls F_{GPP} in wintertime when air temperature was very low, V_{PD} is the one in summer when soil water was abundant and temperature was stable (Anthoni et al., 2002). The V_{PD}

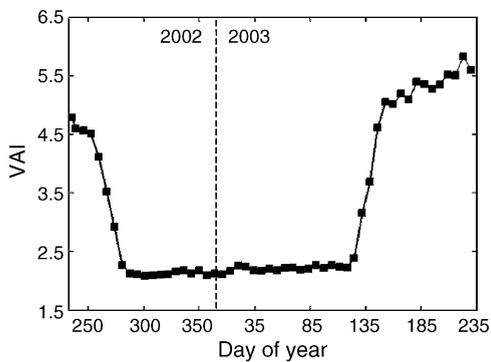


Fig. 7. Seasonal development of V_{AI} from August 2002 to August 2003.

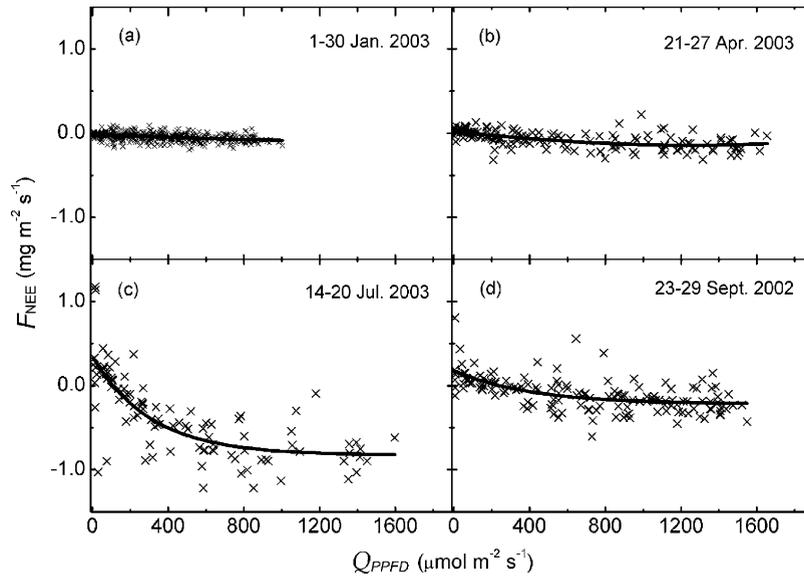


Fig. 8. Example of light response curves of F_{NEE} at different growth stages from August 2002 to August 2003.

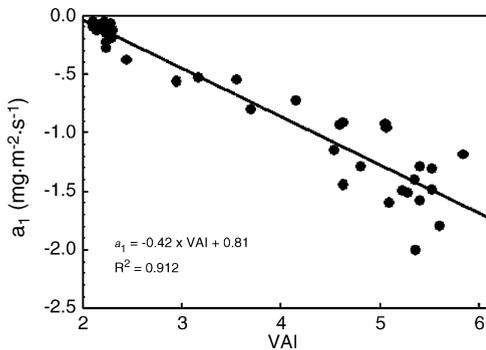


Fig. 9. The relationship between a_1 and VAI .

was highest in spring and autumn and significantly influenced the ecosystem photosynthesis capacity (Table 1).

Parameter R_D in Eq. (6) can be explained as the mean of daytime respiration of each time window and

can be used to analyze the relationship between ecosystem respiration and environmental variables. Soil temperature was the only controlling factor on respiration at seasonal scale ($p < 0.001$). The dependence of ecosystem respiration on temperature may reflect the different temperature sensitivities for autotrophic and heterotrophic respiration and turnover times of the multiple carbon pools (Xu and Baldocchi, 2004).

Partial correlation analysis between residuals (R_D minus predicted R_D from quadratic polynomial driven by soil temperature at 5 cm deep) and other physical variables showed that surface soil moisture is one of the most important limiting factors besides soil temperature in winter, spring and autumn (Table 1). Soil temperature was the only significant driver for ecosystem respiration when surface soil water content was abundant (Table 1).

