Journal of Geographical Sciences 13, 4 (2003) 429–437 ISSN: 1009–637X www.geog.cn

CO_2 processes in an alpine grassland ecosystem on the Tibetan Plateau

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Abstract: In this paper, the CO_2 concentrations profile from 1.5 m depth in soil to 32 m height in atmosphere were measured from July 2000 to July 2001 in an alpine grassland ecosystem located in the permafrost area on the Tibetan Plateau, which revealed that CO_2 concentrations varied greatly during this study period. Mean concentrations during the whole experiment in the atmosphere were absolutely lower than the CO_2 concentrations in soil, which resulted in CO_2 emissions from the alpine steppe soil to the atmosphere. The highest CO_2 concentration was found at a depth of 1.5 m in soil while the lowest CO_2 concentration occurred in the atmosphere. Mean CO_2 concentrations in soil generally increased with depth. This was the compositive influence of the increasing soil moistures and decreasing soil pH, which induced the increasing biological activities with depth. Temporally, the CO_2 concentrations at different layers in air remained a more steady state because of the atmospheric turbulent milking. During the seasonal variations, CO_2 concentrations at surface soil interface showed symmetrical patterns, with the lowest accumulation of CO_2 occurring in the late winter and the highest CO_2 concentration in the growing seasons.
Key words: CO_2; soil; atmosphere; alpine grassland; Tibetan Plateau
CLC number: S153

1 Introduction

The current concern about global climate change has made it of great interest to find out the real causes of air temperature rising. Observations and further analyses suggest that greenhouse gas increases are responsible for the climate change (Tett *et al.*, 1999; Crowley, 2000). Among all the greenhouse gases in atmosphere, the increasing concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) contribute more than 70% of the global warming (Lashof *et al.*, 1990; Rodhe, 1990). Carbon dioxide is the primary gas involved in the exchange for C between the atmosphere and the Earth, and it is responsible for 50% of all greenhouse forcing (Rodhe, 1990). The concentration of atmospheric CO_2 has increased from 280 p.p.m.v. since pre-industrial period (pre-1800) to current about 380 p.p.m.v. which is still increasing at a rate of 3 p.p.m.v. per year (Neftel *et al.*, 1985; Friedli *et al.*, 1986; Fan *et al.*, 1998; Monnin *et al.*, 2001). Beside anthropogenic changes, a large amount of C is returned to the biosphere from the atmosphere by plant photosynthesis and subsequently released from biota to the atmosphere by respiration or burning of plants, so the release of CO_2 from terrestrial biota has contributed significantly to the present atmospheric CO_2 concentration (Sommerfeld, 1993).

Carbon exchange between the terrestrial biosphere and the atmosphere is one of the key processes that need to be assessed in the context of the Tokyo Protocol (IGPB Terrestrial Carbon Working Group, 1998). Overview of the current state of the knowledge of global and regional patterns of C exchange by terrestrial ecosystems showed that much of the exchange is affected by human activities (including changing land use and more subtle management effects, such as reduced fire frequency leading to woody encroachment) and is coupled to other climatological and biogeochemical processes (Caspersen *et al.*, 2000; Falkowski *et al.*, 2000; Schimel *et al.*, 2001). The net C exchange of terrestrial ecosystems is the result of a delicate

Received date: 2003-02-20 **Accepted date:** 2003-05-22
Foundation item: .National Key Project for Basic Research on Tibetan Plateau (G1998040800)
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balance between uptake (photosynthesis) and loss (respiration), and shows strong diurnal, seasonal and annual variabilities (Valentini *et al.*, 2000). Soils store two or three times more C than exists in the atmosphere as CO_2, and it is thought that the temperature sensitivity of decomposing organic matter in soil partly determines how much C will be transferred to the atmosphere as a result of global warming (Davidson *et al.*, 2000). Environmental factors such as soil moistures and temperatures influence soil biological activity and CO_2 diffusion, and therefore they have pronounced influences on the seasonal dynamics of C exchange (Keeling *et al.*, 1995; Davidson *et al.*, 1998; Tufekcioglu *et al.*, 2001). According to the previous studies, some other factors such as nitrogen deposition, the availability of soil organic matter, soil pH, and density of plant roots, providing the substrates for soil biological activity, may also control the overall magnitudes of the soil-atmospheric CO_2 exchange (Kelting *et al.*, 1998; Nadelhoffer *et al.*, 1999; Tufekcioglu *et al.*, 1999; Rosenfeld, 2001). The above studies were all limited to the C sequences in soil, plant or atmosphere respectively. Few researches have been done about the C processes within the soil-biosphere-atmosphere profile in one unique site point. It is of great importance to improve the general understanding of C exchange in an integrated ecosystem throughout soil, biosphere and atmosphere.

