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Response of CO_2 Flux to Environmental Variables in Two Larch Forest Ecosystems in East Asia

By

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Summary

WANG H., SAIGUSA N., ZU Y., YAMAMOTO S., KONDO H., YANG F., WANG W., HIRANO T. & FUJINUMA Y. 2005. Response of CO_2 flux to environmental variables in two larch forest ecosystems in East Asia. - Phyton (Horn, Austria) 45 (4): (339)-(346).

The relationships between CO_2 fluxes in larch forest ecosystems and environmental variables were investigated. The results indicate that the ecosystem CO_2 uptake tended to decrease with an increasing vapor pressure deficit (VPD) when the VPD exceeded 15 hPa at both the Laoshan site (LS) in Northeast China and at the Tomakomai site (TFS) in northern Japan. The similarity of the VPD threshold value indicates that the larch forests at these two sites have a similar response to a dry environment. The carbon uptake rate of the larch forest was significantly lower on cloudy days (3.62 $\mu mol\ m^{-2}\ s^{-1}$ at LS and 3.76 $\mu mol\ m^{-2}\ s^{-1}$ at TFS) than on clear days (6.18 $\mu mol\ m^{-2}\ s^{-1}$ at LS and 6.53 $\mu mol\ m^{-2}\ s^{-1}$ at TFS) due to the significantly reduced incident radiation on cloudy days. However, the light-use efficiency of larch forests was much higher on cloudy than on clear days. This was due not only to the more diffused radiation on the cloudy days but also to a low VPD. Beyond our expectation, the air temperature showed almost no effect on the light-use efficiency of the larch forests.

Introduction

It is widely agreed that the increasing atmospheric greenhouse gases, especially anthropogenic CO_2, are responsible for the recent climate warming.

Forest ecosystems constitute a large component of the terrestrial biosphere

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and will likely play a significant role in the regulation of the atmospheric CO_2 level (WOFSY & al. 1993, BALDOCCHI & al. 1997).

Larch forests are typical in northern Eurasia and cover a vast area in the north temperate and boreal region. Larch forests, for example, cover 277.5×10^6 ha in the Siberian region (SHVIDENKO & NILSSON 1994), 15.6×10^6 ha in northeast China, where Dahurian larch (*Larix gmelini*) grows (JIANG & ZHOU 2002), and 47×10^4 ha in Hokkaido Island in Japan, where planted Japanese larch (*Larix kaempferi*) grows (HIRANO & al. 2003). Hence, as a large carbon pool, the carbon budget of larch forest ecosystems has attracted much attention. To understand the carbon sequestration ability of larch forests at the present time under different environmental conditions and to evaluate/predict the effect of climate change on its large carbon pool, an eddy covariance flux observation was carried out at the Tomakomai site (TFS) in northern Japan and at the Laoshan site (LS) in northeast China. Flux measurements indicate that the larch forest sequestered 140~293 g C m^{-2} yr^{-1} at TFS (HIRANO & al. 2003, WANG & al. 2004), which is much more than that sequestered by the larch forest in the Siberian region (HOLLINGER & al. 1998). However, due to the large diversity in the growing environment and the uncertainty of the effect of environmental factors, it is impossible to estimate the carbon sequestration ability of a larch forest ecosystem by simply extrapolating the results obtained at flux observation sites. In this study, we investigated some of the issues surrounding the environment-CO_2 flux relationship for larch forests during the growing season.

Material and Methods

This study was carried out at the Tomakomai Flux Research Site (TFS, 42°44' N, 141°31'E) in Hokkaido, Japan, and at the Laoshan Flux Research Site (LS, 45°20' N, 127°34'E) in northeast China. Both sites are larch plantations located in cool temperate region. The larch species are Dahurian larch (*Larix gmelini*) at LS and Japanese larch (*L. kaempferi*) at TFS. The soil is classified as a typical dark-brown forest soil at LS and as an immature volcanogenous regosol at TFS. The LS site is located about 370 m above mean sea level and is characterized by a mean air temperature of 2.8 °C and an annual precipitation of 740 mm. The TFS site is located at an elevation of 125 m, with a mean air temperature of 7.4 °C and an annual precipitation of 1250 mm (HIRANO & al. 2003, WANG & al. 2004, 2005).