Table 1
P values of partial correlation analysis between a_1 residuals, R_D residuals and environmental factors

| Seasons | a_1 residuals vs. | | | | R_D residuals vs. | | |
|---------------|---------------------|----------|----------|-------|---------------------|----------|-------|
| | T_s | S_{50} | V_{PD} | T_a | S_{10} | S_{50} | T_a |
| Winter | 0.65 | 0.008* | 0.95 | 0.99 | 0.033* | 0.11 | 0.25 |
| Summer | 0.37 | 0.18 | 0.002* | 0.46 | 0.063* | 0.76 | 0.61 |
| Spring/autumn | 0.84 | 0.16 | 0.067* | 0.56 | 0.81 | 0.79 | 0.81 |

Note: T_s , soil temperature at 5 cm depth; S_{10} , soil volume water content at 10 cm depth; S_{50} , soil volume water content at 50 cm depth; V_{PD} , V_{PD} at 40 m height; T_a , atmospheric temperature at 40 m height.

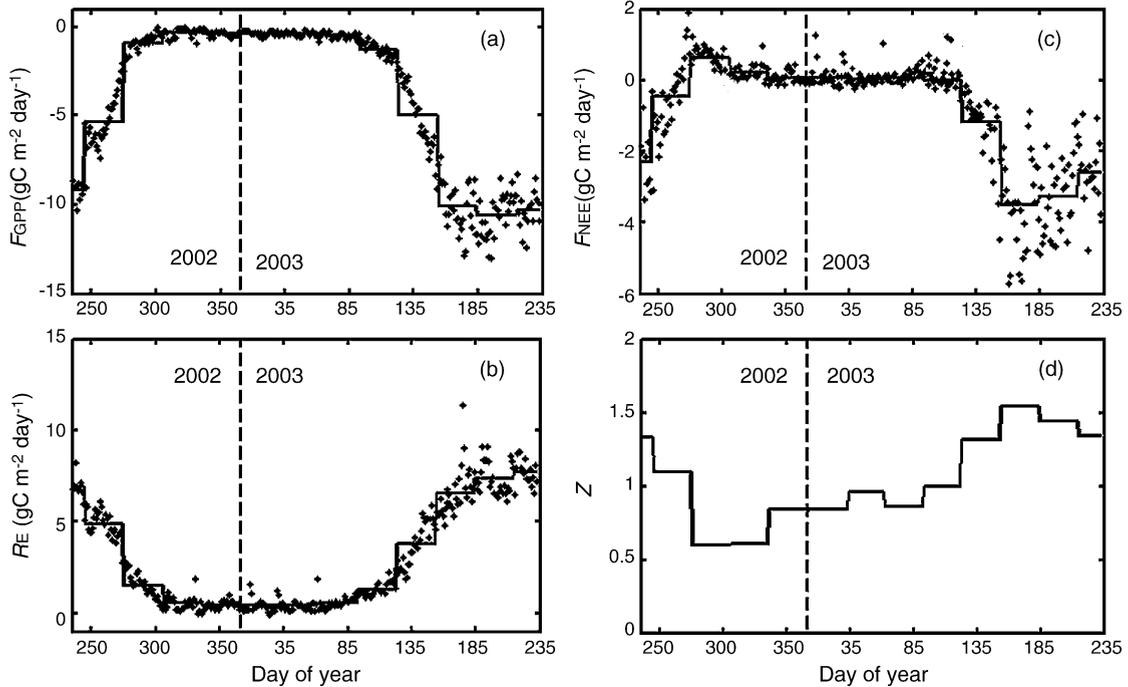


Fig. 10. Seasonal course of daily-integrated F_{GPP} (a), R_E (b), F_{NEE} (c) and monthly averaged z (d). The stair line is the monthly mean value of the corresponding variable.

3.3. Annual course of daily-integrated flux

The measurements of F_{NEE} and calculated F_{GPP} and R_E were integrated daily to provide daily values of carbon exchange (Fig. 10a–c). The year can be divided into four characteristic periods in terms of F_{NEE} , we will call ‘winter’, ‘spring’, ‘summer’ and ‘autumn’ for convenience, even if they do not correspond exactly to the meteorological seasons.

During the winter, which extends from early October to late March (day 275 of year 2002 to day 85 of year 2003), the forest emitted CO₂ in general. The leaf area was constant and F_{GPP} was still less than zero, which is consistent with Fig. 8a (Zhang et al., 2003; Dolman et al., 2002). The close daily pattern between the u_* filtered flux from open-path system and flux from the closed-path system (Fig. 5) eliminated the doubt on technique, although there are physical or physiological reasons to be explored. Due to the cold weather and very low surface soil moisture from day 350 of year 2002 to day 85 of year 2003, ecosystem respiration was very weak.

