Meteorological control on CO_2 flux above broad-leaved Korean pine mixed forest in Changbai Mountains

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Abstract The impacts of temperature, photosynthetic active radiation (PAR) and vapor pressure deficit (VPD) on CO_2 flux above broad-leaved Korean pine mixed forest in the Changbai Mountains were studied based on eddy covariance and meteorological factors measurements. The results showed that, daytime CO_2 flux was mainly controlled by PAR and they fit Michaelis-Menten equation. Meanwhile VPD also had an influence on the daytime flux. Drier air reduced the CO_2 assimilation of the ecosystem, the drier the air, the more the reduction of the assimilation. And the forest was more sensitive to VPD in June than that in July and August. The respiration of the ecosystem was mainly controlled by soil temperature and they fit exponential equation. It was found that this relationship was also correlated with seasons; respiration from April to July was higher than that from August to November under the same temperature. Daily net carbon exchange of the ecosystem and the daily mean air temperature fit exponential equation. It was also found that seasonal trend of net carbon exchange was the result of comprehensive impacts of temperature and PAR and so on. These resulted in the biggest CO_2 uptake in June and those in July and August were next. Annual carbon uptake of the forest ecosystem in 2003 was -184 $gC \cdot m^{-2}$.

Keywords: CO_2 flux, soil temperature, PAR, broad-leaved Korean pine mixed forest.

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Increasing of the CO_2 concentration is considered as the important reason of global warming. As one of the continental ecosystem with the biggest area, forest ecosystem can uptake a large amount of carbon dioxide by photosynthesis and restore it for a long time. So studying on CO_2 flux of forest ecosystem is always being a focus of global change researches[1—3]. It was difficult to carry out ecosystem-scale research on forest CO_2 flux by direct measurement in the past because of high vegetation. So many researches aimed at definite component, such as forest soil, individual plant, leaves[9—11], stems[11] and so on. Some studies estimated ecosystem-scale carbon exchange indirectly. And a few papers estimated it using the dynamics methods in atmospheric boundary layer meteorology[13]. But these results were generally based on short period measurements and experiments. The eddy covariance technique developed in recent years made ecosystem scale CO_2 flux measurements possible. CO_2 monitoring stations have been constructed all over the world, and regional measurement nets, such as CARBOEUROFLUX, AMERIFLUX, ASIAFLUX, etc. were established. The eddy covariance technique has become an important tool for carbon exchange researches. A lot of stations were constructed in forest sites due to the significance of forest in carbon sequestration. 80 out of 140 stations of FLUXNET in 2001 were constructed in forest[14]. ChinaFlux was established in 2002, including 5 forest sites.

For the undisturbed natural forest ecosystem, plant construction and soil characteristics keep relatively stable. CO_2 flux is mainly affected by environments in which meteorological factor is most concerned as they are directly associated with global warming. Many studies on the influences have been done[16—18]. But there are differences among the sites because of the diversity of climate, ecosystem type, etc. The broad-leaved Korean pine mixed forest in the Changbai Mountains is the typical vegetation in the temperate zone. It is at eastern end of NECT and very sensitive to climate change. It will be aimed at in this paper and the influence of meteorological factors on its CO_2 flux will be analyzed based on the year-round measurements. The annual dynamic of CO_2 flux will also be expounded. We hope that these results could provide a basis for carbon cycle researches in forest ecosystem.

1 Materials and methods

1.1 Site description

The measurement was carried out in the broad-leaved Korean pine mixed forest near the Changbai Mountains forest Ecosystem Research Station, CAS. The measurement tower is situated at 42°24′09″N, 128°05′45″E with an elevation of 738 m. Annual mean temperature and total precipitation are 3.6℃ and 695 mm, respectively. Soil is montane dark brown forest soil. The surface is flat and the forest is matured natural forest. The forest surrounding the tower is dominated by Korean pine (*Pinus koriaensis*), Tuan linden (*Tilia amurensis*), Mono maple (*Acer mimo*), Manchurian ash (*Fraxinus mandshurica*), Mongolian oak (*Quercus mongolica*), elm (*Ulmus glabra*) and other deciduous species interspersed. The forest is of multi-layer structure, with understory coverage 40%. Average crown height is 26 m and stem density is 560 stems hm^{-2}.