The closed path eddy covariance method was used to measure the CO_2 flux at both sites. The measurement height was 27 m and 29 m above ground at TFS and LS, respectively. The flux observation started in August 2000 at TFS and in May 2002 at LS. At TFS, fluctuations in the CO_2 concentration were measured using an infrared CO_2/H_2O analyzer (LI6262, LICOR, USA); the wind velocity and virtual temperature were determined using a 3-D anemometer (DA-600-3TV, KAIJO, Japan). At LS, an infrared CO_2/H_2O analyzer (LI7000, LICOR, USA) and an anemometer (SAT550, KAIJO, Japan) were used to measure the CO_2 concentration and wind velocity, respectively. The raw flux data were recorded at a rate of 10 Hz at both sites. Parallel to the flux measurement, some meteorological and soil variables, such as air temperature, humidity, net radiation, photosynthetic active radiation (PAR), soil temperature, soil water content, and soil heat flux, were measured at both sites. The available photosynthetic active radiation (APAR) was calculated from the incident PAR by excluding the canopy reflected and transmitted PAR.

The CO_2 flux was calculated half-hourly as the covariance between vertical wind speed and CO_2 densities. 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 to be zero, 3) made a WPL correction for air density fluctuations, and 4) corrected the lag time for the response of the CO_2 concentration caused by a long air-sampling tube (SAIGUSA & al. 2002, WANG & al. 2004). The CO_2 storage was estimated from the temporal change in the CO_2 concentration at the height of the flux measurement plane (HOLLINGER & al. 1994, HIRANO & al. 2003). The net ecosystem CO_2 exchange (NEE) was calculated as the sum of the CO_2 flux and the corresponding storage. The daytime ecosystem respiration (RE) was estimated from the air temperature using the relationships between NEE and the temperature derived from data obtained during windy nights. The gross primary production (GPP) was estimated as the residue between RE and NEE (GPP=RE-NEE). In this study, we followed the meteorological convention of denoting a minus NEE value to be the forest ecosystem uptake.

Results and Discussion

Fig. 1 shows the temporal variation of the half-hourly mean CO_2 flux and the corresponding environmental variables at LS and TFS for June 2002. The maximum half-hourly PAR on clear days was around 2000 μmol m^{-2} s^{-1} at both sites, while the monthly mean PAR at LS was 463 μmol m^{-2} s^{-1}, 13.5% higher than that at TFS (408 μmol m^{-2} s^{-1}) due to a relatively smaller number of cloudy days. The air temperature was 17.8 °C at LS, which was higher than that of 12.6 °C at TFS. Correspondingly, the vapor pressure deficit (VPD) was also higher at LS than at TFS. There was no single half-hourly VPD value exceeding 15 hPa at TFS, while the maximum VPD exceeded 30 hPa at LS. The NEE varied generally from positive (release of CO_2) at night to negative (uptake CO_2) in the daytime. The half-hourly maximum net CO_2 uptake was about 40 μmol m^{-2} s^{-1} at both sites, which is 4 times higher than that observed at a larch forest ecosystem in the Siberian region (HOLLINGER & al. 1998).

