CO₂, Water Vapor and Energy Fluxes in a Larch Forest in Northeast China

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Abstract

A flux observation site was built in northeast China to identify the energy, H₂O and CO₂ fluxes of a larch forest ecosystem and the effect of environmental variables. The energy balance was estimated to be 86% using half-hourly flux data, but the energy was completely closed when the accumulated data was used. This indicated the possibility of energy storage in the forest at this site. Radiation plays an important role in controlling the ecosystem carbon sequestration. The ecosystem sequestered 6.18 $\mu\text{mol m}^{-2} \text{s}^{-1}$ on clear days, much higher than the 3.62 $\mu\text{mol m}^{-2} \text{s}^{-1}$ on cloudy days. However, the light use efficiency of the ecosystem was much higher on cloudy days than on clear days, the reason being generally ascribed to the more diffuse radiation on cloudy days. However, the lower vapor pressure deficit on cloudy days than on clear days also contributed to this result.

Keywords: CO₂ flux, Eddy covariance method, Energy flux, Larch forest.

1. Introduction

Temperate and boreal ecosystems are expected to function as a net carbon sink (Tans *et al.*, 1990). Larch forest, as one of the most important components of the boreal forest in Eurasia, is believed to play an important role in supporting the net carbon gain (Gower and Richards, 1990). However, due to the variation in environmental conditions, such as meteorological, topographical and pedologic characteristics, the carbon exchange rate for larch forest in different regions varies greatly. Studies indicate that a larch forest in Northern Japan sequestered about 140–293 g C m⁻² yr⁻¹ in 2001 (Hirano *et al.*, 2003; Wang *et al.*, 2004), while a larch forest in Siberia sequestered only 90 g C m⁻² yr⁻¹ (Hollinger *et al.*, 1998). To understand the energy and carbon fluxes of larch forest between the two regions, an observation site, Laoshan flux site, was established in northeast China in 2002. This is also the first forest flux observation site using the eddy covariance method in China. In this study, we mainly analyzed the responses of energy and CO₂ fluxes of the larch forest ecosystem to environmental variables in the growing season.

2. Study Site

Laoshan flux site (LS, 45°20' N, 127°34' E) is located in an artificial larch (*Larix gmelinii*) forest in northeast China (Fig. 1), which belongs to the southern distribution edge of the *Larix gmelinii* species. The elevation of the tower site is about 370 m above sea level (ASL). There is a mountain of about 700 m ASL on the north of the site and the flux tower was built on a southern-toward slope of about

5–6 degrees. The western part of the tower was a low hill covered with broad-leaved forest. A typical temperate monsoon climate dominates this region. The annual mean precipitation is 724 mm, and the annual mean temperature is 2.8 °C (Shi *et al.*, 2001).

The forest was planted in 1969 as a pure larch forest. However, during the long period of natural evolution, some broad leaf species, such as birch (*Betula platyphylla*) and ash (*Flaxinus mandshurica*), invaded into the forest as canopy species. The composition of the forest is 88%, 7.5% and 4% in basal area and 81.3%, 7.8% and 6.3% in individual numbers for larch, birch and ash, respectively. The mean canopy height of the forest is about 17 m. Shrub species, such as *Ulmus propinqua*, *Corylus heterophylla*, *Lonicera ruprechtiana*, *Syringa mandshurica*, *Rubus sachalinensis*, *Sorbaria solbifolia*, *Acanthopanax senticosus*, *Aralia elata*

Fig. 1 Position of Laoshan flux site

etc., have also been found in the forest. The forest floor is covered with abundant herbs, which mainly belong to the *Cyperaceous* and *Liliaceous* families (Shi *et al.*, 2001). The soil was a typical dark brown forest soil.

3. Method and Instrumentation

3.1 Flux measurement and calculation

Sensible heat, latent heat, H_2O and CO_2 fluxes over the larch forest were continuously measured using a closed path eddy covariance system. Wind velocity and virtual temperature were measured using a three-dimensional ultrasonic anemometer (SAT-550, KAIJO, Japan), which was set at 29 m above ground. Concentrations of CO_2 and H_2O were measured with a closed path CO_2/H_2O infrared gas analyzer (IRGA) (LI-7000, LICOR, USA). The gain of CO_2 and H_2O of the analyzer was checked once a day automatically by flowing two standard CO_2 gases of 320 ppmv and 420 ppmv. The raw data of the three components of wind velocity from the anemometer and vapor and CO_2 concentration from IRGA was recorded at a rate of 10 Hz using a data logger (CR 23X, CSI, USA).