1.2 Measurements

The height of the meteorological tower at the observation site is 62 m. The sensors of eddy flux were installed at an arm located 40 m (one and half tree height) above ground and extended 3 m upwind of the tower. The flux measurement system consisted of a triaxial sonic anemometer (CAST3, Campbell, USA) and a fast response open-path CO_2/H_2O infrared gas analyzer (Li-7500, LiCor Inc., USA). Sampling frequency was 10 Hz both for the sonic anemometer and for infrared gas analyzer. The samples were stored in data logger (CR5000, Campbell Scientific, USA) and 30 min mean values were calculated. In addition, routine meteorological gradient system was installed on the tower, including 7-level temperature and humidity (HMP45C, Vaisala, Helsinki, Finland), with the heights of 2.5, 8, 22, 26, 32, 50, 60 m. Senor of photosynthetic active radiation (LI-190Sb, LiCor Inc., USA) was mounted at 32 m height. Senor of soil temperature (105T, Campbell, USA) was positioned at 0, 5, 10, 20, 50, 100 cm depths. These factors were sampled in 0.5 Hz and the data were stored in the data loggers (CR23X and CR10X, Campbell Scientific, USA). Averages in 30 min were also calculated by the data loggers and stored. The measurements were started from 24 August, 2002 and the data of 2003 were used in this paper.

1.3 Flux calculations and corrections

From the time series of vertical wind velocity and temperature, carbon dioxide density and water vapor density, the fluxes were calculated online with 30 min interval using the calculation software. Turbulent carbon dioxide fluxes (F_c), latent heat flux (λE) and sensible heat flux (H) were determined as

$$F_c = \rho\overline{c'w'}, \tag{1}$$

$$\lambda E = \lambda\rho\overline{w'q'}, \tag{2}$$

$$H = \rho C_p\overline{T'w'}, \tag{3}$$

where ρ is the density of dry air, w the vertical wind speed, c the mixing ratio of CO_2, λ the latent heat of vaporization, E the vapor flux, q the specific humidity, C_p the specific heat capacity of dry air and T the sonic temperature. Overbars denote time averages and primes denote the deviation from mean. Both the CO_2 flux (F_c) and latent flux (λE) were corrected for density effects using the method suggested by Webb[20]. To investigate the influence of various coordinate rotations, we also made a 3D rotation and a planar-fit rotation[21]. However, differences in the annual carbon flux were small (0.5% for 3D and 2.3% for planar-fit).

The storage of CO_2 below the measuring height of the eddy covariance system (F_s) was determined as the time change of the CO_2 concentration measured by Li-7500 at 40 m of the tower. Final CO_2 fluxes were calculated as the sum of the turbulent flux and the storage term

$$\mathrm{NEE} = F_c + F_s.$$

Fluxes into the ecosystem (e.g. assimilation) are noted with a negative sign, while fluxes from the ecosystem to the atmosphere (e.g. respiration) are given with a positive sign.

The flux measurements were screened strictly to accurately describe the ecological process. Samples with deviations bigger than three times of standard deviation were deleted. And the samples under weak turbulence (friction velocity $u^* < 0.2\ \mathrm{m \cdot s^{-1}}$) were also discarded[26]. The threshold of u^* was similar with that in the forest site[26—29].

Usable data covered 86.9% of the measurements. Small gaps (shorter than 3 h) were filled by interpolation. The larger gaps were filled by eqs. (4) and (5) for daytime and nighttime respectively.

2 Results

2.1 Influence of photosynthetic active radiation on daytime CO_2 flux

The impacts of photosynthetic active radiation on CO_2 occurred in the daytime of growing season and their relationship can be described by Michaelis-Menten equation:

$$\mathrm{NEE} = a_1 - \frac{a_2\,\mathrm{PAR}}{a_3 + \mathrm{PAR}}, \tag{4}$$

where a_1 is the dark respiration parameter, a_2 the maximum rate of photosynthesis, and a_3 the Michaelis-Menten constant.

The parameters of eq. (4) were calculated for growing season in month-length window by the least square method according to the measurements. The results are listed in table 1. It can be seen that a_1 and a_2 were lower in early (May) and end (September) growing season, bigger in middle growing season (June to August). a_3 was between 400—630 $\mu\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$. These reflected the dynamics of assimilation and respiration of the ecosystem. The correlation R^2 expressed the contribution of PAR to daytime CO_2 flux. And the result showed that PAR contributed 53.9%—61.4% to the variations of daytime carbon flux.

2.2 Impact of soil temperature on ecosystem respiration

One of the impacts of soil temperature on ecosystem is implied in its determination on phenology of the forest plant. Especially for the forest to the north of temperate zone where experiences hot and cold seasons, length of growing season dependent on temperature is a very important factor to carbon balance[30—33]. But for a definite site, respiration (R_e) and soil temperature (T_s) are fit exponential[22—25]:

Table 1 The parameters of eq. (4) and the correlation in growing season

Month	a_1/$\mathrm{mgCO_2 \cdot m^{-2} \cdot s^{-1}}$	a_2/$\mathrm{mgCO_2 \cdot m^{-2} \cdot s^{-1}}$	a_3/$\mu\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$	R^2
May	0.127	0.717	570	−0.575
June	0.250	1.277	397	−0.565
July	0.260	1.423	543	−0.614
August	0.238	1.240	480	−0.587
September	0.123	0.862	630	−0.539

$$R_e = b_1 \exp(b_2 T_S), \qquad (5)$$

where b_1 and b_2 are coefficients that are related with properties of the ecosystem, such as soil, vegetation and structure and so on. We estimated the coefficients according to the measurements and gave $b_1 = 0.0356$, $b_2 = 0.1296$[26].