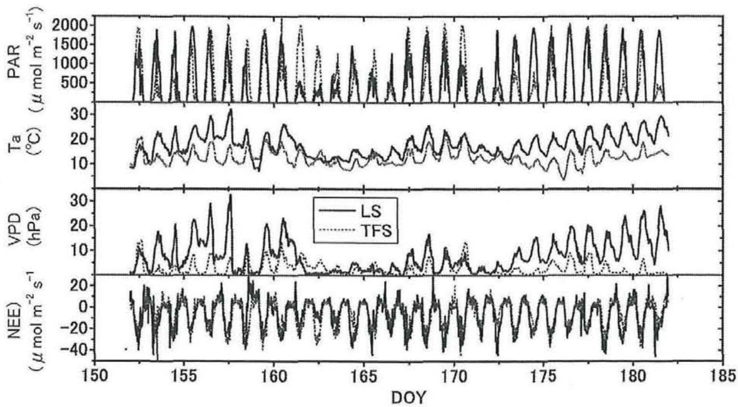

Fig. 1. Temporal variation of PAR, air temperature (Ta), vapor pressure deficit (VPD), and corresponding NEE at LS (thick solid lines) and TFS (thin dash lines) in June 2002.

Temperature is an important factor affecting the carbon budget of an ecosystem, causing it to act as a carbon sink or source (VALENTINI & al. 2000). Fig. 2 shows the exponential relationships between ecosystem respiration and air temperature (RE-Ta) on calm (friction velocity $U^*<0.20$ m s^{-1}) and windy nights ($U^*>=0.20$ m s^{-1}) at both LS and TFS. The results clearly indicate that the ecosystem respiration would be lower evaluated under calm night conditions at both sites, and are consistent with other studies using the eddy covariance technique (BALDOCCHI & al. 1997, SAIGUSA & al. 2002). Furthermore, the RE-Ta relation shows that the nighttime NEE (RE) at LS has a greater dependency on the U* than at TFS. That is, at a same temperature, the difference in RE between windy and calm night tends to be larger at LS than at TFS. For example, the RE differences between windy and calm nights at LS and TFS were estimated to be, respectively, 1.62 μmol m^{-2} s^{-1} and 0.76 μmol m^{-2} s^{-1} at 0 °C, 2.92 μmol m^{-2} s^{-1} and 1.97 μmol m^{-2} s^{-1} at 10 °C, and 5.15 μmol m^{-2} s^{-1} and 5.04 μmol m^{-2} s^{-1} at 20 °C. This result might be caused by the more complicated topography that characterizes the LS site.

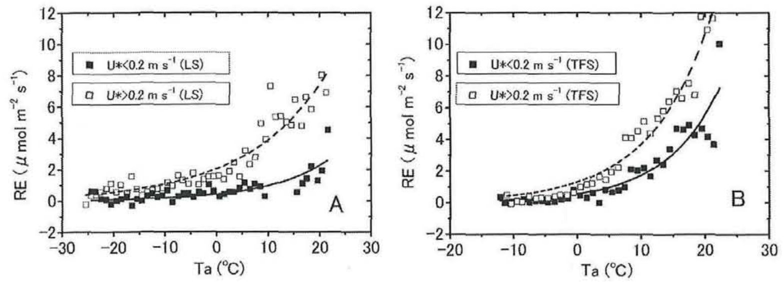

Fig. 2. Ecosystem respiration (RE) as a function of the air temperature (Ta) at LS (A) and TFS (B) on calm (■ and solid line: $U^*<0.20$ m s^{-1}) and windy (□ and dash line: $U^*>=0.20$ m s^{-1}) nights. The curves are empirical regression results with $RE=0.401e^{0.0862Ta}$ ($U^*<0.20$) and $RE=2.0221e^{0.0649Ta}$ ($U^*>=0.20$) for LS and $RE=0.5448e^{0.116Ta}$ ($U^*<0.20$) and $RE=1.301e^{0.1048Ta}$ ($U^*>=0.20$) for TFS.

