

An old-growth subtropical Asian evergreen forest as a large carbon sink

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ARTICLE INFO

Article history:

Received 30 June 2010

Received in revised form

20 December 2010

Accepted 20 December 2010

Keywords:

Eddy covariance

Biometric method

Old-growth

Management

ABSTRACT

Old-growth forests are primarily found in mountain ranges that are less favorable or accessible for land use. Consequently, there are fewer scientific studies on old-growth forests. The eddy covariance method has been widely used as an alternative approach to studying an ecosystem's carbon balance, but only a few eddy flux sites are located in old-growth forest. This fact will hinder our ability to test hypotheses such as whether or not old-growth forests are carbon neutral. The eddy covariance approach was used to examine the carbon balance of a 300-year-old subtropical evergreen broadleaved forest that is located in the center of the largest subtropical land area in the world. The post-QA/QC (quality assurance and control) eddy covariance based NEP was $\sim 9 \text{ tC ha}^{-1} \text{ yr}^{-1}$, which suggested that this forest acts as a large carbon sink. The inventory data within the footprint of the eddy flux show that $\sim 6 \text{ tC ha}^{-1} \text{ yr}^{-1}$ was contributed by biomass and necromass. The large-and-old trees sequestered carbon. Approximately 60% of the biomass increment is contributed by the growth of large trees (DBH > 60 cm). The high-altitude-induced low temperature and the high diffusion-irradiation ratio caused by cloudiness were suggested as two reasons for the large carbon sink in the forest we studied. To analyze the complex structure and terrain of this old-growth forest, this study suggested that biometric measurements carried out simultaneously with eddy flux measurements were necessary.

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1. Introduction

During the International Biosphere Program (IBP), the hypothetical trend of gross primary production, stand respiration, net ecosystem production and biomass in an age-series of a dense pure stand was tested (Kira and Shidei, 1967). This hypothesis suggests that old-growth forests exist in a carbon-neutral state, in which photosynthetic carbon uptake is balanced by respiratory carbon release, and was advanced by E.P. Odum in the context of ecosystem succession (Odum, 1969). During the IBP campaign, it was difficult to measure the net ecosystem production (NEP, the net balance between photosynthesis and respiration) directly. Nevertheless, the methodology for net primary production (NPP) estimation, which was developed based on plant allometry, was widely accepted and

mature. Therefore, analysis of the trend of NPP with stand age was traditionally used to test the above mentioned hypothesis (Gower et al., 1996; Ryan et al., 1997). Inventory data in a natural subalpine forest, however, did not support the decrease of NPP with stand age, which is observed true in pure stand (Carey et al., 2001). Moreover, the necromass and soil carbon were usually ignored because NPP only accounts for biomass carbon. In contrast, the forest soil can accumulate carbon at a relatively high rate (Zhou et al., 2006). Consequently, we need a new method that can directly measure NEP to test this hypothesis.

The micrometeorological-based eddy covariance technique provides an alternative way to measure NEP directly (Baldocchi and Meyers, 1988; Wofsy et al., 1993; Goulden et al., 1996; Valentini et al., 2000; Magnani et al., 2007). However, very few eddy flux sites are distributed in forests in the later succession stage (Buchmann and Schulze, 1999). Interestingly, even when old, the NEP of some forests which were detected by eddy covariance is still positive (Hollinger et al., 1994; Law et al., 2001; Knohl et al., 2003). The hypothesis that old-growth forests act as carbon sinks has been

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readdressed and supported through a literature review-based dataset from 519 plots (Luyssaert et al., 2008). Although half of the primary forests were located on tropical and subtropical land, no tropical or subtropical sites were included in the 519 plots. Thus, the investigation of the NEP of old-growth forests in tropical and subtropical areas is necessary and to advance our knowledge concerning old-growth forest and global carbon cycling.

Subtropical China lacks a dry belt because of the influence of the Tibet Plateau (Wu, 1980; Kira, 1991). Primary subtropical evergreen broadleaved forests are widely distributed in areas of subtropical China that have been carefully protected in the past. In this study, we applied both the eddy covariance and biometry method to investigate the carbon budget of a 300-year-old subtropical evergreen broadleaved forest in Yunnan, China. The objective of this study is to test the old-growth carbon neutral hypothesis.