As "the third pole" of the earth, the Tibetan Plateau is one and the only active continental collision area in the world, with a mean altitude of the plateau is more than 4000 m above the sea level and an area of about 2,500,000 km^2. Great uplift of the plateau since Late Cenozoic has been strongly affecting the physical environment of the plateau itself and its neighboring regions. Meanwhile, the plateau is also a sensitive monitor of climate change in the Asian monsoon region, which is closely related to the global change (Zheng *et al.*, 2000). Due to the topographic features and the characteristics of the atmospheric circulation, typical alpine zones of forest, meadow, grassland and desert appear in succession from southeast to northwest in the plateau (Zheng *et al.*, 1979). Alpine grassland is one of the most important ecosystems on the Tibetan Plateau, which occupied almost 1/3 of the whole plateau area. Besides, the area is special for its lacking of human activities, so this is an ideal place to examine the C exchange within the whole soil-biosphere-atmosphere system.

The aim of the present study was (1) to measure CO_2 concentrations within the layers near ground to determine the C exchange in the alpine grassland ecosystem on the Tibetan Plateau; and (2) to analyse the relationships between C exchange and environmental factors.

2 Experimental design

We hypothesized that C exchange would happen between different layers near ground, and the exchange should be controlled by the environmental factors, such as temperatures, moistures and soil pH and so on. To check up the above hypotheses, we carried out the CO_2 concentration profile measurements in a typical alpine grassland ecosystem on the Tibetan Plateau.

2.1 Sampling site

The study was carried out on the top of the hill in Wudaoliang, Qinghai Province, China (35.13°N, 93.05°E). The altitude of the study site is 4767 m above the sea level. The climate in this area is the sub-frigid and semi-arid zone. The average monthly air temperatures were all below 0°C except growing seasons (from June to September), and the mean annual temperature was -5.6°C (Sun *et al.*, 1997). The annual mean precipitation in the study area ranged between 200 mm and 400 mm, with 84% of the annual precipitation occurring in growing seasons. There was permafrost soil in the study area. The soil type was the alpine steppe soil. The ecosystem was classified as an alpine grassland ecosystem, and the majority of the vegetation was *Stipa* lawn community dominated by *Stipa purpurea* (Zheng *et al.*, 1979). The leaf area index at site was about 0.63 (from T X Luo, personal communication).

2.2 Materials and methods

CO_2 concentrations at different layers both in soil and in the atmosphere were examined from July 2000 to July 2001. The concentration measurements were made one day for two weeks during the growing season and one day for non-growing seasons. In each measuring day, CO_2 concentrations were measured three times between 10:00 and 16:00 during growing seasons, and only two times between 11:00 and 15:00 during non-growing seasons.

A 32-meter-iron-tower was used to gather the gas samples from the near ground horizons in atmosphere. Four polyvinyl chloride (PVC) pipes (4 mm in diameter) were fixed from the heights of 4, 8, 16 and 32 meters to the ground, respectively. We pumped out all the remaining gas from the pipes before each sampling time in order to get the actual gas concentration at each horizon in the atmosphere. All gas samples were taken with 100 ml polypropylene syringes equipped with three-way stopcocks into polyethylene-coated aluminum bags for further CO_2 concentration analyses (Maljanen *et al.*, 2001). Unfortunately, the CO_2 concentrations at the heights of 16 and 32 meters in atmosphere on December 14, 2000 were missed because the PVC pipes were damaged by a snowstorm.

