DOI: 10.1007/s11430-006-8174-9

Seasonal variations and mechanism for environmental control of NEE of CO_2 concerning the *Potentilla fruticosa* in alpine shrub meadow of Qinghai-Tibet Plateau

LI Yingnian[1], SUN Xiaomin[2], ZHAO Xinquan[1], ZHAO Liang[1], XU Shixiao[1], GU Song[1], ZHANG Fawei[1,3] & YU Guirui[2]

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 University of Chinese Academy of Sciences, Beijing 100049, China

Correspondence should be addressed to Zhao Xinquan (email: xqzhao@nwipb.ac.cn)

Received October 27, 2005; accepted March 10, 2006

Abstract The study by the eddy covariance technique in the alpine shrub meadow of the Qinghai-Tibet Plateau in 2003 and 2004 showed that the net ecosystem carbon dioxide exchange (NEE) exhibited noticeable diurnal and annual variations, with more distinct daily changes during the warmer seasons. The CO_2 emission of the shrub ecosystem culminated in April and September while the CO_2 absorption capacity reached a maximum in July and August. The absorbed carbon dioxide during the two consecutive years was 231.4 and 274.8 g $CO_2 \cdot m^{-2}$ respectively, yielding an average of 253.1 g$CO_2 \cdot m^{-2}$ per year: that accounts for a large proportion of absorbed CO_2 in the region. Obviously, the diurnal carbon flux was negatively related to temperature, radiation and other atmospheric factors. Still, minute discrepancies in kurtosis and duration of carbon emission/absorption were detected between 2003 and 2004. It was found that the CO_2 flux in the daytime was similarly affected by photosynthetic photon flux density in both years. Temperature appears to be the most important determinant of CO_2 flux: specifically, the high temperature during the plant growing season inhibits the carbon absorption capacity. One potential explanation is that soil respiration is enhanced under such condition. Analysis of biomass revealed that the annual net carbon fixed capacity of aboveground and belowground biomass was 544.0 in 2003 and 559.4 g $C \cdot m^{-2}$ in 2004, which coincided with the NEE absorption capacity (63.1 g $C \cdot m^{-2}$ in 2003 and 74.9 g $C \cdot m^{-2}$ in 2004) in the corresponding plant growing season.

Keywords: ***Potentilla fruticosa*** **shrub meadow, yearly meteorological conditions, CO_2 exchange, variations, meteorological factors, aboveground and belowground biomass, LAI.**

It is well known that global warming induced by higher density of greenhouse gases severely threatens sustainable economic and social development and also constitutes a grave challenge to the international community. Continuous, long-duration observations of carbon flux between the underlying surface and atmosphere help promote our understanding of the effects exerted by the terrestrial ecosystem on the global carbon cycling process. The eddy covariance technique, a kind of micro-meteorological technology, is

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

now widely applied to the non-destructive testing of the CO_2 flux in not only forest, shrub, meadow or farmland (among other underlying surfaces), but also the atmosphere, with a view to measuring the flux volume of CO_2/H_2O and energy between vegetation and the atmosphere[1−5]. In China, China FLUX has been initiated using eddy covariance technique, based on CERN (China Ecological Research Net). Moreover, observations and analyses have already been conducted for three years on the flux value of CO_2/H_2O and energy between three different types of vegetation and the atmosphere[5−10] at the Haibei Research Station of Alpine Meadow Ecosystem, the Chinese Academy of Sciences in the North of Qinghai-Tibet Plateau.

The Qinghai-Tibet Plateau, occupying a quarter of China's territory, boasts an average elevation of more than 3000 m and is well-known as "the roof of the world". The specific geographic features not only foster diversified ecosystems, but also make the plateau the most sensitive and precursory area in response to climate change[11]. In addition to the varied topography, unique meteorological factors featured such as intense solar radiation, sharp temperature fluctuation and evident rainfall imbalance lead to a complex and diversified eco-spatial pattern with variable soil respiration and CO_2/H_2O flux, as well as the annual changes of the same ecosystem in different years. *Potentilla fruticosa* is a typical kind of vegetation of deciduous shrub with perennial rootstock occurring in the frigid-temperate zone, extensively distributing in China's alpine areas including West China, North China, Northwest and Southwest alpine region[12]. On the Qinghai-Tibet Plateau, the plant grows on smooth, shady slopes (2700−4500 m above sea level) where the soil is rather moist. Its distribution coverage is the second, only next to that of *Kobresia pygmaea* meadow in the region. In spite of a simple plant community, *Potentilla fruticosa* enjoys such abundant varieties and high bio-productivity that it can provide fine pastures[12] and improve terrestrial carbon cycling. Although studies have been conducted on the CO_2 flux in different ecosystems on the plateau[5−10], these studies are merely based on short-term findings. This paper analyzes the seasonal variation of CO_2 flux on the basis of observational data on alpine shrub vegetation (*P. fruticosa*) in two consecutive years, for the purpose of revealing the effects of climate on CO_2 flux.

1 Materials and methods

1.1 Site description

Data were collected at the Haibei Research Station of Alpine Meadow Ecosystem, the Chinese Academy of Sciences. Situated in the northeast of the Qinghai-Tibet Plateau, the station is located in the west of Datong River valley, at the base of the south slope of East Lenglong Range (north branch of Qilian Mountains) at 37°29′−37°45′N and 101°12′−101°23′E. The station boasts a vast topography and an elevation of 3200 to 3600 m. The area manifests meteorologically evident continental features, due to its location in the Asian continent hinterland. Therefore, owing to the low alpine temperature, only two seasons can be distinguished here: a cold (dry) season and a warm (humid) season. The average annual temperature was no higher than −1℃ with lower than 10℃ in July and below −15℃ in January. Total mean annual rainfall was approximately 580 mm, and precipitation between May and September accounted for 80% of the total amount. Even during July, the hottest month of the year, there were frosts, icing and snowfall (sleet). In general, the regional climate is characterized by a frigid, dry and long cold season and a cool, moist and short warm season[13].

The research region is located in a shrub meadow, northeast of Haibei Station. During the study, the shrub was 30−60 cm high with the coverage percentage of 50%−60%. Also, 47 kinds of herbaceous plants could be found in the lower grass, averaging 8−16 cm in height, and belonging to 15 families and 37 genera. Aside from *Potentilla* shrub, the constructive species included *Stipa aliena, Helictotrichon tibeticum, Elymus nutans, Festuna rubra, Kobresia capillifolia, Aster flaccidus, Poa orinosa, Oxytropis ochrocephala, Polygonum viviparum, Leontopodium nanum*. The soil is classified as Mollic Gryic Cambisols.