2. Methods

2.1. Site description

The study site is located in the Ailao Mountain Nature Reserve (24°32'N, 101°01'E; 2476 m elevation) in the Yunnan Province, SW China. In this area, an old-growth subtropical evergreen broadleaved forest is spread widely and well protected. The forest in our study had a stand age >300 years and was free of management. The dominant species in this community are *Lithocarpus chintungensis*, *Rhododendron leptothrium*, *Vaccinium duclouxii*, *Lithocarpus xylocarpus*, *Castanopsis wattii*, *Schima noronhae*, *Hartia sinensis*, and *Manglietia insignis*. The tree density is 2728 ha⁻¹, the median tree height is 9.0 m, median diameter at breast height is 9.5 cm, and the median basal area in the plot is 91 m² ha⁻¹ (Schaefer et al., 2008). The leaf area index measured by the canopy analyzer (LAI-2000, Li-Cor Inc., Lincoln, NE, USA) was ~5.0. The estimated total stand biomass was 499 t ha⁻¹. Mean annual air temperature is 11.3 °C, with monthly mean values ranging from 5.4 to 23.5 °C. The site receives an annual average of 1840 mm of precipitation, based on more than 20 years of data collected at a meteorological station. The region has two distinct seasons influenced by a monsoon climate. The wet season occurs from May through October, and the dry season from November to April. The soils are loamy Alfisols. The 3–7 cm organic carbon horizon has a pH of 4.5 and organic carbon and total nitrogen contents of 304 and 18 g kg⁻¹, respectively (Liu et al., 2002; Chan et al., 2006).

2.2. Micrometeorological based eddy flux carbon budget estimation

Seven levels (1.5, 4.0, 10.0, 18.0, 24.0, 30.0, 34.0 m) of instrument arms were mounted on a triangular meteorological tower within the study area. The instruments on the tower are divided into four categories: (1) an eddy covariance system; (2) a mean wind, temperature, humidity, and light profile measurement system; (3) a soil temperature and heat flux measurement system; and (4) other instruments for routine meteorological measurements. The data were collected continuously beginning in November 2008.

The eddy covariance system was installed at a height of 34 m. The flux system consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA) and an open-path CO₂/H₂O infrared gas analyzer (Li-7500, Li-Cor Inc., Lincoln, NE, USA). The sampling frequency for both instruments was 10 Hz and employed a datalogger (CR5000, Li-Cor Inc., USA). Instruments for measuring air humidity, air temperature (HMP45C, Vaisala, Helsinki, Finland), and wind speed (A100R, Vector Instruments, Denhighshire, UK) were installed at seven heights with a sampling interval of 30 min. Instruments for measuring wind direction (W200P, Vector Instruments, Denhighshire, UK) and rainfall (RainGauge 52203,

Young, Traverse City, MI, USA) were installed at the top of the tower at a height of 34 m. Photosynthetically active radiation (PAR) was measured using linear sensors (LQS70-10, APOGEE, USA). The net radiation was calculated from the downward and upward, short- and long-wave radiation (CNR-1/CM11, Kipp & Zonen, Delft, the Netherlands). The profiles of soil moisture and temperature were measured using the appropriate sensors (CS616_L, Campbell, USA; and 105T/107L, Campbell, USA, respectively). Two soil heat flux plates (HFP01, HukseFlux, the Netherlands), installed in south- and north-facing orientations, were used to measure the average soil heat flux.

An online eddy flux data-processing program (<http://159.226.111.49:8080/CernWebProject2.4/dataprocess.jsp>) was used to obtain the annual sum of the ecosystem's carbon exchange (Li et al., 2008). Here, we briefly introduce the data processing flow because the original paper describing the procedure was written in Chinese. The method involved the following steps: (1) a three-dimensional rotation of the coordinate was applied to the wind components to remove the effects on airflow of instrument tilt or irregularities (Tanner and Thurtell, 1969); (2) the flux data were corrected for variations in air density caused by the transfer of heat and water vapor (Webb et al., 1980); (3) the storage flux was added by using the CO₂ concentration data measured using the Li-7500 instrument (Zha et al., 2004); (4) the data collected during periods of rainfall were excluded from the analysis; (5) the net ecosystem exchange (NEE) data with values greater than 3 mg CO₂ m⁻² s⁻¹ and less than -3 mg CO₂ m⁻² s⁻¹ were excluded; (6) spikes in the data were defined as values that exceed 5.5 times the standard deviation in a window of 10 values, and the data in such spikes were deleted; (7) nighttime negative data were excluded; (8) the threshold of friction velocity was determined according to Zhu et al. (2005); and (9) data gaps were filled by nonlinear regression with a 10-day window (Falge et al., 2001).