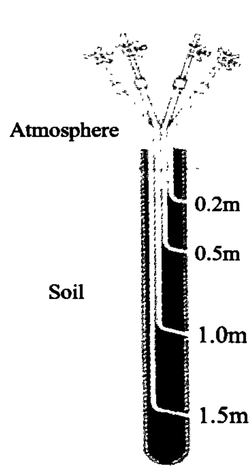

Figure 1 Diagram of the sampler used to measure soil CO_2 at different depths

We gathered the soil gas samples at depths of 0.2, 0.5, 1.0 and 1.5 m from the soil surface. The below-ground gas samples were gathered through soil gas samplers, which were similar with Burton's facilities (1994). Our gas samplers were made of stainless steel tubes. The outside tube has a diameter of 10 cm, and the diameter of the inside pipes was 8 mm. The top of the inside pipes were tightened with three-way stopcocks, thereby dividing the inner soil gas from the outer atmosphere without a direct contact (Figure 1). Three sampling plots were selected on different vegetation biomass of the study site, and three sample wells were dug on July 20, 2000. The samplers were put in each well osculated to the soil profile in order to get the exact CO_2 concentrations at different soil layers. During the sampling time, gas samples were gathered from each air tightened pipes with polypropylene syringes into polyethylene-coated aluminum bags. Furthermore, the soil surface CO_2 fluxes were also measured using static chamber technique (Maljanen *et al.*, 2001). At the same time of gas sampling, a soil temperature profile at depths of 0.05, 0.1, 0.15, 0.2, 0.5, 1.0 and 1.5 m was measured, in order to relate the soil gas concentrations to prevailing environmental conditions (Tuittila *et al.*, 2000). Soil temperatures at depths of 0.5 m, 1.0 m, and 1.5 m were measured all the experimental time, and others were measured only during the growing seasons. Soil samples from layers of 0-10, 10-20 and 20-30 cm were taken using a soil core (3.2 cm diameter) at the end of each measuring day during the growing seasons. Plant samples (including above-ground vegetation and root) were taken at the end of the experiments.

2.3 Sample analyses

The plant samples (both above and below ground) were all dried at 60 ℃ over 48 hours. After the amount of biomass was estimated, the samples were used to measure organic carbon by digestion with potassium dichromate and back-titrating with 0.025 M ferrous ammonium sulphate (Kalembasa *et al.*, 1973) and total nitrogen by Kjeldahl (Bremner, 1965). The soil moisture was determined by oven dry method at 60 ℃ for 48 hours. Soil pH was measured using a glass electrode by a 1:2 soil-to-water ratio. Soil organic carbon and total nitrogen were measured using the same method with the plant samples. CO_2 concentrations were measured by a CO_2 infrared analyzer (LI-COR6252). The CO_2 flux was calculated from the concentration change over the sampling period (Pei *et al.*, 2003).

Mean values, standard deviations, significance and correlations coefficients were estimated using an Excel spreadsheet (Microsoft Corp., USA).

3 Results

3.1 Soil and vegetation characteristics

The alpine steppe soil at our study site had a lighter texture (sandy loam), and the other physical and chemical characteristics of surface soil were showed in Table 1. Higher C storage was found in 20-30 cm depth of this sandy loam soil. Soil moisture increased with depth, while soil pH decreased gradually with depth. Deeper layer's soil temperature ranged from about -10 to 11 ℃, and the variation of upper layer's temperature varied more widely (Figure 2). Among these three layers, the lowest temperature was found in January at a depth of 50 cm and the highest in July at the same depth. The variation of deeper layer temperatures had a distinct time lag following the temperature variations of the upper horizons. These deeper soil temperatures indicated that soil remained frozen throughout the year at a depth of 1.5 m. The vegetation biomass of the study site was slightly lower than other grasslands in the plain areas (Table 2). The ratio of biomass between below-ground and above-ground was about 16:1, which was higher than those of plain areas (Chen *et al.*, 2000). The vegetation root system here was likely stronger than the plain areas due to the frigid climate.