During the spring, which extends from early April to late May (days 86–155 of year 2003), G_{PP} rapidly increased in magnitude. This is consistent with the quick increase in V_{AI} (Fig. 7) and temperature (Fig. 6a). The forest was a carbon source caused by the rapidly

rising temperature and surface soil moisture from day 85 to day 110 of year 2003.

Absolute values of F_{NEE} , R_E and F_{GPP} reached their maximum in summer, which extends from late May to late August (days 156–235 of year 2003 and days 236–243 of year 2002). The forest captured the greatest amount of CO₂ in July, but due to the higher R_E at the higher temperature, July was only the second strongest carbon sink month. F_{NEE} was strongest, and peaked at 6 g m⁻² day⁻¹, in June.

F_{NEE} , F_{GPP} and R_E declined from the end of August to early October (days 244–274 of year 2002), the autumn, from day to day due to the cooler weather and defoliation.

The maximum daily values of R_E did not correspond to days with the highest F_{GPP} values. By contrast, the days with highest R_E occurred later than that of F_{GPP} , consistent with the report of Flanagan et al. (2002).

To assess the status of ecosystem carbon balance, Falge et al. (2001) defined an index z , which can be calculated from absolute value of eddy-covariance measurements as $F_{NEE}/R_E + 1$ or F_{GPP}/R_E . When $z > 1$ the system is storing carbon, when $z = 1$ the system is in carbon balance, and R_H equals F_{NPP} . We calculated the index z from F_{GPP}/R_E to observe the seasonal carbon balance of this 200-year-old mixed forest (Fig. 10d).

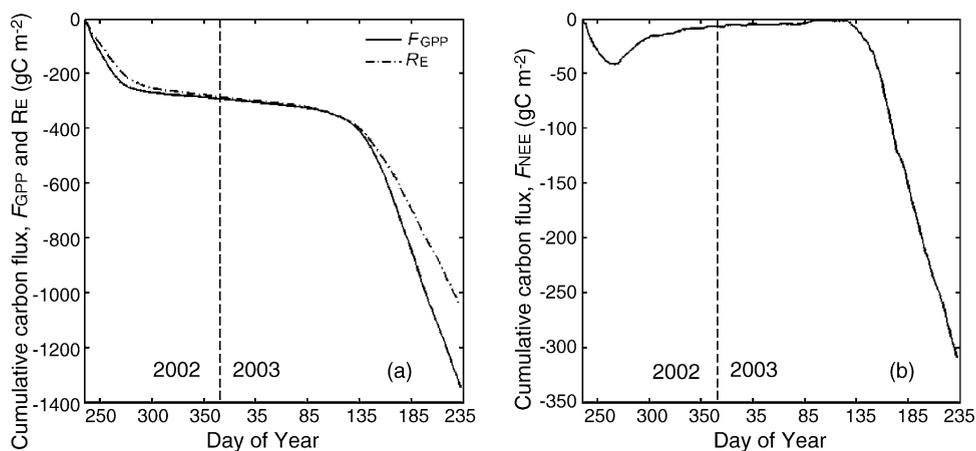


Fig. 11. Cumulative (a) gross ecosystem exchange (F_{GPP}), ecosystem respiration (R_E) and (b) net ecosystem exchange (F_{NEE}) from August 2002 to August 2003.

The z varied between 1 and 1.6 during growing seasons (late spring, summer and autumn) and between 0.5 and 1.0 in winter and early spring. The z was biggest in June and smallest in October and November. Our z values were consistent with the theoretical analysis of Falge et al. (2001). The variation of z values showed that the estimates from eddy-covariance flux correctly reflected the status of carbon metabolism in this old forest.

3.4. Estimation of seasonal and annual ecosystem uptake and release

The cumulative F_{GPP} , R_E and F_{NEE} from 24 August 2002 to 24 August 2003 are presented in Fig. 11 and Table 2. Uncertainties by gap filling and estimation of daytime respiration were estimated in a non-linear model fitting process (Matlab, Mathworks).

As shown in Fig. 11 and Table 2, the annual F_{NEE} was $-308 \pm 116 \text{ g C m}^{-2}$, the estimates of annual gross carbon gain and loss at this forest were -1432 ± 216 and $-1124 \pm 181 \text{ g C m}^{-2}$ separately. Based on the cumulative F_{NEE} data, the 200-year-old growth mixed broad-leaved Korean pine forest ecosystem was a strong sink of CO_2 from August 2002 to August 2003. F_{GPP}/R_E was about 1.27 and very close to that of Harvard forest ($42^\circ 32' \text{N}$, $72^\circ 11' \text{W}$, MA, USA) located at similar latitude as our site (Falge et al., 2001).