Micrometeorological theories and hypotheses are generally most accurate under neutral conditions. To avoid the effects of calm conditions and strong wind, we separately identified nighttime and daytime data collected under neutral conditions (Neutral conditions were defined as follows: $-1 < (z - d)/L < 1$, where z is the measurement height, d is the zero displacement height, and L is the Monin–Obukhov length (Rannik et al., 2003; Yang et al., 2007)). Daytime data were related to the photosynthetic active radiation using the Michaelis–Menten equation, and the nighttime data were related to soil temperature at a depth of 5 cm using the Lloyd–Taylor equation (Falge et al., 2001). Finally, data collected under neutral conditions were extrapolated for the entire year.

2.3. Tree inventory and litterfall production estimation

We inventoried 1 ha of forest within the footprint of the eddy flux tower in November 2003. All trees with a diameter at breast height (DBH) larger than 2 cm were identified, tagged, measured, and mapped. Red paint was used to mark the measurement height of stems, which ensured comparable measurements of DBH afterward. Site specific allometric equations were used to derive biomass from DBH (Xie et al., 1996). Biomass was converted to carbon density by a factor of 0.5 (Tan et al., 2010). In November 2007, we re-measured tree DBH to obtain estimates of the biomass carbon budget, such as recruitment, growth, and mortality. Coarse woody debris (CWD) respiration was calculated by inventory based CWD carbon density and density dependent decomposition rate in the same plots (Yang, 2007).

The aboveground litter was captured by 25 litter traps (1 m × 1 m) that were randomly distributed in the 1 ha plot. Litters were collected at the last day of every monthly and then sorted into leaves, branches, flowers, fruits, epiphytic materials and “mixed matter”. Every component was dried to a constant weight at 80 °C and weighted separately.

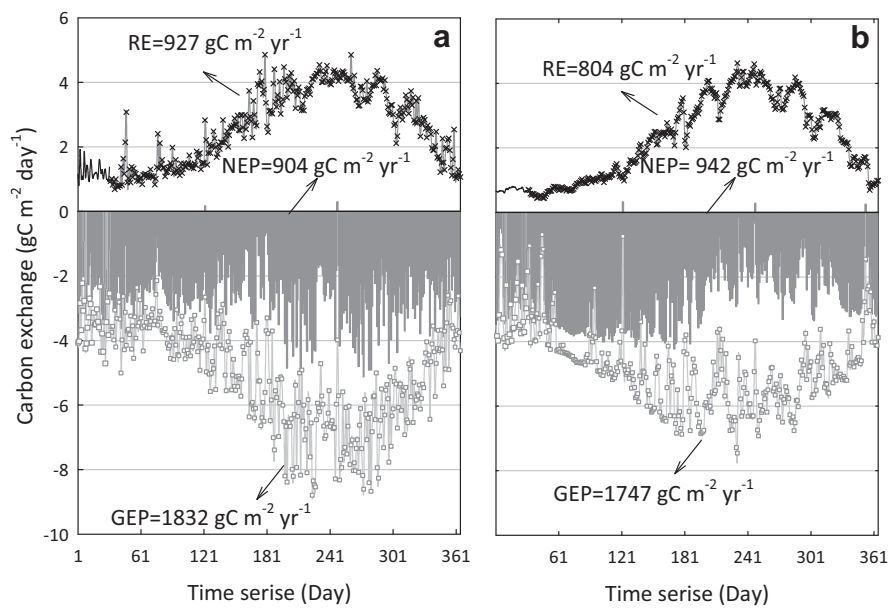


Fig. 1. The annual variation of the ecosystem carbon fluxes during Dec. 01, 2008 and Nov. 30, 2009 in the Ailaoshan subtropical evergreen broadleaved forest, China. (a) The result obtained using the online flux procedure provided by ChinaFLUX. (b) The result obtained using data measured under neutral conditions. RE, GEP and NEP indicate the ecosystem respiration, gross ecosystem exchange, and net ecosystem exchange, respectively. GEE and NEE equals GPP (gross primary production) and NEP but are opposite in signs.