3.2 CO_2 concentration profile

CO_2 concentrations showed great variations within the soil-atmosphere profile during the study period. The lowest CO_2 concentration occurred in the atmosphere. In general, the mean concentrations in the atmosphere were all much lower than the CO_2 concentrations in soil. The largest accumulation of CO_2 was found at a depth of 1.5 m in soil. Variation of soil CO_2 concentrations showed a significant pattern with depth. Soil CO_2 concentrations in our study increased with depth, which is similar to the studies at the Canadian Agriculture Research Station, Delhi, Ontario (Burton *et al.*, 1994). Furthermore, the standard deviations of CO_2 concentrations in atmosphere were all much lower than those in soil, so the CO_2 concentrations in air showed better stabilities than CO_2 concentrations below-ground (Figure 3).

3.3 Temporal variations of CO_2 concentrations

Soil-atmospheric CO_2 concentration profiles varied significantly during the study period, both temporally and with depth. Seasonal variation of CO_2 concentrations at

Table 1 Soil characteristics in Wudaoliang, Qinghai

Depth (cm)	Moisture (%)	pH	Organic C (%)	Total N (%)
0 - 10	3.61	9.02	0.15	0.04
10 - 20	5.05	9.03	0.15	0.04
20 - 30	7.28	8.90	0.32	0.07
30 - 40	7.49	8.90	0.26	0.06
40 - 50	8.17	8.78	0.25	0.06
50 - 70	8.36	8.96	0.15	0.05
70 - 100	9.47	8.96	0.17	0.05
100 - 120	10.67	8.87	0.17	0.05
120 - 150	13.75	9.00	0.11	0.04

Table 2 Vegetation characteristics in Wudaoliang, Qinghai

	Biomass (g/m^2)	Total C (%)	Total N (%)
Fresh	50.52	39.39	1.51
Litter	4.85	35.69	0.82
Root	871.18	25.04	0.93

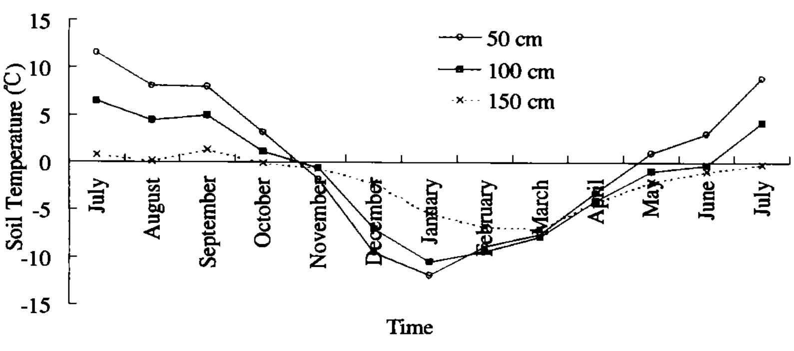

Figure 2 Seasonal variation of soil temperatures (℃) in Wudaoliang, Qinghai

upper layers in soil showed very distinct patterns (Figure 4). Soil CO_2 concentrations at upper layers decreased gradually in the fall, and the lowest accumulation of CO_2 occurred in the late winter. Soil CO_2 concentrations increased to the highest point in the growing season. This phenomenon was similar with the results at the Canadian Agriculture Research Station, Delhi, Ontario (Burton *et al*., 1994). However, the accumulation of CO_2 concentrations at 1.5 m depth did not exhibit the same trend, the high accumulations of CO_2 were found during the non-growing season. CO_2 concentrations at different heights in air showed more steady-states, but the variations at all horizons did not show any distinct trends during the study period.