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

1.2 Methods

The data were collected by the eddy covariance technical system, consisting of CSAT-3 (Campbell, USA), an open-path infrared CO_2/H_2O analyzer (L1-7500, LI-Cor Inc., USA), long/short wave radiation sensors (CM11, Kipp&Zonen, USA), a photosynthetic photon flux density sensor (LI-190Sb, LiCor Inc., USA), soil temperature sensors (105T, Campbell, USA) and an air temperature and humidity detector (HMP45C, Vaisala, Helsinki, Finland). The frequency of the flux data was 10 Hz, and of the meteorological data 0.5 Hz, when all the variants were represented by the 30 min. average values. This paper focuses on the carbon flux and climatic conditions in 2003 and 2004. In the warm season, the CO_2/H_2O analyzer was apt to be covered with dew in its probe head, especially during the night and in the rain, which affected the flux observation demonstrated by evident discrete points. Therefore, such aberrances should be eliminated in calculation process. All flux data were modified through WPL[14]. The modification method was used to remedy the flux data loss or data error during the nighttime using eq. (1), which results from F_c (flux) of the frictional velocity threshold U>0.2 $m \cdot s^{-1}$) and T_s (5 cm soil temperature). Eq. (2) remedies the flux loss during the daytime and includes the flux or F_c and the photosynthetic photon flux density or PAR[15−18].

$$F_c = R_{10} Q_{10}^{(T_s - 10)/10}, \quad (1)$$

$$F_c = \frac{a_1 \cdot \mathrm{PAR}}{a_2 + \mathrm{PAR}} + a_0, \quad (2)$$

where R_{10} is the system respiratory capacity in 10℃; Q_{10} is the relatively increased volume of the ecosystem respiratory capacity as the temperature rises by every 10℃; a_0, a_1 and a_2 are fitting constants, representing respectively the dark respiration intensity, maximum photosynthetic intensity and relative constant of the system. When data errors that couldn't be revised by the above method occurred (such as errors due to power failure), linear interpolation was employed.

The aboveground and belowground biomass measurement near the observation tower was conducted in the middle and at the end of every month during the plant growing season. In the aboveground biomass measurement, 6 sampling plots (50 cm × 50 cm) were chosen at random and cut from the soil surface by scissors. As to the belowground biomass measurement, the secondary plots (25 cm × 25 cm) were chosen from the surface samples at random and removed with a spade and knife in three layers (0−10, 10−20 and 20−40 cm, respectively) Grassroots were sieved and rinsed before desiccating in the heating-oven in a constant temperature of 65℃, until the samples maintained a constant weight. Finally, the biomass of unit soil area (g/m^2) was calculated. When testing the aboveground biomass in 2000 and 2005, LI-3100A (LI Cor, USA) was used to determine the leaf area index (LAI). In this paper, the LAI in 2003 and 2004 were modified and estimated through the regression relation between the leaf area index and seasonal variance of aboveground biomass. The CO_2 emission of soil respiration was referred to the average data from July 2000 to June 2001 and the synchronic meteorological records.

2 Results and analysis

2.1 Seasonal variance of meteorological factors

Fig.1 compares the CO_2 exchange volumes and variations of other relative meteorological factors. Specifically, Fig. 1(b) shows that many annual averages or totals are the same in both years, except for the fact that the average temperature in 2003 (−1.2℃) was slightly higher than that in 2004 (−1.9℃), but slightly lower in spring 2004 than in spring 2003. In terms of different months, the temperature from January to March in 2003 was rather high and the air was dry compared with 2004. The monthly average temperature in 2004 was slightly low from January to February and from September to November and slightly high in July and December compared with that of the same periods in 2003, with no perceptible differences in remaining months. The total solar radiation and photosynthetic photon flux density (Fig. 1(e), (f)) were noticeably higher in April, July and November, 2004, but lower in June, August and September than that of the same periods in 2003. As to the soil temperature in 2004, it was higher in January, July and December, lower in February, June, and Septem ber to November than those in 2003. There was 21% more rainfall from June to August in 2003 than that in 2004 in growing

