Characterizing CO_2 fluxes for growing and non-growing seasons in a shrub ecosystem on the Qinghai-Tibet Plateau

XU Shixiao[1,3], ZHAO Xinquan[1], FU Yuling[2], ZHAO Liang[1], LI Yingnian[1], CAO Guangmin[1], GU Song[1], WANG Qinxue[4] & DU Mingyuan[5]

1. Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining 810001, China;
2. Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China;
3. Graduate School of the Chinese Academy of Sciences, Beijing 100136, China;
4. National Institute for Environmental Studies, Tsukuba 305-8569, Japan;
5. National Institute for Agro-Environmental Science, Tsukuba 305-8604, Japan

Correspondence should be addressed to Zhao Xinquan (email: xqzhao@public.xn.qh.cn)

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Abstract To assess carbon budget for shrub ecosystems on the Qinghai-Tibet Plateau, CO_2 flux was measured with an open-path eddy covariance system for an alpine shrub ecosystem during growing and non-growing seasons. CO_2 flux dynamics was distinct between the two seasons. During the growing season from May to September, the ecosystem exhibited net CO_2 uptake from 08:00 to 19:00 (Beijing Standard Time), but net CO_2 emission from 19:00 to 08:00. Maximum CO_2 uptake appeared around 12:00 with values of 0.71, 1.19, 1.46 and 0.67 g CO_2 m^{-2} h^{-1} for June, July, August and September, respectively. Diurnal fluctuation of CO_2 flux showed higher correlation with photosynthetic photon flux density than temperature. The maximum net CO_2 influx occurred in August with a value of 247 g CO_2 m^{-2}. The total CO_2 uptake by the ecosystem was up to 583 g CO_2 m^{-2} for the growing season. During the non-growing season from January to April and from October to December, CO_2 flux showed small fluctuation with the largest net CO_2 efflux of 0.30 g CO_2 m^{-2} h^{-1} in April. The diurnal CO_2 flux was close to zero during most time of the day, but showed a small net CO_2 efflux from 11:00 to 18:00. Diurnal CO_2 flux, is significantly correlated to diurnal temperature in the non-growing season. The maximum monthly net CO_2 efflux appeared in April, with a value of 105 g CO_2 m^{-2}. The total net CO_2 efflux for the whole non-growing season was 356 g CO_2 m^{-2}.

Keywords: alpine shrub ecosystem, CO_2 flux, carbon dynamics, growing season, non-growing season.

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Most long-term carbon flux studies have focused on various forest ecosystems, but less attention has been directed to grassland ecosystems, though the later covers the largest area among the four major natural biomes including (aquatic, grasslands, forests and desert) on the earth. Only temperate grassland ecosystems comprise 32% of the earth's natural vegetation[1−4]. Some studies indicate that grasslands may behave as a significant carbon sink for balancing the carbon budget in global terrestrial ecosystems[5−8], but others suggest that the carbon budget of grassland ecosystems is near equilibrium[9−11]. Kim et al. reported that a temperate grassland ecosystem dominated by warm season tall grass in Kansas State had a net fixing capacity of 750 g CO_2 m^{-2} in its growing season from May to October, but the ecosystem released about 3 g CO_2 m^{-2} per day into the atmosphere during a drought period[10]. Dugas et al. showed evidence that a native prairie dominated by big bluestem and little bluestem (Blackland Research Center, Temple, Texas) was in approximate equilibrium for C budget[12].

As a unique geographic unit, the Qinghai-Tibet Plateau has an average altitude over 4000 m above sea level and covers about 2.5×10^6 km^2. Climate on the plateau is characterized by long, cold non-growing season and short, cool growing season. Precipitation concentrates in the growing season when daytime air temperatures are high, which is potentially favorable for plant growth. The Qinghai-Tibet Plateau also possesses the largest area of natural grasslands in China. The grassland ecosystem on the plateau is hypothesized to play an important role in the carbon balance in both the regional and global ecosystems, but little evidence is available for testing the hypothesis[13]. We expected a high net primary productivity of the alpine shrub ecosystem during the short growing season because of the favorable environmental conditions with abundant rainfall and moderate daytime temperature, but low nighttime temperature[14].