3. Results

Although the strong seasonality of gross primary production and ecosystem respiration was observed, little seasonality of the NEP was detected in our studied site (Fig. 1). Ecosystems act as a carbon sink year-round even in the dry and cool sub-season (November to February). The annual sum of NEP was 9.04 tC ha⁻¹, which was consistent with the neutral-condition-based NEP (9.42 tC ha⁻¹ yr⁻¹). The mean annual carbon sequestration rate by biomass and necromass was 5.74 t tC ha⁻¹ during 2003–2007 (Table 1). The growth of large trees (DBH > 60 cm) contributes greater than half of the sequestered carbon. There was one large tree with a DBH of 85.09 cm that died in the inventory interval. This random

Table 1
The carbon budget (ton carbon) for tree biomass and necromass from November 2003–November 2007 in a 1 ha plot within the footprint of the eddy covariance measurement in the Ailaoshan subtropical evergreen broadleaved forest, China.

DBH Class	2–10 cm	10–35 cm	35–60 cm	>60 cm	Total
<i>Changes in tree biomass</i>					
Recruitment (N = 77) ^a	0.01	0.26	2.89	2.11	5.27
Growth (N = 1221)	0.72	2.90	8.17	13.91	25.71
Mortality (N = 30) ^b	-0.63	-1.45	0.00	-2.83	-4.91
Outgrowth ^a	-0.26	-2.89	-2.11	0.00	-5.26
Net	-0.16	-1.18	8.95	13.19	20.80
<i>Changes in necromass</i>					
Mortality input ^b	4.91				
Respiration losses ^c	-2.76				
Subtotal	2.15				
Total change in biomass and necromass	22.95 ^d				

^a Recruitment into a size class is equal and opposite to the outgrowth from the next small class.
^b Mortality losses from biomass are equal to the input to necromass.
^c The total carbon density of coarse woody debris is 36.33 tC ha⁻¹ (Yang, 2007). The mean decomposition constant for dominant species was 0.019. Therefore, the total respiration losses during the four years were estimated to be 2.76 tC ha⁻¹.
^d Indicates the annual stand biomass and necromass change, which is 5.74 (22.95/4) tC ha⁻¹ yr⁻¹ during the study period.

event caused the mortality input to become unbalanced by respiration losses. The biomass increment rate increased with DBH class in a logistic manner (Fig. 2). The annual litterfall production of our studied forest was 4.31 tC ha⁻¹ yr⁻¹.

4. Discussion

The idea that old-growth forests (stand age > 200 yr) act as carbon sinks was reported by several studies in coniferous and mixed forests (Hollinger et al., 1994; Law et al., 2001; Roser et al., 2002; Knohl et al., 2003; Paw et al., 2004; Desai et al., 2005; Guan et al., 2006). The mean NEP for boreal and temperate forests based on a review dataset was 2.4 tC ha⁻¹ yr⁻¹, of which 17% was contributed by stem growth, 29% by coarse woody debris, and more than half by root and soil organic matter (Luyssaert et al., 2008). The self-thinning theory predicts an NEP of (the ratio between heterotrophic respiration and net primary production ~0.65, gross primary production ~20 tC ha⁻¹ yr⁻¹) 4.24 tC ha⁻¹

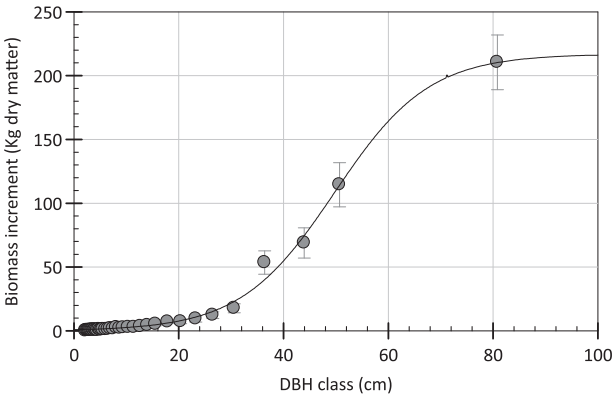


Fig. 2. The relationship between the biomass increment and DBH classes during 2003 and 2007 in a 1 ha plot within the footprint of the eddy flux tower in the Ailaoshan subtropical evergreen broadleaved forest, China. The data were fit by a logistic equation ($y = \frac{216.92}{1 + 252.58 \exp(-0.000512 \times 216.92 \times x)}$, $r^2 = 0.9955$).

yr^{-1} in the forest we studied (Luyssaert et al., 2008). The stand-procedure-based NEP was consistent with the neutral-condition-based NEP, and both suggested that the forest in our study had an NEP of roughly $9 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Fig. 1). To our knowledge, this NEP is the largest reported in an old-growth forest.