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

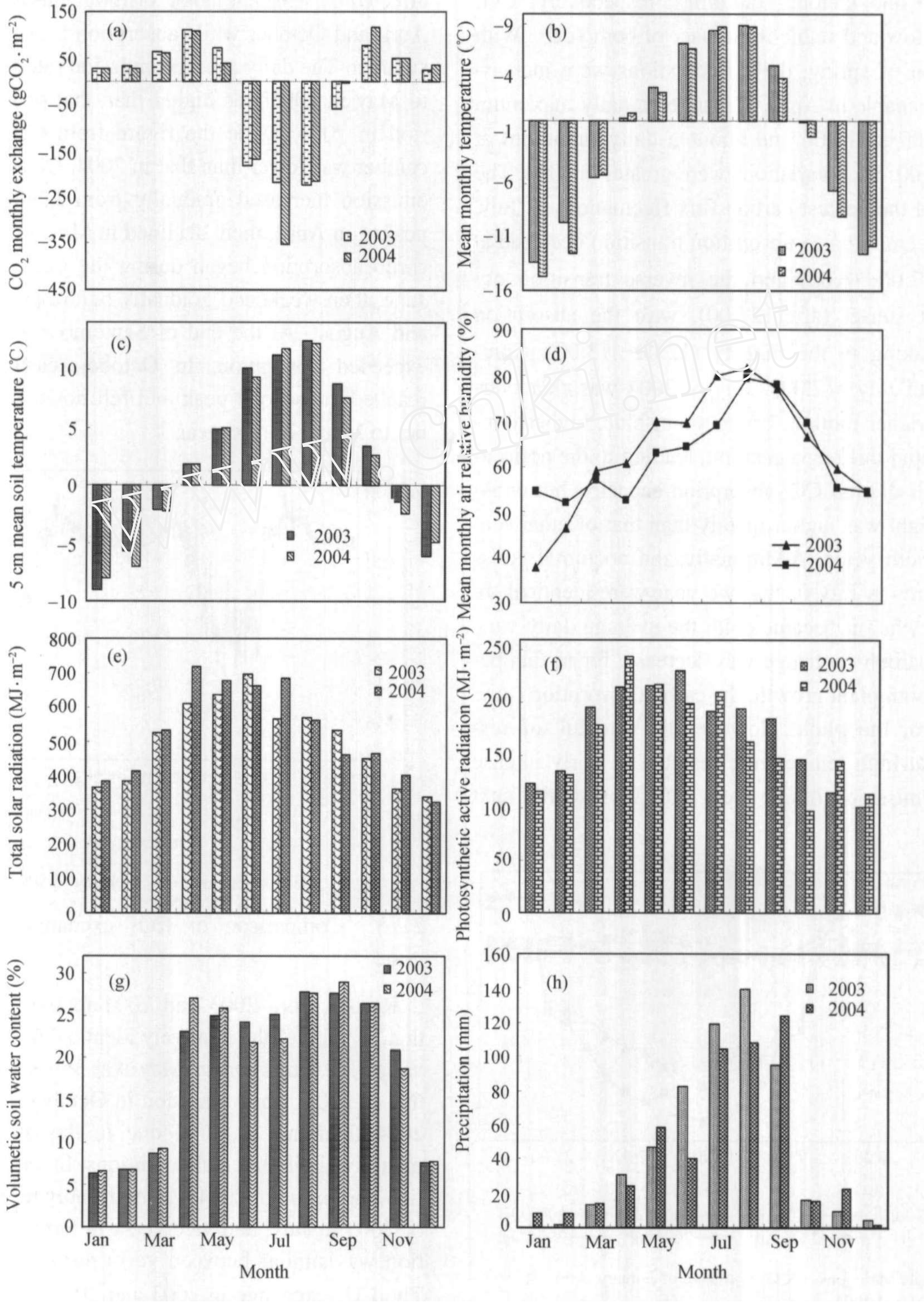

Fig. 1. Monthly variations comparison of CO_2 exchange volume and other relative meteorological factors between 2003 and 2004.

seasons, which boosted the air and soil humidity (Fig. 1(d), (g)). In addition, the yearly average soil temperature was not evidently varied from each other in spite of the higher mean air temperature in 2003 than in 2004.

2.2 CO_2 exchange variations

2.2.1 Daily CO_2 exchange variations

Fig. 2 shows daily average CO_2 exchange in 2003 and 2004 in January (winter), April (spring), July

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

(summer) and October (autumn), respectively; CO_2 flux was low and stable in January of both years. With the advent of spring, daily fluctuations were increasingly noticeable in April. It reached a daily maximum from 14:00 to 17:00 and about a daily minimum at about 10:00. Such variations were greater in 2003. The shrub had the acutest carbon flux fluctuations in July, when the emission-to-absorption transition occurred at sunrise (7:00—8:00) and the reverse transition occurred at sunset (after 21:00), with the absorption value peaking in the midday (12:00—13:00). Compared with July of 2003, July of 2004 was characterized, by richer rainfall, brighter sunshine, higher temperature and thicker vegetation, leading to the noticeably higher diurnal CO_2 absorption capacity, but emission at night was higher in July than that of other seasons in both years. Additionally, the nocturnal emission figures in July of the two year were identical. In October, when it became cold, the average daily variance of carbon exchange was decrease, for in this period, without plant growth, the carbon absorption came to a halt on the whole. However, the forceful soil respiration at high temperature resulted in fairly intense carbon emission volume from afternoon to the next morning.

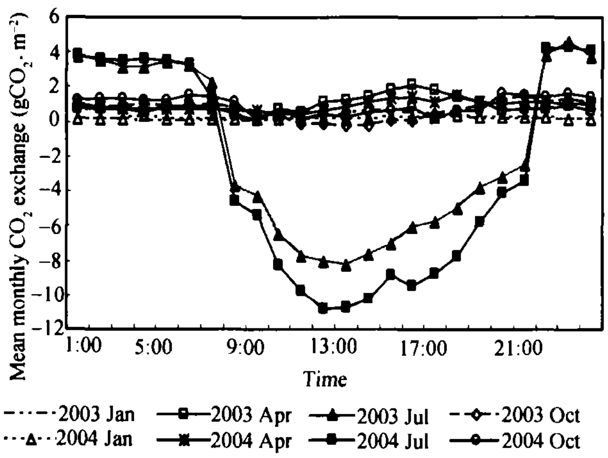

Fig. 2. Daily variations of CO_2 exchange of January, April, July, October in 2003 and 2004.

2.2.2 Seasonal variations of CO_2 exchange

Fig. 3 shows the net daily carbon exchange volume of the *Potentilla fruticosa* shrub in 2003 and 2004. It was concluded that on the Qinghai-Tibet Plateau, the monthly carbon exchanges of the shrub were evidently affected by seasonal factor. Carbon emission peaked in April and October while absorption peaked during the summer. The daily average emission rate from January to May in 2003 was higher than that of the same period in 2004, while the figure from October to December was lower than that in 2004. Generally, carbon emission increased gradually from January to April, peaked in April, then, declined in May. In contrast, the shrub absorption began during the initial ten days in June, then weakened gradually before peaking in July and August. At the end of September, CO_2 emission exceeded absorption. In October, carbon emission reached the second peak and fell down from November to March of next year.

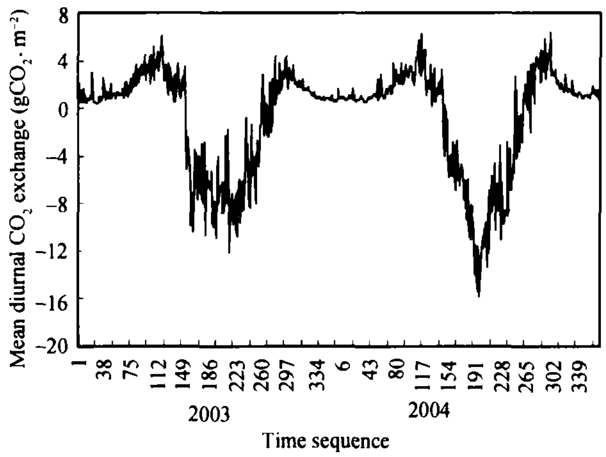

Fig. 3. Daily variation of CO_2 exchange in 2003 and 2004.

2.2.3 Comparison of CO_2 exchange in different years

Results from 2003 and 2004 in Fig. 1(a) indicate that, in spite of the relatively identical trends of annual variability, emission in May was lower in 2004 than that in 2003, while emission in October was higher in 2004 than that in 2003 due to the discrepancy of monthly environmental conditions. In terms of absorption, the figure of 2004 was noticeably higher than that of 2003 in July, and vice versa in September; absorption was similar between years during other months. The CO_2 exchange in 2003 and 2004 was −231.4 and −274.8 g $CO_2 \cdot m^{-2}$ respectively. The absorption in 2004 was 43.3 g $CO_2 \cdot m^{-2}$, higher than the absorption in 2003. Therefore, the carbon absorption of the shrub ecological system seem to be carbon sequestration and was quantitatively higher than the mixed grassland in Mandan, America[19]. Table 1 lists the dates of meas-

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

Table 1 Variations of daily net CO_2 absorption and emission exchange in 2003 and 2004

Year	Emission time	Lasting periods/d	Emission capacity($gCO_2{\cdot}m^{-2}$)	Emission ratio($gCO_2{\cdot}m^{-2}{\cdot}d^{-1}$)	Absorption time	Lasting periods(d)	Absorption capacity($gCO_2{\cdot}m^{-2}$)	Absorption ratio($gCO_2{\cdot}m^{-2}{\cdot}d^{-1}$)
2003	Jan. 1—May 31	151	306.8	2.03	Jun. 1—Sep. 29	121	692.1	5.72
	Sep. 30—Dec.31	93	153.4	1.65				
2004	Jan. 1—May 25	146	268.4	1.84	May 26—Sep. 14	112	767.8	6.86
	Sep. 15—Dec. 31	108	227.3	2.10				

urement, duration of measurement, and emission and absorption values in 2003 and 2004. Carbon emission volumes were 460.3 and 495.6 g $CO_2{\cdot}m^{-2}$, respectively in the non-growing season and absorption volumes of 692.1 and 767.8 g $CO_2{\cdot}m^{-2}$, respectively in the growing season in 2003 and 2004.