Alpine shrub is one of the dominant vegetation with cold resistant xerophytes or mesophytes on the Qinghai-Tibet Plateau. The vegetation distributes continuously or in large pieces among the alpine forest and other alpine vegetations. Within China, the alpine shrub covers a total area of about 116400 km^2 mainly on the plateau, which takes the largest alpine shrub area in the world[14]. Long-term monitoring and characterizing CO_2 dynamics for the alpine shrub ecosystem on the Qinghai-Tibet Plateau therefore will facilitate determination of source or sink status of grassland ecosystems on the plateau.

1 Materials and methods

1.1 Site description

Measurements of CO_2 flux and environmental factors were conducted at Haibei Alpine Meadow Ecosystem Research Station (Haibei Research Station), the Chinese Academy of Sciences. The station is located in the northeast of Qinghai-Tibet Plateau, in a large valley oriented northwest-southeast and surrounded by the Qilian Mountain (37°37'N,101°19'E, 3200 m a.s.l.). The Datong River passes through the south of the area. The climate at the Haibei Research Station is dominated by the southeast monsoon and high pressure from Siberia. It has a continental-type climate, with severe and long winter from October to next April, and short and cool summer from May to September. The average annual air temperature for the 25 years from 1976 to 2001 was −1.7℃ with extremes of maximum 27.6℃ and minimum −37.1℃. The average temperature in the warmest month (July) and the coldest month (January) is 9.8℃ and −14.8℃, respectively. The average annual precipitation from 1976 to 2001 was 560 mm, and 80% of that rainfall was concentrated within the growing season from May through September[15]. The soil of the study site is classified as Mollic Gryic Cambisols according to the Chinese national soil survey classification system, which is characterized by high organic matter (189.5 t hm^{-2}, 0—10 cm), underdeveloped and thin soil layers. Nitrogen and phosphorus exist mostly in the organic state with a weak mineralization process. Nitrogen storage, mainly in the form of organic nitrogen, was 10.63 t hm^{-2} in the soil pool. The amount of accumulated mineralized nitrogen was only 1.59% of the total nitrogen. The soil nitrogen nutritive condition was characterized by abundant total nitrogen and a lack of available nitrogen.

1.2 Methods

An eddy covariance observation tower was established in a typical alpine shrub ecosystem, 8 km away from the Haibei Research Station in August 2002. Fetch of observation tower is about 60-cm-high alpine shrub dominated by *Potentilla fruticosa* and jointed by *Kobresia capillifolia, Kobresia humilis* and *Saussurea superba,* and the land surface there is often covered with thick moss and litter layer. With an even topography and no apparent fluctuation within a scope of several kilometers, this place is an ideal one for measuring CO_2 flux. From 1 January to 31 December 2003, continuous CO_2 flux measurement was carried out in the alpine shrub ecosystem. CO_2 flux (F_{CO_2}) of alpine shrub ecosystem could be calculated by a formula listed as the following:

$$F_{CO_2} = \overline{w's'} = \frac{1}{T}\int_0^T ws\mathrm{d}t \approx \frac{1}{N}\sum_{i=1}^{N} w's', \quad (1)$$

where w' is atmosphere vertical instantaneous fluctuations, s' is fluctuations of atmosphere CO_2 density. w' was measured using the three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Utah, USA); s' was measured using the anemometer's temperature and open-path CO_2/H_2O analyzer (Li-7500, Li-Cor, USA) at 10 Hz. The overline in the formula represents the average value during a certain period of time[16]. Other micrometerorological measurements such as photosynthetic photon flux density (PPFD), soil temperature and soil water were measured at the same site using quantum sensor (Li-190SB, Li-Cor, USA), thermocouple (105T, CSI, USA) and soil moisture sensor (TDR, CS615, CSI., USA), respectively. Measuring system was installed with a height of 2.20 m. Calculated flux data and ancillary data were recorded with a data acquisition system (CR5000, Campbell Scientific Inc., Utah, USA) at 30 min intervals.