Further analysis found that respiration before middle July was always higher than that after middle August under the same soil temperature. So the measurement was divided into two sections from the end of July. And the coefficients were estimated by the least square method for the two sections separately. As a result, two equations with evident difference were obtained and the coefficients and correlations were (fig. 1)

$$b_1 = 0.0459, \quad b_2 = 0.1295, \quad R^2=0.773 \quad \text{(early period)}, \qquad (6)$$

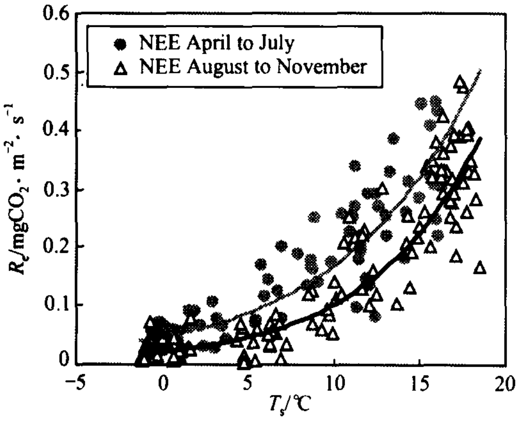

Fig. 1. Relationship between R_e and T_s for the two periods.

$$b_1 = 0.0211, \quad b_2 = 0.1579, \quad R^2=0.776 \quad \text{(late period)}. \qquad (7)$$

Figure 1 shows that respiration during the early period was bigger than that during the late period under the same soil temperature. The reason may be as follows: when spring comes, air temperature rises first and then does the surface soil. Plant above the ground and shallow roots grow and the respiration increases. In autumn, cold air makes the plants deciduous and respiration decreases. Drop of the soil temperature happens later than that of air temperature. Compared with the plant in autumn under the same soil temperature, plant in spring is in the more active life stage and has bigger respiration. The widely used temperature index of shallow soil for respiration might have its limitation in some degree.

2.3 Impact of VPD on daytime CO_2 flux

Measurements of CO_2 flux were divided into 3 classes corresponding to divisions of VPD. And the parameters of eq. (4) were estimated by the least square method for the 3-class measurements respectively. a_1 took the values in table 1. The result showed that a_2 and a_3 were sensitive to VPD (fig. 2). Bigger VPD resulted in lower values of a_2 and a_3, namely decreased the assimilation of CO_2 in daytime. The higher the VPD, the larger the decrease of the assimilation of CO_2. This may result from the influence of drier air on the leaf physiology. It also could be seen that the ecosystem was more sensitive to VPD in June than that in July and August. Anthoni et al.[34] found the inverse relationship between CO_2 flux and VPD

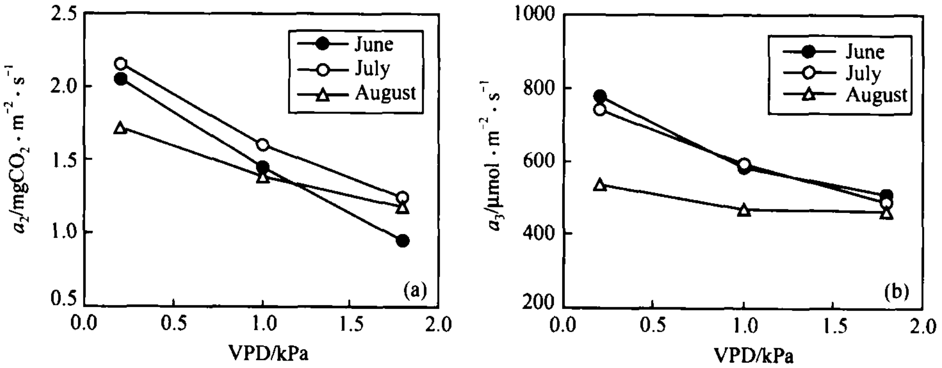

Fig. 2. Variation of a_2 and a_3 with VPD from June to August.

and suggested that a term should be added to eq. (4) to express the impact of VPD. But we suggest that this influence should be reflected on the magnitude of parameters of eq. (4) because VPD changes the leaf physiology. This made eq. (4) more meaningful.