Differences could be observed in terms of CO_2 emission/absorption period and value owing to the different yearly climate conditions in 2003 and 2004, which also resulted in the different unit emission rate and unit absorption rate. June 1 in 2003 was the emission-to-absorption transitional day, and September 30 was the absorption-to-emission transitional day. The transitional dates in 2004, however, were May 26 and September 15. Carbon absorption of the shrub occurred six days earlier in 2004, suggesting a six day advance of the vegetation phenological phase. Because the air temperature declined sharply in the early winter season which resulted in vegetation growth stopping about 20 days earlier in 2004, the CO_2 absorption-to-emission transition came 20 days earlier, additionally. The daily average emission rate from January to May in 2003 was higher than that of the same period in 2004, while the figure from October to December was lower than that in 2004. However, in terms of absorption stage, the absorbed volume and rate in 2004 were evidently higher than those in 2003, in spite of the less absorption days.

2.3 Relationship between CO_2 net ecosystem exchange and meteorological factors in different years

Fig. 1 shows that except that the annual mean temperature in 2003 was higher than that in 2004, the other meteorological factors merely differed from each other, but the CO_2 daily exchange volume in July 2003 was quite different from that in July 2004. Therefore, the analysis of July's observational data was used to understand the relationship between CO_2 exchange volume and meteorological factors. Based on daily 30 min observed photosynthetic photon flux density (PAR), ≥10 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ was considered as daytime, the relationship between the daytime CO_2 gross fluxes and PAR was measured in July 2003 and 2004 (Fig. 4). The formulated equations were as follows:

$$2003:\ Fc = \frac{-0.5783PAR}{356.4941 + PAR} + 0.0884,$$

$$2004:\ Fc = \frac{-0.6557PAR}{317.6152 + PAR} + 0.0719.$$

Fig. 4 shows the change tendencies of the daytime CO_2 gross fluxes with PAR change in July 2003 and July 2004 were the same, but the discrepancies of maximum photosynthetic coefficients and dark respiration coefficients were 0.0764 and 0.0165 respectively, and the system constant discrepancy was 38.8789. This indicates that the daytime PAR would have a different effect on CO_2 gross fluxes in different years. But from the degree of the coefficient discrepancy, the inter-year effect difference was not so significant, e.g. Fig. 4 showed that the PAR was approximately 750—1500 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$, although the model curve differed significantly between years, the margin difference of CO_2 gross fluxes was only about 0.1 g $CO_2{\cdot}m^{-2}$.

Generally speaking, the seasonal variation of plant phenologies could affect CO_2 flux dramatically, especially in the area north of the temperate zone or at high altitude[20, 21]. In the blooming season of the *P. fruticosa* brushwood meadow region, precipitation was relatively abundant, enough to meet the demands of the growth. The temperature determined the growth time and growth rate etc. of the plants, thus it was one of the key influential factors of CO_2 flux. Generally, the 5 cm soil temperature fluctuated dramatically during the day time, so many researchers prefer to adapt the exponential relation of the nighttime ecosystem respiratory intensity and 5 cm soil temperature to explain temperature effects. Plants in the *P. fruticosa*

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

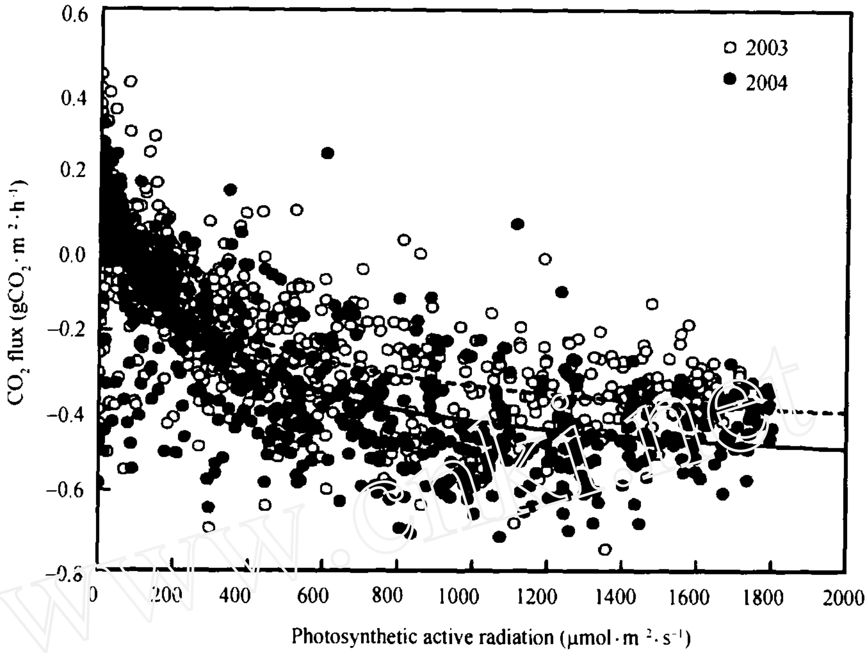

Fig. 4. The comparison of the relationship between CO_2 flux and photosynthetic photon flux density in *potentilla froticosa* Shrub on the Qinghai-Tibetan Plateau in 20003 and 2004.

brushwood meadow region started growing in early to mid May, and stopped when the daily average temperature dropped below 5℃. Here we used the day-to-day average temperature (T_a) (5℃$\geqslant T_a \geqslant$0℃) to set up the correlation between the CO_2 exchange volume (F_c) for 2003 and 2004 (Fig. 5) and the daily F_c of the corresponding period (F_c), and formulate the following cubic regression equation was found as follows:

$$F_c=0.0175T_a^3-0.3268T_a^2+0.8026T_a-0.9589,$$
$$(n=139, R=0.5667, P<0.001).$$

The linear regression slope and intercept of the 2003 and 2004 day-to-day mean temperature and day-to-day CO_2 exchange volume differed from each other significantly, and the slope of the 2004 was higher than that of the 2003 (Fig. 5). Judging from the comprehensive data of 2 years and the model equations, during the growth period (May 16—Sep. 30), when the daily average temperature was comparatively low (generally under 2℃), the CO_2 absorption of the ecosystem was low, usually occurring in the early or late part of the growth season. When the air temperature was between 2℃ and 10℃, the absorption increased with increasing temperature; When the air temperature was beyond 10℃, CO_2 absorption decreased slightly with increasing temperature. A possible explanation is that when temperature increases, the soil respires and releases larger volumes of CO_2, leading to decreased net CO_2 absorption. The CO_2 absorption and release of the lower surface was complicated, influenced by climatic factors, and by plant growth and soil respiration.