Should we doubt this surprising result (Jarvis et al., 2001)? It is important to consider the plausibility of a carbon sink of $900 \text{ gC m}^{-2} \text{ yr}^{-1}$ for a 300-year-old evergreen forest. An unmanaged 250-year-old deciduous forest in central Germany was reported to represent a carbon sink of 494 and $490 \text{ gC m}^{-2} \text{ yr}^{-1}$ in 2000 and 2001, respectively, after correction for friction velocity (Knobl et al., 2003). In this forest, 177 days in 2000 and 152 days in 2001 were marked by a net carbon uptake. Therefore, on the remaining days in each year (188 days in 2000 and 213 days in 2001), the ecosystem was a net carbon source. If an ecosystem is to represent a carbon sink of 494 or $490 \text{ gC m}^{-2} \text{ yr}^{-1}$ year-round, then carbon uptake during the growing season must exceed these values. In the present study, the summed NEP from May to October, which is considered the wet season, based on the long-term climate data, (here, this period of 184 days corresponds to the growing season in a deciduous forest) was 549 and 403 gC m^{-2} for the standard procedure and for the data collected under neutral conditions, respectively. In fact, the peak net carbon uptake during the growing season in a deciduous forest (approximately $9 \text{ g m}^{-2} \text{ day}^{-1}$) (Knobl et al., 2003) is much larger than that in the evergreen forest of the present study (approximately $5 \text{ g m}^{-2} \text{ day}^{-1}$). This comparison indicates that our estimate of the NEP in the ‘corresponding growing season’ is reasonable.

Therefore, the following is a question to consider: Is the net carbon uptake of 400 gC m^{-2} in the present study site during the dry season (corresponding to the non-growing season in a deciduous forest) an impossible figure? Ecosystem photosynthetic capacity (P_{max}) and light use efficiency (α_{yield}) were lower in the dry season than in the wet season (Fig. 3). Nevertheless, the ecosystem dark respiration (R_d) was much lower during the dry season. GEP decline in during the dry season, along with a marked decline in RE (Fig. 1). Therefore, it is possible for the forest in our study to have a net carbon uptake of 400 gC m^{-2} during the dry season, which is similar to that of the wet season. Interestingly, the large carbon sinks for the Amazonian and Asia tropical rain forest during the dry season indicates that this result is not surprising (Saleska et al., 2003; Zhang et al., 2010).

Although the eddy covariance technique has been successfully applied in the studies of ecosystems' carbon dioxide exchange, uncertainties in the annual carbon uptake cannot be ignored in the case of non-ideal conditions (e.g., calm zone, complex terrain) (Baldocchi, 2003). The underestimation of the nighttime ecosystem respiration is attributed to the decoupling of airspaces within and above the canopy, the loss of CO_2 -rich draining cool air, the occurrence of minor and brief fluctuations that cannot be detected by the eddy covariance system, and the use of improper data-processing procedures (Goulden et al., 1996; Baldocchi, 2003; Loescher et al., 2006; Kutsch et al., 2008). Therefore, it is necessary to carry out QA/QC for the eddy flux dataset (supplementary material). The following are important implications for QA/QC:

- 1) To avoid the effects of calm nights and strong winds, the NEE was estimated based on data collected during neutral conditions. We found no difference in the NEE values between neutral conditions and those calculated based on the standard procedure (Fig. 1).
- 2) In the tall forest at the present study site, the ecosystem energy balance closure is estimated to exceed 87%. This result is similar to or slightly higher than the mean value calculated for multiple forest sites (Aubinet et al., 2000; Wilson et al., 2002).