Owing to malfunction of the instrumentations or power failure, missing data are unavoidable. Exponential regression of nighttime F_{CO_2} with u^*>0.2 m s^{-1} against soil temperature at a depth of 5 cm every months were used to fill data gaps for nighttime

$$Fco_2 = b_0 \exp(b_1 T_{soil}). \quad (2)$$

For the daytime, data gaps were filled using the logarithm relationship of PPFD and net CO_2 flux (F_{CO_2}) as

$$Fco_2 = a_1 \times \mathrm{PPFD}/(a_2 + \mathrm{PPFD}) + a_0. \quad (3)$$

2 Results

2.1 Diurnal variation of CO_2 flux

There was a large diurnal variation of monthly averaged CO_2 flux during the growing season (fig. 1). The maximum CO_2 influx appeared around 12:00 (Beijing Standard Time) was 0.71, 1.19, 1.46 and 0.67 g CO_2 m^{-2} h^{-1} for June, July, August and September, respectively. Net CO_2 influx of the ecosystem was observed in the daytime from 08:00 to19:00, whereas net efflux of CO_2 in the nighttime from 19:00 to 08:00. It seems that there was a net CO_2 efflux occurring at around 15:00 in May and the largest hourly net efflux of CO_2 was 0.23 g CO_2 m^{-2} h^{-1} (fig. 1).

The diurnal variation pattern of monthly averaged CO_2 flux during the non-growing season was different from that during the growing season (fig. 2). The monthly averaged CO_2 flux during most daytime in

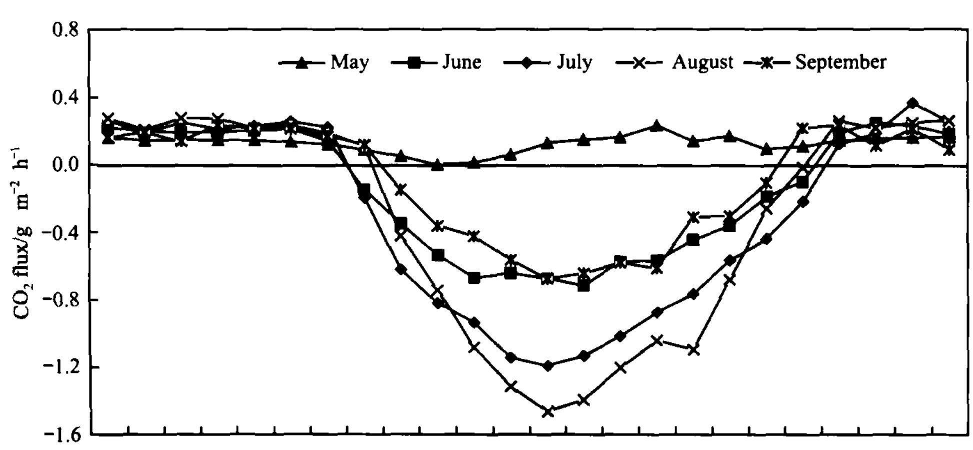

Fig. 1. Diurnal variation of monthly averaged CO_2 flux during the growing season from May to September in the alpine shrub ecosystem on the Qinghai-Tibet Plateau.