In the alpine meadow region of Qinghai-Tibet Plateau, the higher the temperature was, the higher the respiration and release of CO_2 was. In order to explain the case, the alpine soil respiration data from July 2000 to June 2001[22] was used to show the relationship between the quantity of CO_2 released from the soil and the temperature of the corresponding time period (Fig. 6). There was a positive correlation between the soil respiration and temperature conditions. This suggests that when temperature is high in the some seasons or years, the soil respiration strengthened and the CO_2 discharge amount increased, causing CO_2 absorption to decrease when the temperatures were very high.

These analyses show that in the alpine *P. fruticosa* brushwood meadow region of Tibet Plateau, the CO_2 exchange volume emerged great difference when the climates were different, especially the temperature

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

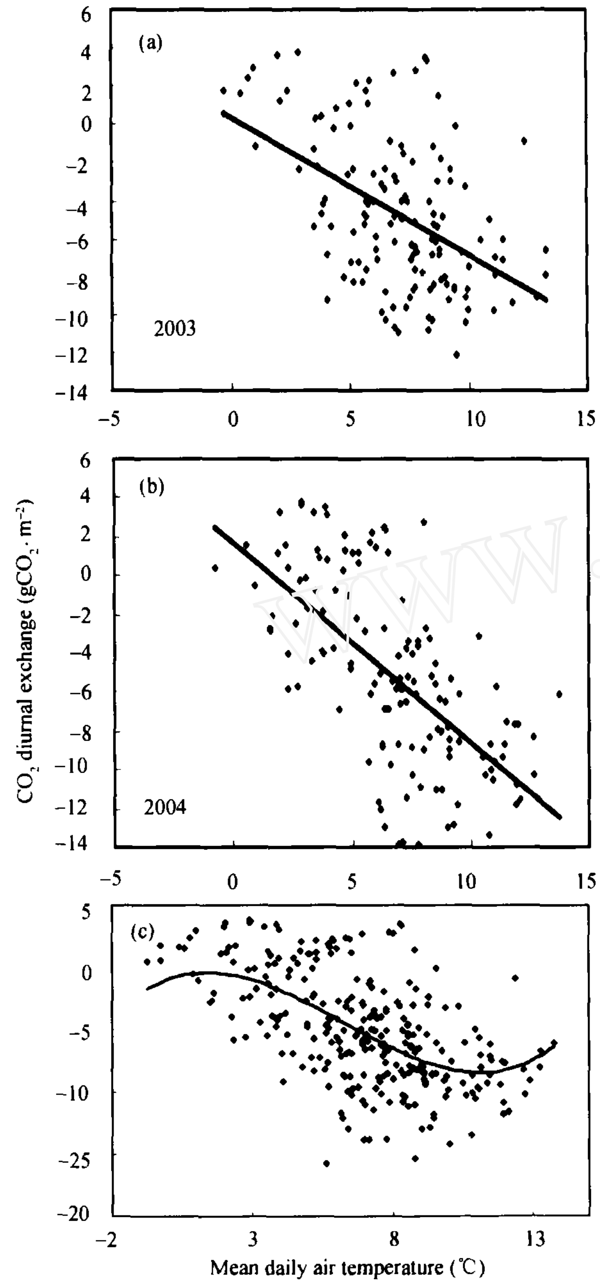

Fig. 5. The relationship between diurnal CO_2 exchange and mean daily air temperature in plant growing season in *Potentilla froticosa* shrub on the Qinghai-Tibetan Plateau.

difference between years. In the growth period of June—September, the average temperature of 2003 was 0.3℃ higher than in 2004, radiation was similar between years, and the CO_2 daily mean exchange and absorption volume of the corresponding period was 0.45 g $CO_2 \cdot m^{-2}$ lower in 2003 than in 2004 (Fig. 1(b)). Therefore, comparing with PAR, the CO_2 daily exchange volume seems to be more sensitive to the average temperature.

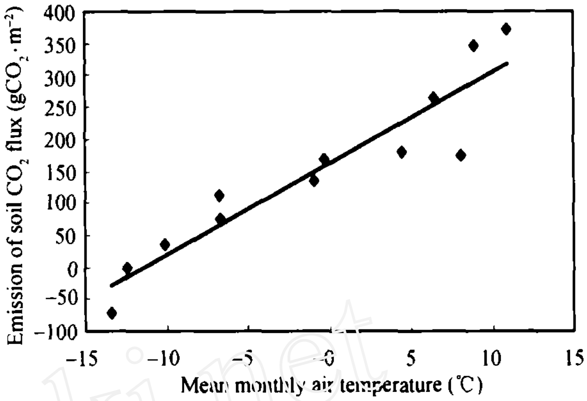

Fig. 6. The relationship between mean monthly air temperature and Mat Cyro sod soil CO_2 emission from July 2000 to June 2001.

According to the observation data in 2003 and 2004 of the CO_2 daily exchange volume and meteorological factors, the results showed that there were significantly negative correlations between the CO_2 daily exchange and the air temperature, soil temperature, atmosphere and ground long-wave radiation, net radiation, pre-cipitation. Slightly negative correlations between the CO_2 daily exchange and relative air humidity, total solar radiation, PAR, air pressure were found, whereas there was a positive correlation between the CO_2 daily exchange and wind speed. Fig. 7 shows the relationship between the CO_2 daily exchange volume and partial routine meteorological elements. The relationship between the CO_2 daily exchange volume and temperature was great (Fig. 7(a), (b)). When the daily average temperature was under 0℃ (3℃, 5 cm soil temperature), the CO_2 daily exchanges was mostly in the release condition, i.e. more emission than absorption, and there was an obvious positive correlation between the release quantity and temperature; When it was over 0℃, CO_2 absorption was more than emission and CO_2 absorption increased linearly with increasing temperature. The ground long-wave radiation had a similar effect on CO_2 daily exchange volume and temperature (Fig. 7(c)). The relationship between the CO_2 daily exchange volume and precipitation was negative (Fig. 7(d)), the CO_2 exchange volume was in release condition ordinarily during cold season and in the absorption condition during growing season.