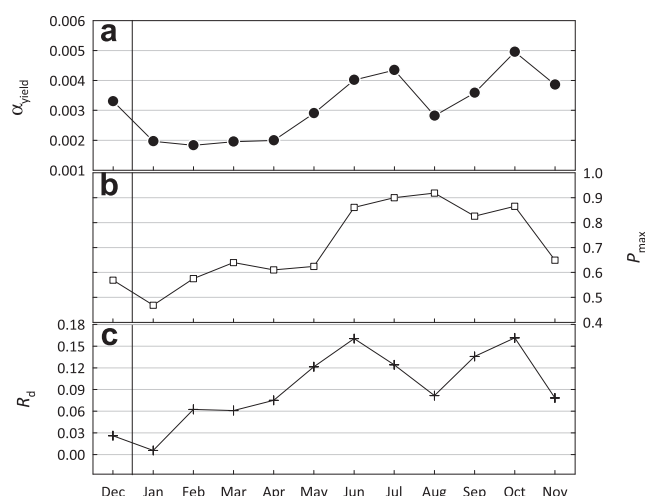


Fig. 3. The monthly variation of day-time net ecosystem carbon exchange light response parameters during Dec. 01, 2008 and Nov. 30, 2009 in the Ailaoan subtropical evergreen broadleaved forest, China. (a) The apparent quantum yield (α_{yield} , $\text{mg CO}_2 \mu\text{mol photons}^{-1}$); (b) The maximum net photosynthesis rate (P_{max} , $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$); (c) The dark respiration (R_d , $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$).

The QA/QC work suggested that our annual sum of NEP was reasonably reliable. However, what we should point out is that the nighttime eddy flux in the ecosystem we studied will increased with u^* to a certain value then decrease to a low level which may be connected with advection (Aubinet, 2008; Aubinet et al., 2010), turbulent intermittency (Cava et al., 2008) or sampling frequency (Katul et al., 2005) (Fig. 4). This feature may induce underestimation of nighttime ecosystem respiration and overestimation of NEP.

There are two main sources of uncertainty in stand biomass dynamic estimation: allometric equations and inventory. Site-specific allometric equations were used in this study. They were generated by the destructive sampling of 33 trees in the nearby forest with the same forest type as ours, and the R^2 values all exceeded 0.87 (Xie et al., 1996). In the 1 ha plot we studied, 130 trees were mounted with dendrometers in May 2009. The dendrometer-based DBH increment during June 2009 and June 2010 was similar but slightly higher than the inventory-based average annual DBH increment during 2003 and 2007 in the same tree individual (Zheng et al., 2010 Unpublished data).

Because it is possible for an evergreen forest to uptake $\sim 9 \text{ tC ha}^{-1} \text{ yr}^{-1}$, the next question we addressed was how NEP allocated among stem growth, necromass, and soil organic matter. The inventory data based on the 1 ha plot within the footprint of the eddy flux shows that $5.74 \text{ tC ha}^{-1} \text{ yr}^{-1}$ of stem growth and necromass were (Table 1). This observation indicates that more than half of the NEP was contributed by stem growth in this forest. The conventional opinion that old trees cease to sequester carbon was not supported by our study. It is commonly accepted that large trees tend to be old. The logistic style relationship between the tree size class and biomass increment suggested that old trees sequestered the most carbon (Fig. 2).

The difference between eddy flux and biometric measurements did not sufficiently indicate that the $3\text{--}4 \text{ tC ha}^{-1} \text{ yr}^{-1}$ was accumulated by organic soil matter. First, the investigation intervals between the eddy flux (Dec. 2008–Nov. 2009) and biometric measurement (Nov. 2003–Nov. 2007) were different. Second, the eddy footprint and inventory plot were not identical. Third, there is a time lag between ecosystem photosynthesis derived from the eddy flux and tree growth derived from the biometric measurement. Fourth, a severe drought took place during our investigation interval (Qiu, 2010). Only $\sim 60\%$ of the average annual rainfall amount was