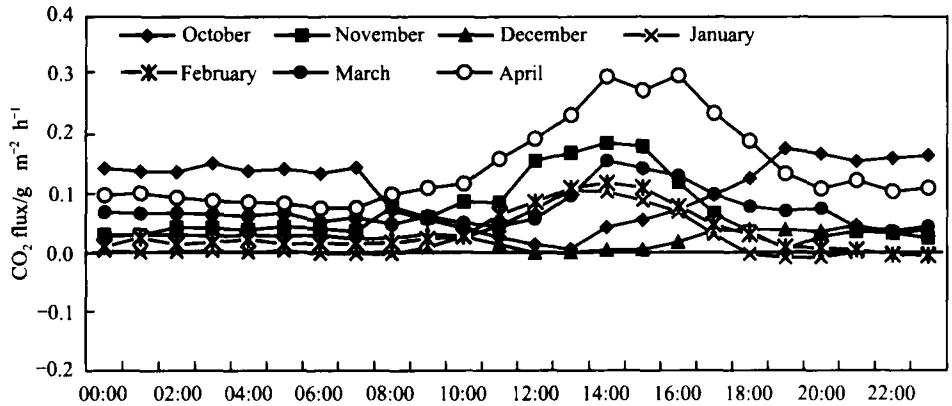

Fig. 2. Diurnal variation pattern of monthly averaged CO_2 flux during the non-growing season from October to December and from January to April in the alpine shrub ecosystem on the Qinghai-Tibet Plateau.

the non-growing season was close to zero, but net efflux was observed from 11:00 to 18:00 with the peak values generally appearing from 14:00 to 16:00. The peak CO_2 efflux of monthly averaged values were 0.18, 0.19, 0.03, 0.10, 0.12, 0.16 and 0.30 g CO_2 m^{-2} h^{-1} for each month from October to December, and from January to April of 2003, respectively (fig. 2).

2.2 Monthly net CO_2 flux

During the growing season from May to September, monthly net CO_2 flux was positive except for May (fig. 3). Large monthly net CO_2 influx occurred in July and August, which were estimated to be 229 and 247 g CO_2 m^{-2}, respectively. The total value of net CO_2 influx for the growing season was higher than that of the net CO_2 efflux in the non-growing season. The total net CO_2 influx was estimated as 673 g CO_2 m^{-2} for the period from June to September, and the total net CO_2 influx volume for the whole growing season from May to September was 583 g CO_2 m^{-2}. In the non-growing season, except for the small amount of monthly net CO_2 efflux in December and January, the monthly net CO_2 efflux was significant from January to April, and from October to December. The largest monthly CO_2 efflux was 105 g CO_2 m^{-2}, which occurred in April. The total CO_2 efflux during the whole non-growing season was estimated as 356 g CO_2 m^{-2}.

2.3 Variation patterns of CO_2 flux and major environmental factors

We obtained the averages of the hourly CO_2 fluxes, soil temperature, soil moisture and PPFD for the

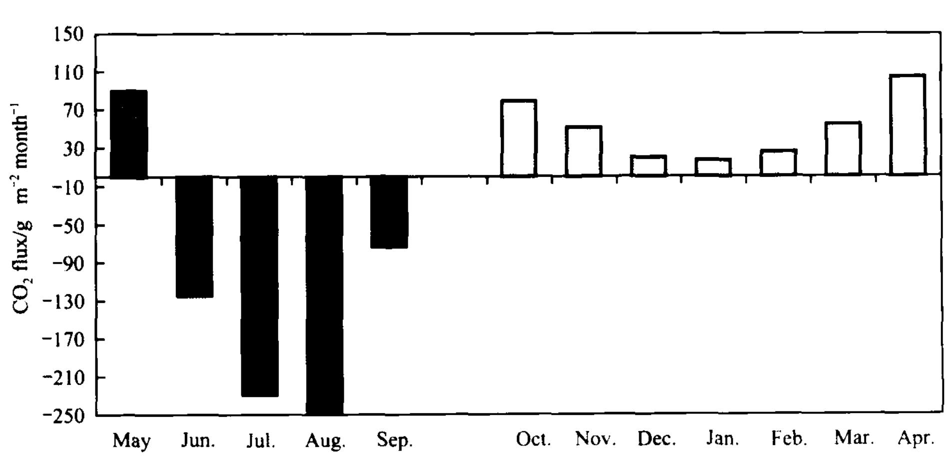

Fig. 3. Monthly net CO_2 flux in the alpine shrub ecosystem on the Qinghai-Tibet Plateau.