Data analysis indicated that the durations of the daily temperature of ≥0℃ in 2003 and 2004 oc-

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

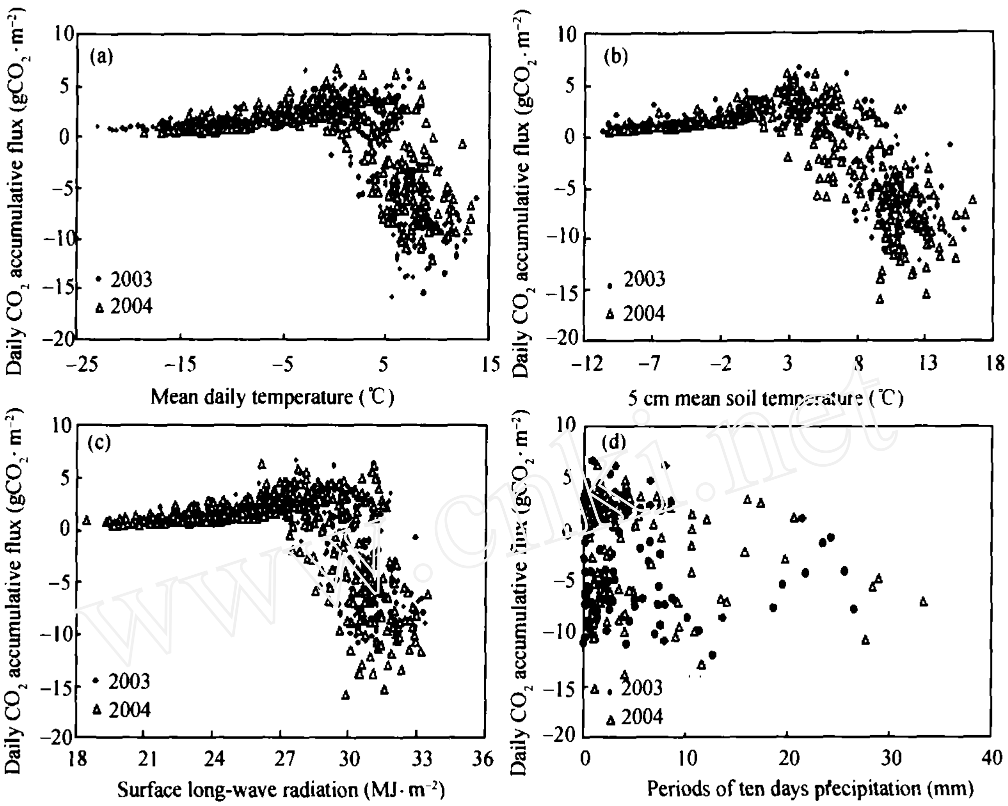

Fig. 7. The relationship between CO_2 diurnal exchange and main meteorological factors in 2003 and 2004.

curred in May 23—Oct. 10, May 16—Sep. 29, were 140 and 144 d, respectively, and the effective accumulated tempera- ture was 972.9℃ and 935.8℃, respectively. Although effective accumulated temperature was greater in 2003 than that in 2004. When the daily average temperature was ≥0℃, the CO_2 exchange volume was higher in 2004 than in 2003. Indicating that in the Tibet Plateau alpine *P. fruticosa* brushwood meadow region, the high temperature did not mean high CO_2 absorption, contrarily, it was favorable for the soil absorption. Interestingly, in this two years, the period that the CO_2 daily exchange condition changed from the release to absorption was coincidence with the steady temperature that beyond 3℃, and the most of the plant species in the region began to grow . This illuminated that the soil CO_2 emission will be more than plant absorption during plant early growing and only when most of plant species begin to grow, the CO_2 absorption volume of the plants exceeds the soil respiration's.

2.4 *Comparison between fixed carbon capacity and CO_2 exchange*

In the initial and middle ten days of May, when average daily average temperature (DAT)≥0℃, the *P. fruticosa* shrub began to sprout, which was the early growth stage of the vegetation. However, given the daily minimum temperature of below −10℃, the accumulation speed was rather low. The shrub began to grow leaves when the DAT≥3℃ during the last ten days of May. From the middle of June onward, when DAT≥5℃ and favorable conditions such as intense solar radiation, high temperature, and abundant rainfall occurred, dry matter accumulated quickly, reaching maximum biomass at the end of August or the beginning of September. As the temperature and the precipitation declined, the vegetation ceased to grow, withered, and the soil began to freeze, ceasing biomass accumulation and becoming yellow at the onset of the winter dormancy period. However, biomass accumulation speed, date of maximum biomass, and annual aboveground net production differed between years. The biomass amount was 238.5 $g \cdot m^{-2}$ in 2003 and 266.8 $g \cdot m^{-2}$ in 2004. Influenced by different climate conditions in the consecutive two years, the biomass accumulation of June and July in 2004 was greater than that of the same period in 2003, which resulted in

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

the different yearly distribution of the carbon flux. Fig. 8 shows the relationship between the aboveground biomass and the CO_2 daily exchange of the *P. fruticosa* shrub.

In Fig. 8, the biomass accumulations from the end of April to the beginning of June was small in amount and slowed in speed, and the daily CO_2 exchange volume was in the emission phase, when the carbon emission surpassed the carbon absorption owing to the increasing soil temperature and increased rainfall. From the middle ten days of June onward, the strong sunshine elevated the soil CO_2 emission, which together with the favorable hydrothermal conditions expedited the vegetation growth. The vegetation absorbed large volumes of CO_2 in the atmosphere; thus daily CO_2 exchange values were negative (absorption). Subsequently, absorption increased and did not mitigate until at the end of August or the beginning of September when the biomass peaked. Then, even though the biomass was no longer accumulated as the ambient conditions worsened, the soil temperature remained fairly high, and the plant roots continued to grow until the middle of October. In this period, the vegetation CO_2 absorption volume began to reduce, while soil respiration was high; thus, daily CO_2 exchange became positive in the middle of September.