CO_2/H_2O fluxes were calculated half-hourly. To minimize the calculation error, we 1) rejected the noise spikes in the raw data, 2) made a coordinate rotation to force the vertical wind speed zero, 3) made a WPL correction for air density fluctuation, 4) corrected the lag time for the response of CO_2/H_2O concentrations caused by long air sampling tube, 5) calculated CO_2/H_2O fluxes as the covariance of CO_2/H_2O concentrations and vertical wind speed. The carbon storage (Fs) under the canopy was estimated from the temporal difference in CO_2 concentration measured at the flux plane as previously described (Saigusa *et al.*, 2002; Wang *et al.*, 2004). The net ecosystem CO_2 exchange (NEE) is the sum of CO_2 flux (Fc) and Fs, and the minus sign indicates the ecosystem uptake of CO_2 from the atmosphere. The daytime ecosystem respiration (RE) was estimated from the relation between night-time NEE and air temperature (T_a) as shown in Fig. 6, and the gross primary production (GPP) was calculated as the difference between RE and NEE ($GPP=RE-NEE$).

3.2 Meteorological measurement

The incident/reflected long wave and short wave radiation were measured using a net radiometer (MR-40, EKO, Japan) at 21m above ground. Two PAR-02 sensors (PREDE, Japan) loaded on the net radiometer in upward and downward directions were used to monitor the incident and reflected photosynthetic active radiation (PAR). The PAR transmitted through the canopy was measured with PAR sensors set in the forest at 1 m above the ground. Air temperature and relative humidity were measured at 14 m (within the canopy) and 21 m (above the canopy) with humidity/temperature probe (HMP45D, VAISALA, Finland); variation of air pressure was

measured using a barometer. Soil temperature was measured at depths of 5cm, 10cm, 20cm and 50 cm using C-PTG-30 (Climatec, Japan). TDR sensors (CS-615, CSI, USA) were set at depths of 5 and 20 cm to measure soil water content. Variation of Soil heat flux was detected using soil heat flux sensors (MF-81, EKO, Japan) installed at a depth of 5 cm.

4. Results and Discussion

4.1 Energy balance

The accuracy of the eddy covariance measurement at LS was evaluated by checking the energy balance. Generally, the energy balance is expressed as

$$R_n - G = H + LE \quad (1)$$

Where H and LE are sensible and latent heat measured by eddy covariance method, while R_n and G are net radiation and soil heat flux directly measured by meteorological sensors. The left side of equation 1 is generally called available energy, whereas the right side of the equation is known as turbulent energy. Fig. 2 shows that the agreement of turbulent energy with available energy was 86% using half-hourly data. This indicated that the turbulent energy might have been underestimated. However, for the five days from June 1 to June 5, the accumulated turbulent energy and available energy was estimated to be 65.4 and 63.4 MJ m^{-2} , respectively, and the energy was completely closed. Wilson *et al.* (2002) indicated that the energy closure could be expected to improve by about 7% if the heat storage was considered. The energy storage at LS seemed to be much higher than at other flux sites.

Fig. 2 Energy balance at Laoshan flux site using half-hourly data from June 1 to 5, 2002. The linear relation between the turbulent and available energy was $H+LE = 0.86*(R_n-G) + 25.4$ ($R = 0.9539$).

4.2 Response of fluxes to environmental variables

Fig. 3 shows the temporal variation of sensible heat (H), latent heat (LE), H_2O flux (Fh), NEE and environmental variables, such as PAR, air temperature (T_a) and vapor pressure deficit (VPD), in June 2002. All fluxes and environmental variables clearly showed daily variations and peaked (minus peak for NEE and plus peak for the others) in the daytime on clear days. The maximum PAR was about 2000 $\mu mol\ m^{-2}\ s^{-1}$, the VPD was as high as 30 hPa on

Fig. 3 Temporal variation of energy, H₂O, CO₂ fluxes and environmental variables in June 2002.