There was weak photosynthesis in wintertime, but in general the ecosystem emitted CO_2 . The 180 days winter contributed 6.9% of F_{GPP} and 12.5% of R_E of the whole year.

Although the ecosystem carbon metabolism was very active in spring and autumn, the ecosystem

sequestered and emitted almost the same amount of carbon and contributed little to F_{NEE} of whole year. F_{NEE} in spring and autumn were -34.4 and -19.5 g C m^{-2} separately.

Summer is the most significant season as far as the ecosystem carbon balance is concerned. The F_{NEE} during this period was about $-298.0 \pm 65.2 \text{ g C m}^{-2}$. The 90 days of summer contributed 67.0% of F_{GPP} and 58.9% of R_E of whole year.

The annual biomass dry weight growth (D_{WG}), estimated from a plant productivity investigation in 1981 at a plot ca. 100 m from the eddy-covariance site, was about $2019 \text{ g m}^{-2} \text{ yr}^{-1}$ (Lee et al., 1981). As carbon content (I_C) varies from 40% to 50% in different plant parts (Cheng et al., 1984), the annual F_{NPP} , estimated as $D_{WG} \times I_C$, was about $907 \pm 101 \text{ g C m}^{-2}$.

Eddy-covariance data do not provide values of F_{NPP} . For the ratio of F_{NPP}/F_{GPP} can be estimated from the biomass investigation data, we adopted a ratio α of 0.47 ± 0.04 (Waring et al., 1998) to estimate the annual ' F_{NPP} ' from the eddy-covariance F_{GPP} with formula of $F_{NPP} = \alpha F_{GPP}$. The result was $-681 \pm 159 \text{ g C m}^{-2} \text{ yr}^{-1}$ with upper boundary falling into the range by the plant productivity investigation of Lee et al. (1981). The difference between averaged F_{NPP} from plant productivity investigation and that from eddy-covariance was 25%. Reasons to explain the discrepancy include: (1) The F_{NPP} by eddy-covariance technology is more spatially representative than the F_{NPP} from biomass investigation of a 1 ha plot. (2) It is well known that in mature forests biomass production declines as trees age (Gower et al., 1996; Binkley et al., 2002). (3) It had been 22 years since the biomass investigation. The growth rate, although still high

Table 2
Annual and seasonal cumulated carbon sequestration (g C m^{-2}) (24 August 2002–24 August 2003)

| Seasons | Month | F_{GPP} | Errors | R_{E} | Errors | F_{NEE} | Errors |
|------------|-----------|------------------|--------|----------------|--------|------------------|--------|
| Winter | October | -38.1 | 13.6 | 62.1 | 23.6 | 24.0 | 5.0 |
| | November | -9.0 | 6.7 | 16.3 | 6.3 | 7.3 | 3.5 |
| | December | -10.8 | 5.3 | 13.4 | 6.2 | 2.6 | 1.9 |
| | January | -11.0 | 7.9 | 13.3 | 7.5 | 2.3 | 2.2 |
| | February | -10.9 | 6.3 | 11.5 | 5.8 | 0.6 | 1.7 |
| | March | -18.3 | 7.8 | 25.1 | 9.0 | 6.8 | 2.0 |
| | Sum | | -98.1 | 47.6 | 141.7 | 58.4 | 43.6 |
| Spring | April | -42.1 | 22.3 | 43.4 | 19.0 | 1.3 | 12.6 |
| | May | -155.6 | 25.1 | 119.9 | 12.1 | -35.7 | 14.1 |
| | Sum | -197.7 | 47.4 | 163.3 | 31.1 | -34.4 | 26.7 |
| Summer | June | -318.2 | 26.7 | 204.1 | 18.4 | -114.1 | 17.7 |
| | July | -351.4 | 48.0 | 238.1 | 37.7 | -113.2 | 27.6 |
| | August | -290.3 | 35.3 | 219.7 | 29.7 | -70.7 | 19.8 |
| | Sum | -959.9 | 109.9 | 661.9 | 85.8 | -298.0 | 65.2 |
| Autumn | September | -176.2 | 11.4 | 156.7 | 5.9 | -19.5 | 7.7 |
| | Sum | -176.2 | 11.4 | 156.7 | 5.9 | -19.5 | 7.7 |
| Whole year | Sum | -1432 | 216 | 1124 | 181 | -308 | 116 |

because dominant trees are young and productive enough (Fig. 12 and Dai et al., 2002), has declined during the 22 years.