Seasonal variation in leaf areas not only reflected the vegetation growth process, but also affected the vegetation photosynthetic activity and the carbon flow of the ecosystem. Fig. 9 suggests the shrub's LAI in 2003 and 2004 showed evident variations. In early days of April, the grazing and wind blowing made the earth's surface almost bare (the initial value was 0), and the LAI could not be observed until the end of April when the vegetation began to sprout. The index increased as the plants grew, which maximized at the end of August or the beginning of September, up to 2.3. This trend was in coincidence with the process of biomass accumulation. Furthermore, LAI of the shrub was negatively related to the accumulated CO_2 exchange volume, showing that the two indices are directly linked. Specifically, when the leaf area was small, daily CO_2 exchange was in the process of emission; when the leaf area reached a certain amount (about 0.3—0.4), the daily CO_2 exchange switched from emission to absorption; from the end of June to the beginning of August when the plant was in full growth, the daily CO_2 exchange volume was in the process of absorption. However, from the end of August to early of September, the aboveground biomass and LAI were relatively stable, causing a low carbon absorption rate. At the end of September, the

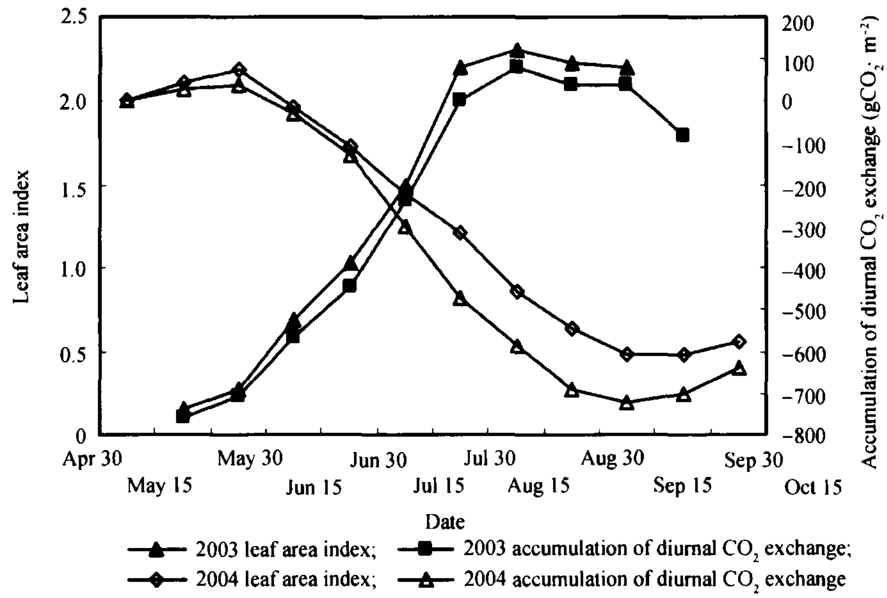

Fig. 8. The process of the aboveground biomass and the accumulation of diurnal CO_2 exchange in *P.Fruticosa* Shrub (from 30 April to 15 October).

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

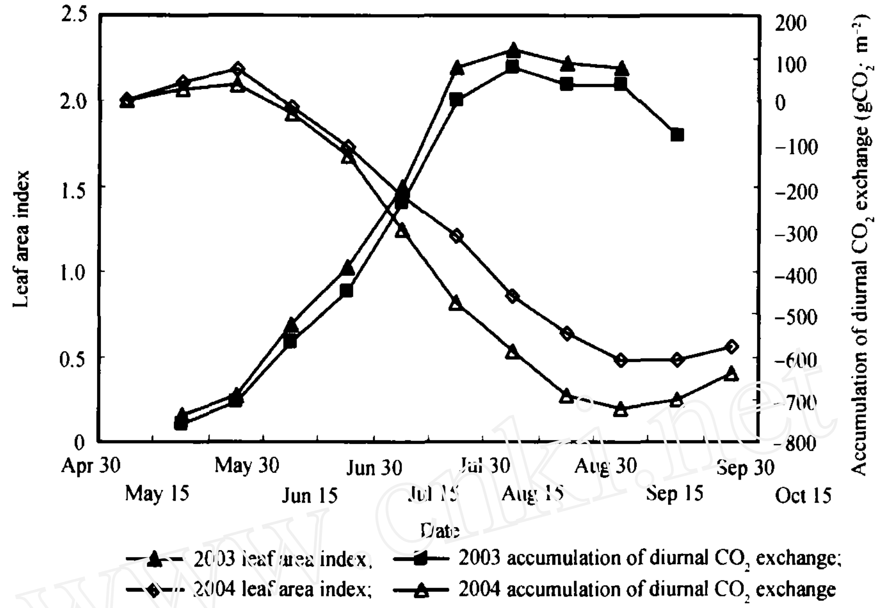

Fig. 9. The process of the vegetation LAI and the accumulation of diurnal CO_2 exchange in *P. Fruticosa* Shrub (from 30 April to 15 October).

exchange switched to emmision.

The turnover value was employed to calculate the underground net primary production (Table 2). Table 2 also indicates the annual net primary production and carbon fixing quantity in 2003 and 2004. Variation in the carbon fixation capacity of above- and below-ground vegetation tracked variation in absorption volme between 2003 (lower) and 2004 (higher). The carbon fixation capacity in 2003 and 2004 was higher than the net carbon absorption volume by 96.0 and 141.3 $g \cdot m^{-2}$ respectively. Since above- and belowground biomass was difficult to measure and the harvest method was error-inclined (affected by such factors as soil respiration, net emission at night, neglected withered leaves, carbon storage of the shrub, and air under the instruments) the results were by no means precise. Therefore, further study should be conducted to prove the conformity between the vegetation carbon fixation capacity and CO_2 net ecosystem exchange absorption.

3 Conclusions

(1) CO_2 Exchange volume of the *P. fruticosa* shrub ecosystem on Qinghai-Tibet Plateau had apparent monthly variation, with two emission peaks occurring in April and October, and two absorption peaks occurring in July and August (growing season).

(2) Results in 2003 to 2004 showed that the general tendencies of CO_2 net exchange in different years were similar. The figures in this regard were –231.4 g CO_2 m^{-2} in 2003 and –274.8 g CO_2 m^{-2} in 2004, which indicated that carbon flow of *P. fruticosa* shrub ecosystem was in an evident absorption state. The CO_2 net emission values in the non-growth period for the two consecutive years were 460.3 and 495.6 g CO_2 m^{-2}, respectively, while in the growth period, the net absorption values were 692.1 and 767.8 g CO_2 m^{-2}, respectively.

Table 2 The comparison of annual net primary production and CO_2 absorption volume in plant growing season in *P. fruticosa* shrub

Year	Item	Net primary production ($g \cdot m^{-2} \cdot a^{-1}$)	Carbon fix coefficient[23,24]	Carbon fix capacity ($g \cdot m^{-2} \cdot a^{-1}$)	Net carbon fix capacity of aboveground and belowground ($gC \cdot m^{-2} \cdot a^{-1}$)	CO_2 annual absorption	
						$/gCO_2 \cdot m^{-2} \cdot a^{-1}$	$/gC \cdot m^{-2} \cdot a^{-1}$
2003	aboveground	238.5	0.45	107.3	544.0	231.4	63.1
	belowground	1091.8	0.40	436.7			
2004	aboveground	247.9	0.45	111.6	559.4	274.8	74.9
	belowground	1119.4	0.40	447.8			

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

(3) Throughout the year, the daily CO_2 exchange as negatively related to most of the meteorological factors, though in different period, such relations differentiated. Specifically, exchange was positively related to temperature and radiation in the emission period, and negatively related with the two factors in the absorption period. Additionally, soil humidity had a larger influence in the emission period than in the absorption period. It was shown that other factors tend not to significantly affect the carbon exchange.