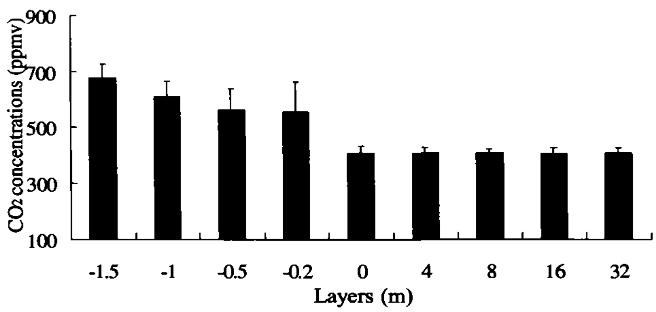

Figure 3 CO_2 concentration profile from soil to atmosphere

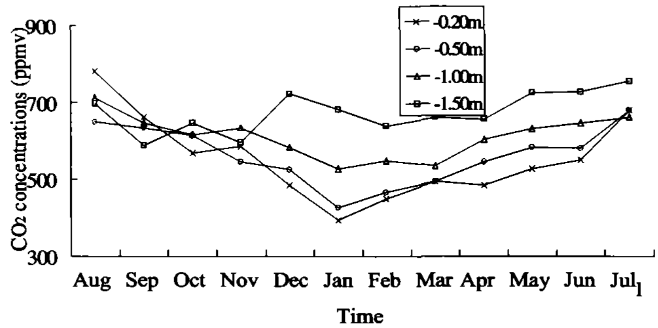

Figure 4 Temporal variations of CO_2 concentrations in the soil

3.4 CO_2 fluxes between soil and atmosphere

The mean CO_2 concentrations in the atmosphere were all much lower than the CO_2 concentrations in the soil, which would introduce CO_2 emissions from the alpine steppe soil to the atmosphere in our study area. Measured fluxes of CO_2 in site from the soil to the atmosphere was about 0.17 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The CO_2 contribution from soil to the atmospheric CO_2 was lower than other grasslands in plain areas (Dugas *et al*., 1997; Dong *et al*., 2000; Mielnick *et al*., 2001). The CO_2 emissions showed a very distinct trend, which decreased in the autumn and increased in the spring (Figure 5). CO_2 emissions during the growing seasons were much higher than those during the non-growing seasons, which accounted for almost 90% of the whole year emissions. The highest mean CO_2 emission occurred in August.

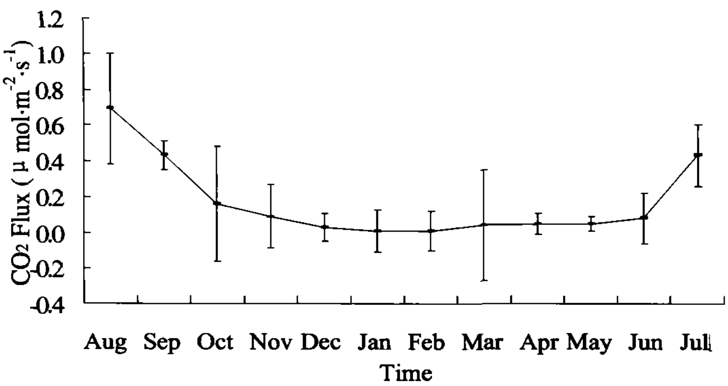

Figure 5 Temporal variation of CO_2 fluxes

4 Discussion

The net carbon exchange of terrestrial ecosystems is the result of a delicate balance between uptake (photosynthesis) and loss (respiration), and shows a strong diurnal, seasonal and annual variability (Valentini *et al*., 2000). Soils store two or three times more carbon than exists in the atmosphere as CO_2, and it is thought that the temperature sensitivity of decomposing organic matter in soil partly determines how much carbon will be transferred to the atmosphere as a result of global warming (Davidson *et al.*, 2000). Generally, concentrations of CO_2 in the soil atmosphere are controlled primarily by the rate of soil respiration (including root respiration and microbial respiration), which is also modified by the rate of CO_2 production by biota within soils (Raich *et al.*, 1992; Kelting *et al.*, 1998).