growing season (153 d) and non-growing season (212 d), respectively. Correlation coefficients were then calculated between the averages of CO_2 flux and those of other environmental variables. During the growing season, no significant correlation was found between the averaged CO_2 flux and soil temperature during either daytime ($P > 0.5$, $R = -0.2689$, $n = 11$) or nighttime ($P > 0.5$, $R = -0.1405$, $n = 11$). No significant correlation was found between the CO_2 flux and soil humidity (from 00:00 to 23:00) in the growing season ($P > 0.5$, $R = -0.2462$, $n = 23$), too. However, CO_2 influx was significantly correlated ($P < 0.01$, $R = -0.9674$, $n = 12$) with averaged PPFD. During the nighttime from 20:00 to 08:00, the averaged CO_2 flux was positive about 0.20 g CO_2 m^{-2} h^{-1}, indicating a net CO_2 emission from the ecosystem (fig. 4). With the increase of PPFD after 08:00, the averaged CO_2 flux turned into net CO_2 uptake (negative value). The maximum of net CO_2 influx value was -0.77 g CO_2 m^{-2} h^{-1} at around 12:00.

During the non-growing season, there was a significant positive correlation between the averages of CO_2 flux and those of soil temperature either for the daytime ($P < 0.01$, $R = 0.8653$, $n = 11$) or for the nighttime ($P < 0.5$, $R = 0.6629$, $n = 11$). The averaged CO_2 efflux obtained from 00:00 to 08:00 was estimated to be -0.03 g CO_2 m^{-2} h^{-1}. A peak averaged CO_2 efflux was 0.12 g CO_2 m^{-2} h^{-1} at 15:00. From then on, the CO_2 efflux decreased gradually until 19:00 (fig. 5).