2.4 Influence of daily mean air temperature on net CO_2 exchange

Figure 3 shows the variation of daily net carbon exchange, NEE_d, versus daily mean air temperature, T_d, at 26 m height. When T_d was lower than 0℃, there was weak and relatively stable CO_2 efflux from the ecosystem, in the magnitude of about 0.56 $gC \cdot m^{-2} \cdot d^{-1}$. When T_d rose from 0℃ to 10℃, NEE_d slightly increased in negative. As T_d was higher than 10℃, NEE_d sharply increased in negative. This pattern could be expounded in exponential

$$NEE_d = 0.580 – 0.014 \exp (0.310 T_d). \qquad (8)$$

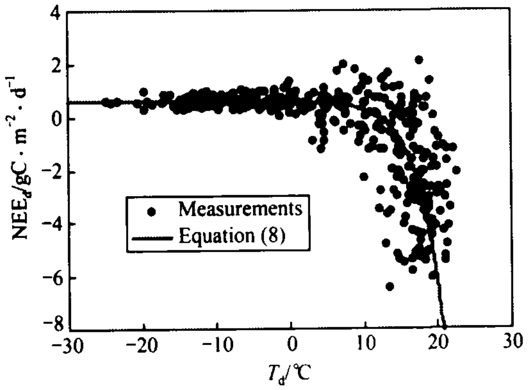

Fig. 3. Relationship between daily net carbon exchange NEE_d and daily mean air temperature T_d.

The sample number n=321 and correlation R^2=0.851. This equation well described the correlations of NEE and T_d for the site.

It also could be found that measurements dispersed when T_d was higher than 5℃. This explained that NEE_d was also impacted by other factors besides temperature, such as phenology, PAR, humidity and so on.

2.5 Seasonal dynamics of net carbon exchange correlated with air temperature and PAR

Figure 4 plots the annual dynamics of monthly sum of net carbon exchange, as well as the monthly mean air temperature and monthly averaged daily sum of PAR. Correlative variation among them was obvious. When air temperature was under 0℃ from January to March, plants were dormant and soil was frozen. Life activity of the ecosystem was weak and small respiration occurred. When air temperature rose to 6.8℃ in April, the plant began to bourgeon and grow. Assimilation and respiration both increased and they were approximately balanced in this month. It was the fast growing season from May to August. Assimilation by photosynthesis surpassed the respiration as the temperature and PAR increased. The ecosystem became sink of carbon. The biggest monthly uptake occurred in June as −114.4 $gC \cdot m^{-2}$. This was due to appreciate temperature and plenty of sunshine. Relatively less uptakes were in July and August (−82.5, −65.1 $gC \cdot m^{-2}$) because of more cloud and rain and aging of the leaves. Temperature in September dropped and leaves were aged. Even some species defoliated. These made assimilation decreased and net carbon exchange of this month was near zero. Cold winter came after October and the characteristic of carbon exchange was similar with that in January to March. The carbon uptake of the ecosystem in 2003 was −184 $gC \cdot m^{-2}$. This was similar to the measurement in near 100-year-old temperate mixed forest in south Ontario in Canada (190 $gC \cdot m^{-2}$)[35].

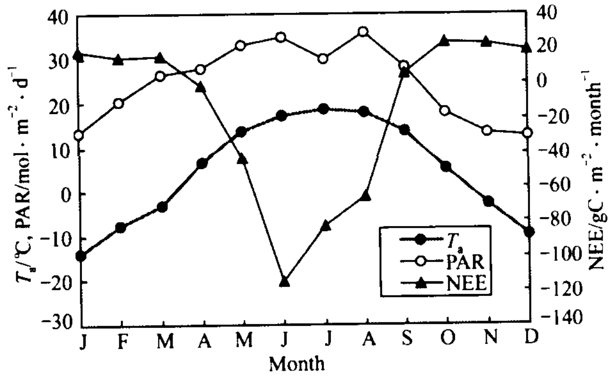

Fig. 4. Correlative annual variation among monthly sum of net carbon exchange NEE and monthly mean air temperature and monthly averaged daily sum of PAR.

3 Conclusion

Temperature and PAR were the main environmental factors that influence the CO_2 flux above forest ecosystem. Under the local climate, dark respiration of the broad-leaved Korean pine mixed forest in the Changbai Mountains was mainly controlled by soil temperature and they fit exponential equation. But respiration from April to June was higher than that from August to November under the similar temperature. This may be caused by the hysteresis of phenology and soil temperature to air temperature. Daytime CO_2 flux was mainly controlled by PAR and they fit Michaelis- Menten equation. Meanwhile, VPD also influenced the flux. Drier air reduced the CO_2 assimilation of the ecosystem, which is more obvious in June.

Annual dynamics of CO_2 flux was a comprehensive result of temperature-dependent phenology and PAR. The measurement showed that, the ecosystem kept small CO_2 efflux in winter season (January to March and October to December), nearly zero net exchange in April and September and showed sink from May to August. The largest uptake occurred in June. Net daily carbon exchange and daily mean temperature fit exponential relation.

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