(4) Comparison of CO_2 exchange volume in 2003 and 2004 showed that in different years, the CO_2 flux in the daytime was mainly affected by temperature and slightly affected by photosynthetic radiation. During the plant growing season (May 16 to September 30), when the daily temperature was low (below 2℃), the ecosystem's carbon absorption capacity was weak; when the temperature was 2℃−10℃, the CO_2 absorption increased as the temperature increased; when the average temperature was higher than 10℃, the CO_2 absorption reduces slightly as the temperature decreases because the strong soil respiration and carbon emission increase at high temperature.

(5) The relationships between variations of aboveground biomass and LAI and CO_2 exchange were negative in the growth period. It was estimated that the annual net carbon fixation capacity of aboveground and belowground vegetation was 544.0 g·C m^{-2} in 2003, and 559.4 g· C m^{-2} in 2004. The annual CO_2 net absorption values of CO_2 during the growth season were 63.1 g·C·m^{-2} in 2003 and 74.9 g C·m^{-2} in 2004. Yearly vegetation carbon absorption positively related with the net carbon fixation capacity.

Acknowledgements This work was mainly supported by the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No. KZCX1-SW-01-01A) and the State Key Basic Research Plan of China (Grant No. 2002CB412 501).

References

1 Yu G R, Zhang L M, Sun X M, et al. Advances in carbon flux observation and research in Asia. Sci China Ser D-Earth Sci, 2005, 48(supp. I): 1−16

2 Baldocchi D. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Glob Change Biol, 2003, 9: 479−492

3 Valentini R, Matteucci G, Dolman A J, et al. Respiration as the main determinant of carbon balance in European forests. Nature, 2000, 404: 861−865

4 Guan D X, Wu J B, Yu G R, et al. Meteorological control on CO_2 flux above broad-leaved Korean pine mixed forest in Changbai Mountains. Sci China Ser D-Earth Sci, 2005, 48(supp.I): 116−122

5 Xu S X, Zhao X Q, Li Y N, et al. Diurnal and monthly variations of carbon dioxide flux in an alpine shrub on the Qinghai-Tibet Plateau. Chin Sci Bull, 2005, 50(6): 539−543

6 Xu S X, Zhao X Q, Fu Y L, et al. Characterizing CO_2 fluxes for growing and non-growing seasons in a shrub ecosystem on the Qinghai-Tibet Plateau. Sci China Ser D-Earth Sci, 2005, 48(supp.I): 133−140

7 Gu S, Tang Y H, Du M Y, et al. Short-term variation of CO_2 flux in relation to environmental controls in an alpine meadow on the Qinghai-Tibetan Plateau. J Geophy Res, 2003, 108(21): 4670, doi: 10. 1029/2003JD003584

8 Kato T, Tang Y H, Gu S, et al. Carbon dioxide exchange between the atmosphere and an alpine meadow ecosystem on the Qinghai-Tibetan Plateau, China. Agr Forest Meteorol, 2004, 124: 121−134

9 Zhao L, Li Y N, Gu S, et al. Carbon dioxide exchange between the atmosphere and an alpine shrubland meadow during the growing season on the Qinghai-Tibetan Plateau. Acta Bot Sin, 2005, 47(3): 271−282

10 Zhao L, Li Y N, Zhao X Q, et al. Comparative study of the net exchange of CO_2 in 3 types of vegetation ecosystems on the Qinghai-Tibetan Plateau. Chin Sci Bull, 2005, 50(16): 1767−1774

11 Feng S, Tang M C, Wang D M. New evidence for the Tibetan Plateau as a startup area of climate change. Chin Sci Bull, 1998, 43(6): 633−636

12 Wang Q J, Zhou X M, Zhang Y Q, et al. Structure characteristics and biomass of *Potentilla fruticosa* shrub in Qinghai-Tibet Plateau, Acta Bot Boreali-occidentalia Sin (in Chinese), 1991, 11(4): 333−340

13 Li Y N, Zhao X Q, Cao G M, et al. Analysis of climate, vegetational productivity background and their correlation of Haibei Alpine Meadow Ecosystem Research Station. Plateau Meteorol (in Chinese), 2004, 23(4): 558−567

14 Webb E K, Pearman G I, Leuning R. Correction of flux measurements for density effects due to heat and water vapor transfer. Q J Roy Meteor Soc, 1980, 106: 85−100

15 Hollinger D Y, Kelliher F M, Byers J N, et al. Carbon dioxide exchange between an undisturbed old-growth temperate forest and the atmosphere. Ecology, 1994, 75(1): 143−150

16 Greco S, Baldocchi D D. Seasonal variations of CO_2 and water vapor exchange rates over a temperate deciduous forest. Glob Change Biol, 1996. 2: 183−197

17 Pilegaard K, Hummelshoj P, Jensen N O, et al. Two years of continuous CO_2 eddy-flux measurements over a Danish beech forest. Agric For Meteorol, 2001, 107: 29−41

18 Knohl A, Schulze A, Kolle O, et al. Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. Agric For Meteorol, 2003, 95: 115−168

19 Myneni R, Nemani R, Running S W. Estimation of global leaf area index and absorbed par using radiative transfer models. IEEE Trans Geosci Remonote Sens, 1997, 35: 1380−1393

20 Myneni R B, Keeling C D, Tucker C J, et al. Increased plant growth in the northern nigh latitudes from 1981−1991. Nature, 1997, 386: 698−702

21 Frank A B, Dugas W A. Carbon dioxide fluxes over a northern semiarid, mixed-grass prairie. Agr Forest Meteorol, 2001, 108: 317−326

22 Cao G M, Li Y N, Zhang J X, et al. Values of carbon dioxide emission from different landuse patterns of alpine meadow. Environ Sci (in Chinese), 2001, 22(6): 14−19

23 Zhang G J, Cao G M, Zhou D W, et al. Carbon dioxide emission of Mat Cryo-sod soil in the Haibei alpine meadow ecosystem. Acta Ecologica Sin (in Chinese), 2001, 21(4): 544−549

24 Li J Z, Zhu G R, Yang T, et al. Studies on decomposition of plants of cellulose root and litter of the alpine meadow. Acta Biologica Plateau Sin (in Chinese), 1984, 4: 107−114

© 1994-2008 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net