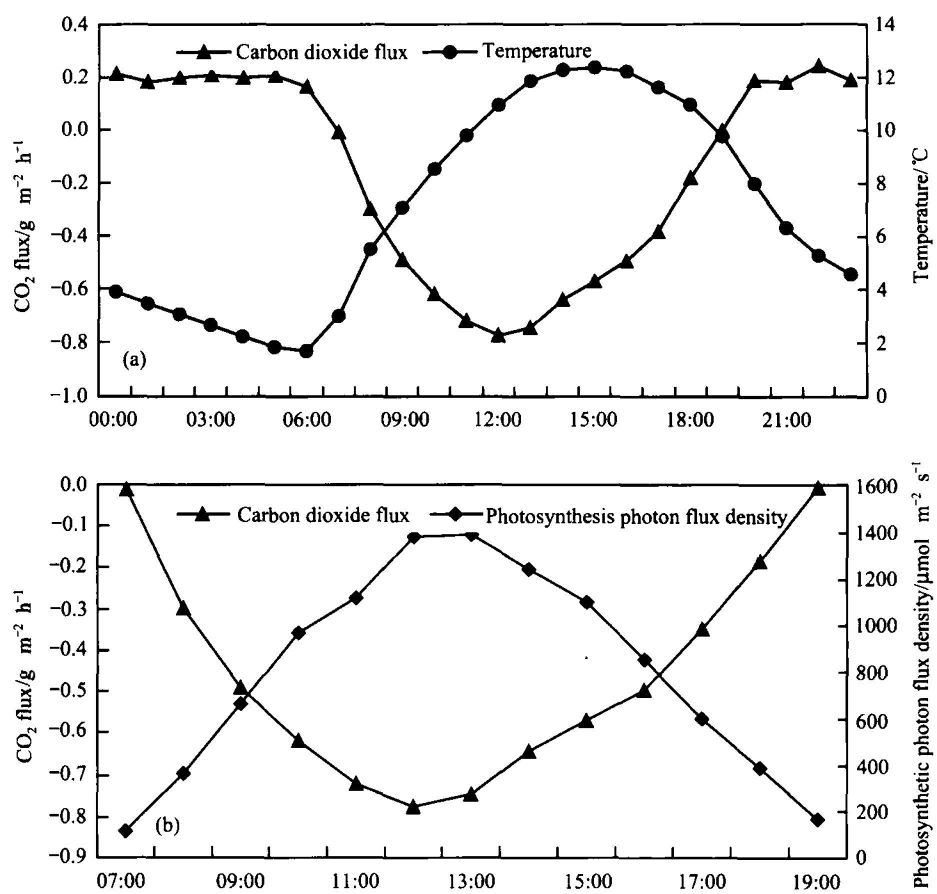

Fig. 4. Diurnal course of averaged CO_2 flux and averaged soil temperature (a), and averaged photosynthetic photon flux density (b) for the growing season in the alpine shrub ecosystem on the Qinghai-Tibet Plateau.

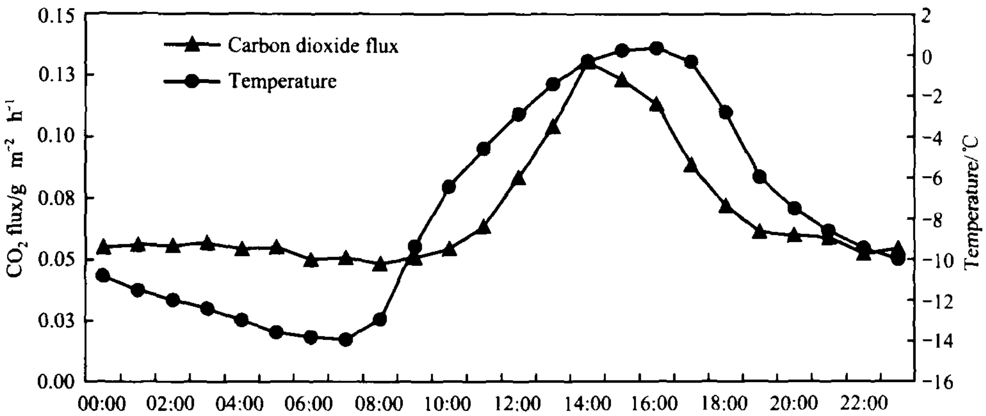

Fig. 5. The diurnal course of averaged CO_2 flux and averaged soil temperature during the non-growing season in a shrub ecosystem on the Qinghai-Tibet Plateau.

3 Discussion and conclusions

3.1 Discussion

Observations of CO_2 flux on the *Leymus chinensis* Steppe in the Inner Mongolia showed an apparent diurnal CO_2 flux variation: CO_2 flux increased since 09:00 and reached its peak value at 12:00, CO_2 flux then decreased gradually and reached a stable value during the nighttime[17]. CO_2 flux showed similar diurnal variation pattern in the alpine shrub ecosystem on the Qinghai-Tibet Plateau in the growing season (fig. 1). The strong solar irradiance and suitable temperature in daytime resulted in the apparent net CO_2 influx during the growing season in the alpine shrub ecosystem. The lower air temperature at the Haibei Research Station during the non-growing season (−14.8℃ in January) could restrain the metabolism activities of soil microbes. CO_2 efflux was close to zero in most time of the day except for small amount of net CO_2 efflux from 11:00 to 18:00 when the soil temperature was high.