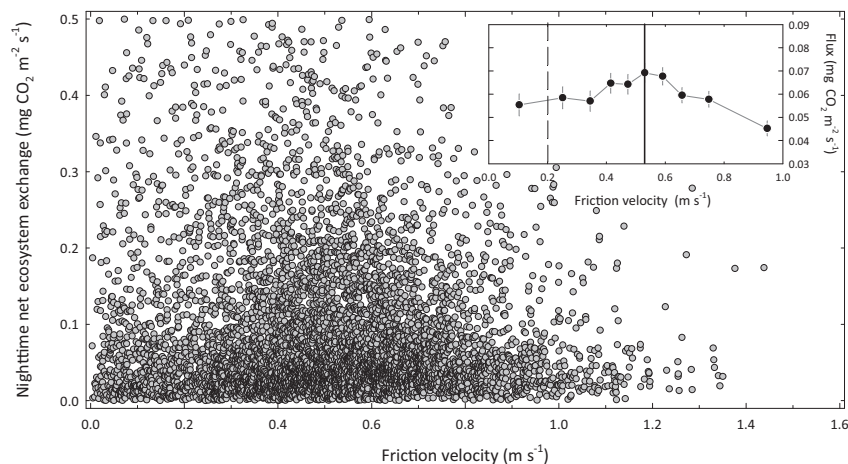


Fig. 4. The relationship between the nighttime net ecosystem carbon exchange and the friction velocity for 30 min data. The friction velocity was the median of each decile, and the nighttime flux was the mean value of each decile for the upper-right panel. The dashed line indicates the widely suggested u^* threshold of 0.2. The solid line represents the peak nighttime respiration under certain level of friction velocity.

observed in the forest. Fifth, the nighttime eddy flux increased with u^* to a certain value then decreased to a low level, which indicates that there was an underestimation of the ecosystem respiration and, subsequently, an overestimation of the NEP (Fig. 4).

Nevertheless, it is conceivable that this forest would be classified as a large carbon sink by the eddy flux and biometric measurement. Such a large carbon sink may exist because:

- 1) High altitudes induce low temperature. The elevation of our forest was ~ 2500 m. Although located in a subtropical area, the mean annual temperature is $\sim 10^\circ\text{C}$, which similar to the result predicted by the temperature elapse rate ($\sim 0.6^\circ\text{C}/100$ m) (Fig. 5). The summer temperature seldom exceeds 20°C . The mean temperature of the hottest month is only $\sim 15^\circ\text{C}$. The “cool summer” restrains ecosystem respiration because the respiration increases exponentially with temperature. In contrast, the less extreme low temperature events produced a “warm winter” for this forest growth because the cold Siberian air flow met the Tibet plateau. The net primary production (NPP) for the forest in this study was $\sim 10 \text{ tC ha}^{-1} \text{ yr}^{-1}$ (biomass increment plus litterfall production), which is comparable to that of a tropical rain forest (Tan et al., 2010). The heterotrophic respiration was low even with the overestimation of NEP by the eddy covariance approach and drought enhanced NEP (reduced respiration, enhanced photosynthesis through increased sunshine hours (Qiu, 2010)) was

taken into account. A similarly low respiration ($1.76 \text{ tC ha}^{-1} \text{ yr}^{-1}$) rate was also observed at a high-altitude subtropical evergreen forest in Taiwan (Chang et al., 2008). The litterfall production and tree mortality obviously surpasses the litterfall decomposition, and the coarse woody debris decomposition was also supported by an accumulated litter layer and a large amount of coarse woody debris on the forest floor. This observation also implies a small amount of heterotrophic respiration. In short, the high altitude induced “warm winter” and “cold summer” was consistent with the high NPP and respiration and was one of the reasons for the existence of such a large carbon sink in this forest.

- 2) A high diffusion-irradiation ratio is caused by clouds. The apparent quantum yield is 0.044 during our study period. This value was higher than the subtropical evergreen coniferous in Qianyanzhou and the broadleaved forest in Dinghushan, China (Zhang et al., 2006), the evergreen beech forest in Maruia, New Zealand (Hollinger et al., 1994), the tropical rain forest in La Selva, Costa Rica (Loescher et al., 2006) and the tropical seasonal rain forest in Xishuangbanna, China (Tan et al., 2009). A high ratio of cloudy days, which are indicated by sunshine hours, was observed in the forest in our study (Fig. 6). The cloudy climate will add to the diffusion radiation ratio and subsequently enhance photosynthesis (Gu et al., 2002). Clouds were also observed to enhance ecosystem carbon uptake in the

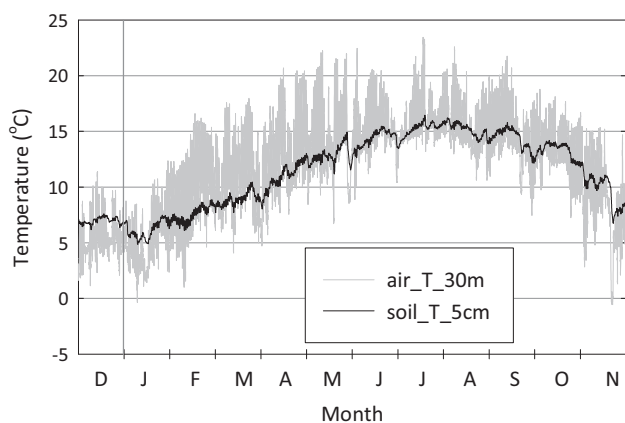


Fig. 5. The temporal dynamic of the air temperature at 30 m, which is directly above the canopy (grey line), and the soil temperature at 5 cm (black line) during Dec. 01, 2008 and Nov. 30, 2009 in a subtropical evergreen broadleaved forest of Ailaoshan, Yunnan, China.