4.1 Variations between CO_2 concentrations and fluxes

Although mean CO_2 concentrations varied greatly with depth in soil, the seasonal variations of CO_2 concentrations showed significant correlations ($R^2>0.85$, $p<0.001$) between the upper layers in the soil. The variation of soil CO_2 concentrations at 1.5 m depth exhibited a different seasonal pattern with those of the other horizons, and the correlation between 1 m and 1.5 m was relatively weak. A significant correlation ($R^2 = 0.63$, $p<0.001$) was also found between CO_2 at soil surface fluxes and soil CO_2 concentrations at -0.2 m depth during the study period (Figure 6). This implies the variation of CO_2 concentrations in the surface horizon was the most direct driving force of CO_2 emissions from the soil to the atmosphere.

The variations of atmospheric CO_2 concentrations at 4 m, 8 m, 16 m and 32 m heights above ground did not show any distinct relationships ($R^2<0.4$) between each other. CO_2 transferred quickly and unpredictably between different layers in the air due to the atmospheric turbulence. The atmospheric CO_2 concentrations varied randomly during the experimental period, and their variations between layers hardly have any significant correlations in the atmosphere. Compared with the turbulent concentrations in the atmosphere, soil CO_2 diffusions from deeper layers to upper layers were generally slow and durative.

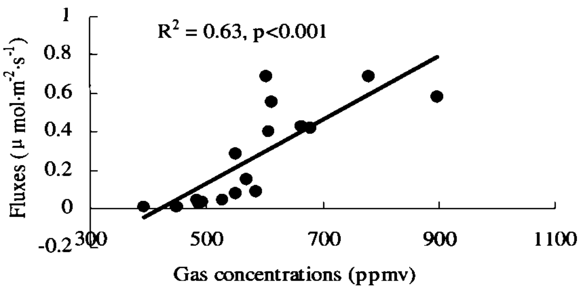

Figure 6 Relationship between CO_2 fluxes and concentrations

4.2 Relationships between temperature and CO_2 variations

Soil temperature has often been described as the dominant independent variable determining the carbon uptake and ecosystem respiration rate (Braswell *et al.*, 1997; Tian *et al.*, 1998; Valentini *et al.*, 2000). In the present study, soil CO_2 concentrations at the upper horizons had a seasonal pattern that closely resembled that of the soil temperature (Figures 2 and 4). The temporal variations of CO_2 concentrations at upper layers can be well explained by the seasonal pattern of soil temperature in our study. Significant correlations between CO_2 concentrations and soil temperatures were also found at depths of 0.5 m and 1.0 m ($R^2 = 0.70$, $p<0.001$) (Figure 7). The annual soil respiration rates were closely correlated with soil temperatures, which agrees well with results of several previous studies that warmer temperatures enhance CO_2 production in different types of soil (Rochette *et al.*, 1999; Waddington *et al.*, 2001).

In our study, soil CO_2 efflux showed an asymmetric pattern during the whole year experiment, which was almost the same as the pattern in northern California forest (Xu *et al.*, 2001). The maximum CO_2 emission occurred in summer, and CO_2 emission decreased to the minimum in the winter. Regression analyses showed that the variation in CO_2 fluxes was positively related to air temperature (Figure 8).

Root respiration and microbial respiration were the main source of soil CO_2. According to Zogg's study (1996), root respiration rates increased sharply with soil temperature in northern hardwood forests, and the similar relationship between root respiration rates and soil temperatures was also found in many kinds of ecosystems (Bowden *et al.*, 1993; Kelting *et al.*, 1998; Tufekcioglu *et al.*, 2001; Burton *et al.*, 2002). As another important component of soil respiration, microbial decomposition and respiration rates were also strongly affected by soil