Fig. 4 Diurnal variation of sensible heat, H₂O and CO₂ fluxes with environmental variables on a clear (June 23) and cloudy (June 20) day.

Fig. 5 The different responses of GPP to PAR on clear and cloudy days. The dash line and the solid line show the best fitted curves for cloudy and clear days, respectively.

clear days. The half-hourly NEE varied from -40 to $30 \mu\text{mol m}^{-2} \text{s}^{-1}$, and the maximum carbon uptake rate was similar to that of a larch forest in northern Japan (Wang *et al.*, 2004), but about 4 times higher than

Fig. 6 Temperature dependence of ecosystem respiration on windy nights ($U^* > 0.20 \text{ m s}^{-1}$).

Fig. 7 Relation between NEE and VPD under strong light condition ($\text{PAR} > 700 \mu\text{mol m}^{-2} \text{s}^{-1}$).

that in Siberia (Hollinger *et al.*, 1998).

The energy, H₂O and CO₂ fluxes also clearly varied with the weather conditions (Fig. 4). On clear days (defined as the daily mean $\text{PAR} > 500 \mu\text{mol m}^{-2} \text{s}^{-1}$), the incident PAR, T_a , VPD, heat and H₂O fluxes were obviously higher than on cloudy days (defined as the daily mean $\text{PAR} < 400 \mu\text{mol m}^{-2} \text{s}^{-1}$), and the NEE was more negative than on cloudy days, which indicated more carbon was assimilated on clear days. However, under the same PAR conditions, the GPP of the ecosystem was obviously higher on cloudy days than on clear days as shown in Fig. 5. For example, when the PAR was 500 and $1000 \mu\text{mol m}^{-2} \text{s}^{-1}$, GPP was estimated as 18.2 and $26.4 \mu\text{mol m}^{-2} \text{s}^{-1}$ on clear days, but greatly enhanced to 24.3 and $36.0 \mu\text{mol m}^{-2} \text{s}^{-1}$ on cloudy days. Many reports indicated the significantly higher light use efficiency of ecosystems on the cloudy days than on clear days (Hollinger *et al.*, 1994; Baldocchi, 1997; Goulden *et al.*, 1997; Gu *et al.*, 1999). It is known that the appearance of cloud in the sky reduces the direct radiation and enhances the portion of diffuse radiation. Gu *et al.* (1999) even pointed out that the absolute amount of diffuse radiation on cloudy days can also be increased if it is not too cloudy. Therefore, most scientists ascribe this phenomenon to the high light use efficiency of diffuse radiation on cloudy days (Hollinger *et al.*, 1994; Goulden *et al.*, 1997).

However, as shown in Fig. 4, the temperature and VPD was rather higher on clear days than on cloudy days. The mean temperature and VPD was 19.9 °C and 11.6 hPa on clear days, but only 15.1 °C and 3.1 hPa on cloudy days, respectively. The higher VPD clearly decreased the ecosystem carbon assimilation ability (Fig. 7). The higher temperature enhanced the ecosystem respiration (Fig. 6), but seemed to have no influence on the GPP (figure was omitted). Therefore, the higher light use efficiency on the cloudy days should not be only ascribed to the more diffuse radiation. Lower VPD was also responsible for it.

5. Conclusions

The energy and CO₂/H₂O fluxes of the larch forest ecosystem greatly varied temporally with the environmental variation. Turbulent energy (H+LE) accounted for 86% of available energy (Rn-G) using half-hourly data, but the energy balance was completely closed when 5-day accumulated energy data was used. This indicated that the energy storage at this site could be considerably high. The ecosystem respiration increased with the increasing temperature exponentially, and the ecosystem carbon assimilation rate tended to decrease with the increasing VPD. The ecosystem carbon uptake rate was much higher on clear days than on cloudy days because that sufficient radiation improved the photosynthesis. While the light use efficiency was much higher on cloudy days than on clear days. The more diffuse radiation and its higher light use efficiency on cloudy days are usually considered to be the main reason, but the lower VPD on cloudy days than on clear days was obviously also responsible for this phenomenon.

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