From weekly soil respiration measurements with a chamber method at the same site, Wang et al. (2004) developed a temperature response function of soil respiration (see also in Guan et al. (2006). Annual soil respiration R_{s} , estimated with this function, was about 502.5 g C m^{-2} . The γ_{s} , contribution of soil surface efflux to ecosystem respiration, varies from 48% to 71% according to Raich and Schlesinger (1992). R_{E} , estimated with $R_{\text{s}}/\gamma_{\text{s}}$, was about $877.3 \pm 169.6 \text{ g C m}^{-2}$. Our R_{E} is close to the upper bound of the estimate. Substituted 49% (Guan et al., 2006) for γ_{s} above, ecosystem respiration R_{E} of this old-growth forest would be about $1031.6 \text{ g C m}^{-2}$. It is very close to $1124 \pm 181 \text{ g C m}^{-2}$ estimated in this paper. Difference in the length of time windows seems to be responsible. Long (yearly or seasonal) windows may introduce a considerable bias in F_{RE} and F_{GPP} estimate (personal communication with Dr. Markus Reichstein). The hybrid time windows, applied in this paper, can minimize the confounding effects of soil water content, temperature and forest phenology (Davidson et al., 1998; Luo et al., 1996; Flanagan et al., 2002).

There are almost no environmental stresses in this area, though the climate is changing as in other parts on this planet (Zhang et al., 2005). The forest growth

only consumes $28.4 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ of the $37.5\text{--}42.5 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ available N (Guo, 1995). The precipitation was 685.8 mm during the investigated period and very close to 700.5 mm , the 20-year average annual precipitation, providing enough water for plant growth. The maximum and minimum daily mean temperature was 25.3 and $-23.5 \text{ }^{\circ}\text{C}$ providing ideal conditions for rapid growth. Low temperature and surface soil moisture significantly limited soil respiration, while rooting zone soil water provided enough water for plant activities in wintertime (Fig. 6a and b).

There are uncertainties in flux measurement, especially in wintertime, even over flat site. The application of the CO_2 budget equation with advection and pressure terms is limited at present by technique and other problems (Lee, 1998; Massman and Lee, 2002; Aubinet et al., 2003; Feigenwinter et al., 2004; Staebler and Fitzjarrald, 2004). Different treatments with nighttime negative fluxes in dormant periods would bring significant differences in estimates of carbon fluxes. Guan et al. (2006) treated all nighttime negative fluxes as gaps and filled them with temperature response function developed with all valid nighttime F_{NEE} of the whole research period. Difference of cumulative F_{NEE} from October 2002 to March 2003 by these two methods was about -80 g C m^{-2} . This is responsible for significant different cumulative F_{NEE} of