A four-years research on CO_2 flux in a mixed-grass prairie on the northern great plain (Mandan) showed that the average net CO_2 influx was 345 g CO_2 m^{-2} in the growing season from 1996 to1999[9], which was much lower than the value of 583 g CO_2 m^{-2} in the current alpine shrub ecosystem. Temperate grassland ecosystem dominated by tall stem grass showed that the average daily CO_2 fluxes from May through October was estimated to be −4.1 g CO_2 m^{-2} d^{-1} (net CO_2 influx), but close to zero during plant senescence, or even to be a CO_2 source at about 3 g CO_2 m^{-2} d^{-1}[10]. The average daily net CO_2 influx of the alpine shrub during the growing season was estimated to be 3.81 g CO_2 m^{-2} d^{-1}, whereas that of net CO_2 efflux during the non-growing season was 1.68 g CO_2 m^{-2} d^{-1}, which were smaller than the temperature grassland mentioned above. The seasonal CO_2 flux variation pattern in the alpine shrub ecosystem is mainly determined by the seasonal variation of climate on the Qinghai-Tibet Plateau. About 80% of the annual precipitation at the Haibei Research Station is concentrated in the growing season. The rich precipitation and moderate temperature during the daytime in addition to the low temperature at night may favor the accumulation of carbon in the alpine plants. High net ecosystem productivity results from high net canopy photosynthesis, which depends mainly on the solar energy available, and low autotrophic and heterotrophic respiration[14]. During the cold period on the Qinghai-Tibet Plateau from December to next February, the low temperature environment could restrain the metabolism activities of soil microbes and slow down the decomposition of organic matter in the soil, and thus resulted in the small CO_2 efflux. After late February, the rise of air temperature and rehabilitation of metabolism activities could result in the increase of CO_2 release. From late April, as plants turn green, the CO_2 absorbed through photosynthesis exceeded the CO_2 released through the respiratory activities of the ecosystem. The alpine shrub ecosystem was a carbon sink for atmospheric CO_2 during the period beginning from June until late September, The CO_2 absorbed from the atmosphere was less than the amount released through the respiratory activities and therefore there was a net CO_2 efflux in the alpine shrub ecosystem from the beginning of October to late November, which is probably due to the withering of plants and reduced photosynthesis. After late November, the CO_2 efflux was gradually diminished as low temperature could restrain the metabolism activities of soil microbes.

The correlation analysis showed that photosynthetic photon flux density is the major environmental factor determining the CO_2 flux during the growing season. In the non-growing season, however, temperature seems the major determinant for the ecosystem CO_2 exchange in alpine shrub. Temperature, as a key factor in affecting CO_2 release, could affect soil CO_2 emission strength mainly through its impact on the metabolism rate of soil organisms during the non-growing season[18,19]. The nighttime temperature during the non-growing season on the Qinghai-Tibet Plateau could be lower than −30℃ in January. Due to the inhibition of the metabolism activities by low temperature, the ecosystem CO_2 flux in the alpine shrub could be close to zero. Despite that the environments for soil microbes in the alpine shrub is extremely cold and moist, the metabolism activities could be enhanced significantly when soil temperature increases[19]. With increase of sunlight radiation and temperature in the morning, soil respiration activities could increase accordingly (fig. 5).

3.2 Conclusions

Carbon dioxide flux for the alpine shrub ecosystem on the Qinghai-Tibet Plateau showed a significant diurnal variation, with the peak CO_2 influx at around 12:00 during the growing season. CO_2 flux, however, showed small diurnal change during the non-growing season with the CO_2 efflux being close to zero in most time of a day, but a small net CO_2 efflux from 11:00 to 17:00.

The total net CO_2 influx during the short growing season in the alpine shrub ecosystem on the Qinghai-Tibet Plateau was 583 g CO_2 m^{-2} in 2003. The maximum values occurred in July and August, which were 229 and 247 g m^{-2}, respectively. The largest CO_2 efflux was estimated to be 105 g CO_2 m^{-2} in April. The total net CO_2 efflux during the non-growing season was 356 g CO_2 m^{-2}. With an annual net CO_2 influx of 227 g CO_2 m^{-2}, the alpine shrub ecosystem on the Qinghai-Tibet Plateau was a carbon sink for atmospheric CO_2 in 2003.

The ecosystem CO_2 influx was mainly affected by the variation of photosynthetic photon flux density during the growing season, but was mainly influenced by soil temperature during the non-growing season in the alpine shrub ecosystem on the Qinghai-Tibet Plateau.

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