Fig. 3 shows the relation between the daytime NEE and the corresponding VPD at the two sites. Here, to avoid disturbance from radiation, only those data obtained under strong light conditions (PAR>700 μmol m^{-2} s^{-1}) are used. The VPD at TFS was obviously lower than that at LS. The maximum VPD at TFS was only 15 hPa, just half of that at LS. This is clearly caused by the higher temperature at LS, although there was more precipitation at LS (109 mm) than at TFS (73 mm) in June 2002. Because most of the half-hourly mean VPD values at TFS are lower than 10 hPa, they have almost no influence on the NEE. This result is consistent with our previous study (WANG & al. 2004). At LS, the carbon uptake rate tends to decrease when VPD exceeds about 15 hPa. The VPD thresholds at LS and TFS are similar in magnitude and are much lower when compared with those obtained for a larch forest in eastern Siberia (HOLLINGER & al. 1998, WANG & al. 2004), indicating that the larch forest ecosystems at LS and TFS tend to have lower endurance against dry environmental conditions.

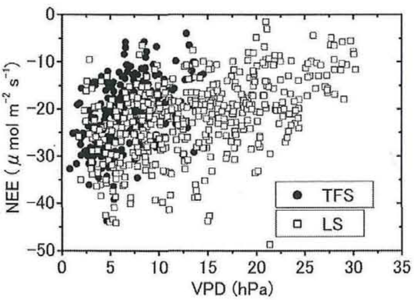

Fig. 3. Effects of the VPD on NEE at LS and TFS in June 2002. Only those NEE data obtained under strong light conditions (PAR>700 μmol m^{-2} s^{-1}) were used to minimize the disturbance from radiation.

The net carbon uptake rate is generally lower for cloudy days (defined as those days with a daily mean PAR lower than 400 μmol m^{-2} s^{-1}) than for clear days (defined as those days with a daily mean PAR higher than 500 μmol m^{-2} s^{-1}) due to reduced incident radiation. The mean NEE values, for example, are -3.62 and -3.76 μmol m^{-2} s^{-1} for cloudy days and -6.18 and -6.53 μmol m^{-2} s^{-1} for clear days for LS and TFS, respectively. By correlating the half-hourly GPP to APAR using the Michaelis-Menten model, we find, however, that the light-use efficiency of the larch forest on cloudy days is significantly higher than that on clear days at both sites. At LS, for example, when the APAR is 500 and 1000 μmol m^{-2} s^{-1}, the GPP is estimated to be 18.24 and 26.40 μmol m^{-2} s^{-1}, respectively, on clear days; however, it is 24.27 and 35.98 μmol m^{-2} s^{-1} on cloudy days, respectively. This result agrees well with those from other studies for different vegetation types (HOLLINGER & al. 1994, BALDOCCHI 1997, GOULDEN & al. 1997, GU & al. 1999). Most scientists ascribed this phenomenon to the large amount of diffused radiation and its high light-use efficiency in cloudy days (HOLLINGER & al. 1994, GOULDEN & al. 1997, FAN & al. 1995).

Our previous analysis indicated that the carbon uptake rate would be decreased when the VPD reaches over 15 hPa at both LS and TFS (WANG & al. 2004). On cloudy days, the VPD is relatively low, and practically no half-hourly VPD value exceeded 15 hPa at both sites. On clear days, however, as much as 41% of the half-hourly VPD exceeded 15 hPa at LS. To further clarify the effect of the VPD on the light-use efficiency, we have correlated the GPP to the APAR under different VPD levels at LS, as shown in Fig. 4 (the graphs for the TFS have been omitted because only a few half-hourly VPD data exceeded 10 hPa). Clearly, the GPP is greatly enhanced with a decrease in the VPD. For cases in which APAR = 300, 600, and 1000 μmol m^{-2} s^{-1}, for example, the GPP is correspondingly estimated to be 15.92, 24.85, and 32.03 μmol m^{-2} s^{-1} when VPD < 10 hPa, 14.36, 21.97, and 27.90 μmol m^{-2} s^{-1} when 10 hPa < VPD < 20 hPa, and 12.95, 19.79, and 25.09 μmol m^{-2} s^{-1} when VPD > 20 hPa. These results indicate that the lower VPD on cloudy days also plays an important role in improving the light-use efficiency.