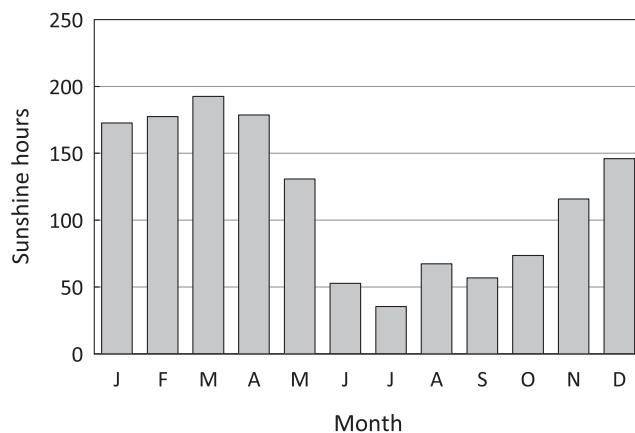


Fig. 6. The monthly variation of sunshine hours in the Ailaoshan subtropical evergreen broadleaved forest. Data were collected from the national Ailaoshan ecological station (average value during 1982 and 2009).

Harvard forest (Min and Wang, 2008). Thus, the high quantum yield and large carbon sink in this forest could be connected to the cloudy climate and diffusion radiation ratio.

5. Implications and conclusions

This study examined the carbon balance of an old-growth subtropical evergreen broadleaved forest, located in the center of the largest subtropical land area in the world. The post-QA/QC eddy covariance based NEP was $\sim 9 \text{ tC ha}^{-1} \text{ yr}^{-1}$, which suggests that this forest acts as a large carbon sink. The inventory data within the footprint of the eddy flux shows that $\sim 6 \text{ tC ha}^{-1} \text{ yr}^{-1}$ was contributed by biomass and necromass. This observation did not sufficiently indicate that $3\text{--}4 \text{ tC ha}^{-1} \text{ yr}^{-1}$ was accumulated by soil organic matter for the methodology differences. The lack of soil carbon data, however, prevents us from making further analysis. Advantages of the eddy covariance approach are that it can provide a high temporal resolution dataset for ecosystem environment response analysis, it is not susceptible to disturbances or harvest for flux measurements, and it possesses a fine spatial scale approximately several km^2 . However, this approach assumes that the underlying surface is horizontally homogenous. It is very difficult for old-growth forests to satisfy this assumption because old-growth forests are often characterized by a complex structure (canopy gaps and a diverse range of tree heights) and mainly occur in the complex – often sloped – terrain of mountain ranges, which are less favorable or accessible for anthropogenic land use (Schulze et al., 2009; Knohl et al., 2009). Thus, biometric measurements carried out simultaneously with eddy flux measurements are necessary in old-growth forest carbon balance studies. It is useful when take the advantages and make comparison of these two methods and track the contribution of NEP by each carbon pools as discussed above.

Although we observed a “surprisingly” large carbon sink $\sim 9 \text{ tC ha}^{-1} \text{ yr}^{-1}$, it is still reasonable and comparable to other findings. The large-and-old trees did not stop sequestering carbon but, rather, sequestered a significant amount of it. Approximately 60% of the biomass increment is contributed by the growth of large trees (DBH > 60 cm). The high-altitude-induced low temperature and the high diffusion-irradiation ratio caused by clouds suggest the reason for the existence of this large carbon sink.

Acknowledgements

We thank the two anonymous reviewers who provided many important and constructive comments on the manuscript. We thank the ChinaFLUX data synthesis center for performing the standard flux-processing procedure. We thank Mr. You Guangyong and Li Linhui for their help with the field work and data collection. This work was supported by the National Science Foundation of China (40571163, 41071071, and 41001063), the Knowledge Innovation Program of the Chinese Academy of Sciences (KZCX2-YW-Q1-05-04), and the Development Program in Basic Science of China (2010CB833501).

Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.atmosenv.2010.12.041.

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