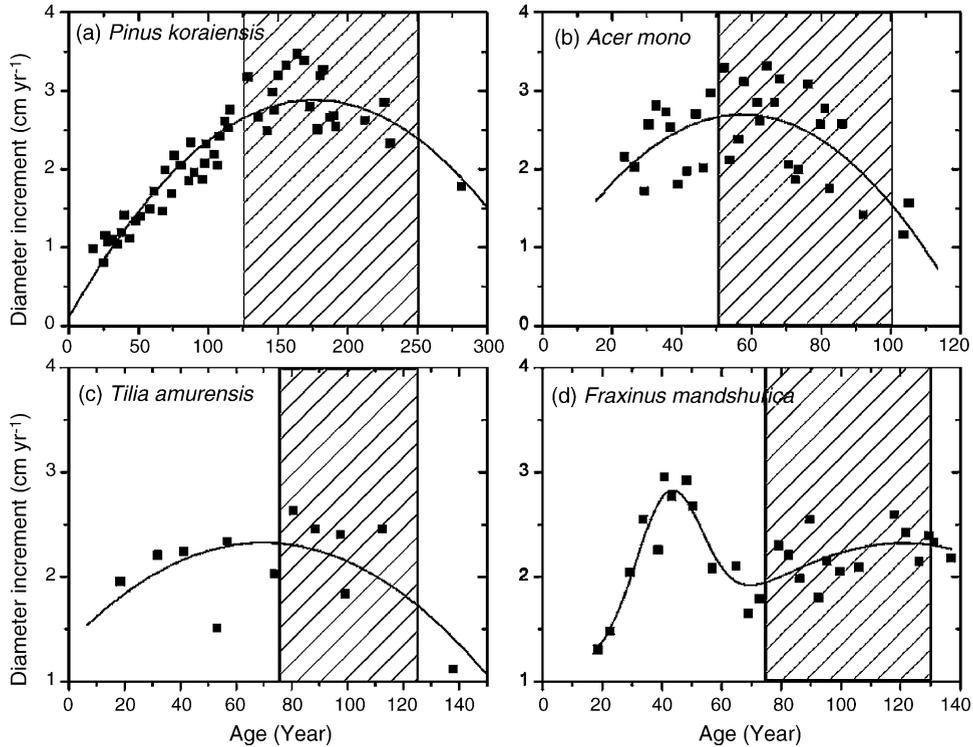


Fig. 12. Relationship between age and yearly DBH increment of *Pinus koraiensis* (a), *Acer mono* (b), *Tilia amurensis* (c) and *Fraxinus mandshurica* (d). The shading portion emphasized dominant age group for corresponding species (adapted from Dai et al., 2002).

between August 2002 and August 2003, -182 g C m^{-2} by Guan et al. (2006) and $-308 \pm 116 \text{ g C m}^{-2}$ in this paper.

The u_* correction is a practical way to minimize underestimates of nighttime net ecosystem exchanges (F_{NEE}) of CO_2 under calm conditions (Goulden et al., 1996; Massman and Lee, 2002). In the literature, researchers often find the u_* threshold by visually examining the scatter of nighttime fluxes versus u_* . Finding a u_* threshold depends on individual researchers' judgment and different researchers may come to different thresholds from the same data set. The u_* threshold for growth period is 0.2 m s^{-1} in Guan et al. (2006) and is little larger than 0.17 m s^{-1} , the u_* threshold determined with MPT technology (Gu et al., 2004) here. This small difference in u_* changed 15% of the valid data from June to September and explained a difference of -23 g C m^{-2} in cumulative F_{NEE} between us. This shows that objective way to determine u_* threshold is critical important to reduce uncertainties and make results compatible.

Significant uncertainties by treatments with winter nighttime negative fluxes and u_* correction suggest the importance of strict refinement of eddy-covariance data, more research on the behaviors of terms in the CO_2

budget equation and the development of new methodologies of experimental design to account for the entire mass balance in a soil-vegetation-atmosphere volume, especially in dormant periods. Integration of researchers and technologies from different disciplines is critically needed to minimize the uncertainties of application of eddy-covariance technology and to interpret the results, such as the daytime negative flux in dormant seasons shown in Fig. 5.

4. Conclusions

We presented data from a CO_2 flux study over a 200-year-old Chinese board-leaved Korean pine mixed forest from August 2002 to August 2003 using the eddy-covariance method. Given the importance of old-growth forests as a major terrestrial carbon store and argument concerning their carbon sink strength, this study will help to reduce uncertainties in carbon accounting.

This ecosystem, a net sink of atmospheric CO_2 , sequestered $-308 \pm 116 \text{ g C m}^{-2}$ during the study period. The estimates of gross carbon gain and loss at this forest were -1432 ± 216 and $1124 \pm 181 \text{ g C m}^{-2}$ separately. The seasonal trend of F_{GPP} and R_{E} followed closely the change in V_{AI} and temperature. There was

weak photosynthesis in winter while the summer is the most significant season as far as ecosystem carbon balance is concerned. The 90 days of summer contributed 67.0% of F_{GPP} 58.9% of R_{E} of whole year. This study shows that old-growth forest can be strong net carbon sink of atmospheric CO_2 .

The carbon metabolism of ecosystems is regulated by environmental factors and hence there are great inter-annual variations in the strength of ecosystem carbon exchange (Flanagan et al., 2002; Paw and Falk, 2003; Baldocchi and Valentini, 2004). There is need to increase the investigation period to accurately describe the status and variation of carbon metabolism for old-growth forests.

There are many uncertainties for determination of absolute values of long-term net carbon exchange even in sites with ideal topography using eddy-covariance method (Massman and Lee, 2002; Baldocchi, 2003). It requires the strict refinement of eddy-covariance data, more research on the behaviors of term in the CO_2 budget equation and the development of new methodologies of experimental design to account for the entire mass balance in a soil-vegetation-atmosphere volume.

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