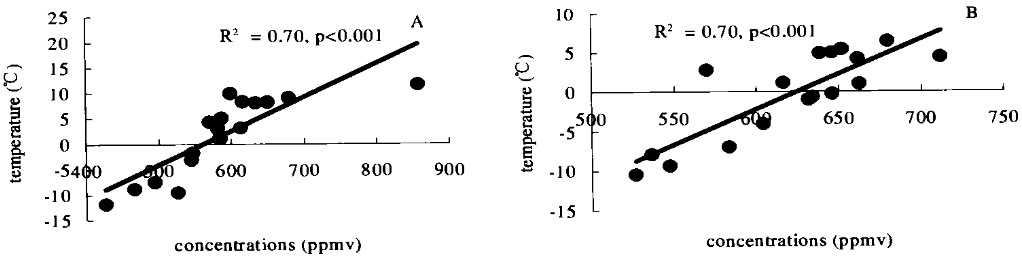

Figure 7 Soil temperatures and CO_2 concentrations at depths of 0.5 m (A) and 1.0 m (B)

temperature (Whalen *et al.*, 1990; Updegraff *et al.*, 1998). Microbial populations may adapt better to changing conditions and warmer temperatures. This is supported by studies that have shown that microbial efficiency is affected by the response of the micro-organisms to temperature and that different microbial communities dominate CO_2 production as temperature increases (Lekkerkerk *et al.*, 1990; Zak *et al.*, 1999; Waddington *et al.*, 2001). So soil temperature was the most important factor driving seasonal variation in soil respiration, and this temperature sensitivity of soil respiration has a profound effect on seasonal variation in soil CO_2 concentrations and soil surface CO_2 fluxes.

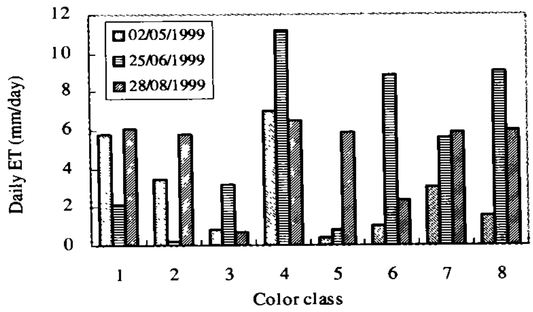

Figure 8 Relationships between soil CO_2 fluxes and temperatures in Wudaoliang, Qinghai

4.3 Influence of soil moisture

It is well known that soil moisture plays a major role in regulating soil atmosphere CO_2 concentrations through the influence on rates of biological activity and gas diffusion (Parfitt *et al.*, 1997). As documented by Tufekcioglu *et al.* (2001), a positive linear relationship between soil moistures and soil respiration rates was found among sites. It means that CO_2 production rates generally increased with soil moisture. Orchard *et al.* (1992) attributed this relationship to the effects of water content on soil microbial communities. While soil temperature was the most important factor driving seasonal variation in soil CO_2 concentrations, it was not significant in terms of explaining variations in depths. Soil CO_2 concentrations increased with depth in our study site, while the soil moistures also increased with depth due to the high surface evaporation in the study site (Gao *et al.*, 1995). According to the previous studies, available moisture exerts a great influence on soil microbial activity, and low soil moisture probably reduces microbial populations (Tester, 1988; Ellert *et al.*, 1999; Xu *et al.*, 2001). Furthermore, gas transfer coefficient was determined by soil physical properties, while the increasing soil moisture represented as a diffusion barrier of soil gas (Ellert *et al.*, 1999). So the concentration gradient of soil atmosphere CO_2 could be explained by the increasing of soil moisture with depth in our study.

During the seasonal pattern, variation of CO_2 concentration at 1.5 m depth showed a contrary trend to the other horizons (Figure 4). Tufekcioglu *et al.* (1999) has studied the root biomass distribution in a private farm, and no roots were observed below 1.25 m depth in dry grassland ecosystems. So the microbial respiration occupied all the soil respiration at 1.5 m depth. Why should soil respiration be higher during the cold winter? According to Grace's explanation, perhaps it was because the soil at 1.5 m depth was wetter for longer, and so microbes that were adapted to work at low temperatures were active for most of the year

(Grace *et al.*, 2000).

Acknowledgements

We would like to thank Liu Yunfen, Ma Zhixue and Shi Buhong for their assistance in field sampling, and we are grateful to Qi Yuchun for the help in laboratory. Thanks also should be given to Luo Tianxiang and Niu Haishan for their suggestions during the data analyses.

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