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

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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 tC ha^{-1} 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 tC ha^{-1} 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.

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 ducluoxii*, *Lithocarpus xylocarpus*, *Castanopsis wattii*, *Schima noronhae*, *Hartia sinensis*, and *Manglietia insignsis*. 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 m^{-2} 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 CO_2/H_2O 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 CO_2 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 CO_2 m^{-2} s^{-1} and less than -3 mg CO_2 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.