The mean air temperature was 15.1 °C and 11.8 °C on cloudy days but rose to 19.9 °C and 13.5 °C on clear days at LS and TFS, respectively. However, the observed temperature variations demonstrated to have minimal impact on the GPP of the larch forest at the two sites (Fig. 5).

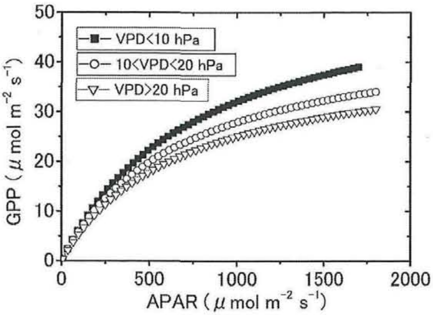

Fig. 4. Variation of the relationship between the GPP and APAR at LS under different VPD levels. The regression results are GPP = 56.54*APAR/(765.3+APAR) (R^2 = 0.8112) when VPD<10hPa, GPP = 46.82*APAR/(678.4+APAR) (R^2 = 0.6630) when 10 <VPD<20 hPa, and GPP = 41.92*APAR/(670.9+APAR) (R^2 = 0.4941) when VPD <20 hPa.

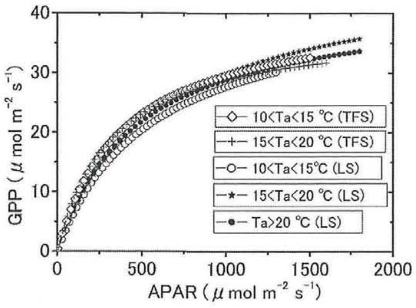

Fig. 5. Variation of the relationship between GPP and APAR at LS and TFS under different temperature conditions. No obvious influence caused by the temperature can be detected for the two sites.

The above analysis results indicate that low VPD is the most important environmental factor affecting the light-use efficiency, together with diffused radiation on cloudy days. To exclude the interference of VPD and clarify the effect of diffused and direct radiation on the light-use efficiency of larch forest ecosystems, we simply selected those GPP data associated with VPD < 10 hPa for clear and cloudy days and plotted them against the APAR, as shown in Fig. 6. As can be seen in the figure, the larch forest ecosystem has higher light-use efficiency on cloudy days than on clear days. Based on the results so far, it is reasonable to believe that the high light-use efficiency of larch forest ecosystems on cloudy days is caused by increased diffused radiation.

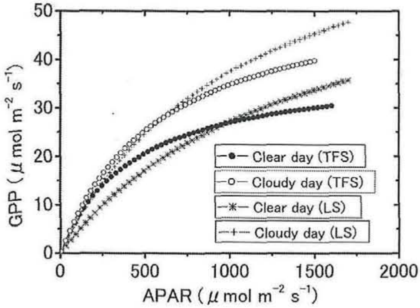

Fig. 6. Response of the GPP to the APAR at LS and TFS on clear and cloudy days under the condition of VPD<10 hPa.

Conclusion

The relationships between the CO_2 fluxes of larch forest ecosystems and environmental variables at LS and TFS were investigated. The carbon uptake rate was greatly influenced by the VPD and tended to decrease with increasing VPD when the VPD exceeded 15 hPa at LS and TFS (WANG & al. 2004). The same VPD threshold at the two sites indicates that the larch ecosystems at both places have similar endurance to dry environment. The light-use efficiency was considerably higher on cloudy days than on clear days. In addition to the identification of the importance of diffused radiation on cloudy days, it was found that a lower VPD also made some contributions. This result agrees well with those of previous studies (HOLLINGER & al. 1994, BALDOCCHI 1997, GU & al. 1999). However, the temperature effect on photosynthesis was found to be minimal at both sites.

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