ORIGINAL ARTICLE

Soil temperature and moisture controls on surface fluxes and profile concentrations of greenhouse gases in karst area in central part of Guizhou Province, southwest China

Liu Fang · Liu Cong-Qiang · Wang Shi-lu · Zhu Zheng-jie

Abstract In order to better understand the spatiotemporal variations and interrelationships of greenhouse gases (GHG), monthly surface fluxes and profile concentrations of GHG (CO_2, N_2O and CH_4) in karst areas in the Guizhou Province, southwest China, were measured from June 2006 to May 2007. GHG fluxes showed high variability, with a range of 460.9–1,281.2 mg m^{-2} h^{-1} for CO_2, -25.4 to 81.5 μg m^{-2} h^{-1} for N_2O and -28.7 to -274.9 μg m^{-2} h^{-1} for CH_4, but no obvious seasonal change trends of the fluxes existed. Profile concentrations of CO_2, N_2O and CH_4 varied between 0.5 and 31.5 mL L^{-1}, 0.273 and 0.734, and 0.1 and 3.5 μL L^{-1}, respectively. In general, concentrations of CO_2 and N_2O increased with depth, while CH_4 had an inverse trend. However, in October, November and January, the reversal of depth patterns of GHG concentrations took place below 15 cm, close to the soil–rock interface. The spatiotemporal distribution of CO_2 in soil profile was significantly positively correlated with that of N_2O ($p < 0.05$–0.01) and negatively correlated with that of CH_4 ($p < 0.01$). The correlation analysis showed that soil temperature and moisture may be responsible for GHG dynamics in the soils, rather than the exchange of GHG between land and atmosphere.

Keywords Greenhouse gases flux · Karst area · Concentration profiles of greenhouse gases

Introduction

The greenhouse gases (GHG), namely carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), account for more than 70% of the predicted global warming (Shrestha et al. 2004). As fluxes of GHG from soil vary largely in different locations or different ecosystems, monitoring the soil–atmosphere exchange rates of these gases in different ecosystems, especially where these have not been studied in detail yet, is of fundamental importance for accurately estimating the inventories of GHG at regional, national or global scale. In addition, concentrations of GHG in soil are also of great importance, since these can provide valuable information about production, consumption and transportation. A great number of soil GHG flux models on the basis of soil profile concentration and the diffusion of gas through the soil have been presented (e.g., Smith and Arah 1992; Hosen et al. 2000; Pumpanen et al. 2003; Tang et al. 2003; Han et al. 2005; Jassal et al. 2005). However, a better understanding of the dynamics of the GHG in soils of various ecosystems is needed for improving GHG flux modeling. Therefore, measurements of GHG fluxes and profile concentrations may be helpful to understand the mechanisms controlling the GHG distribution and dynamics in soil and their losses to the atmosphere (Burton and Beauchamp 1994).
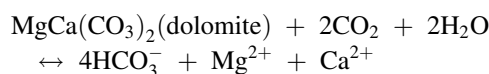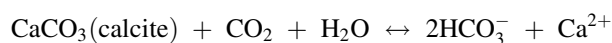
Karst areas comprise approximately 15% of the Earth's land surface and plays an important role in global carbon

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cycles. The source–sink relationship between soil CO_2 and atmosphere CO_2 in karst areas have attracted much attention from scientists. Apart from the respiration of plant roots, oxidation of soil organic matter, activities of soil microbes and atmospheric diffusion (Zheng 1999), CO_2 in soil could come from the dissolution of carbonate rock under acid influence, which comes up to 21–25% of CO_2 generation in karst areas (Li et al. 2002). Furthermore, soil CO_2 can be consumed by carbonate rock weathering under advantageous hydrologic dynamic conditions (Liu and Zhao 1999; Zheng 1999; Liu 2001), which may be deemed as an important continental carbon sink (Gombert 2002). The reactions are described as:

$$CaCO_3(\text{calcite}) + CO_2 + H_2O \leftrightarrow 2HCO_3^- + Ca^{2+}$$

$$MgCa(CO_3)_2(\text{dolomite}) + 2CO_2 + 2H_2O \leftrightarrow 4HCO_3^- + Mg^{2+} + Ca^{2+}$$

Soil N_2O mainly derives from the microbial processes of nitrification and denitrification. CH_4 is controlled by the balance of CH_4 consumption by methanotrophic bacteria in oxidized zones and CH_4 production by methanogenic bacteria in anoxic zones. Numerous studies have shown that the concentrations of CO_2 have important influence on these processes (e.g., Ambus and Robertson 1999; Phillips et al. 2001; Baggs and Blum 2004; Kettunen et al. 2007; Wu et al. 2010), and thus have feedback effect on GHG burden.

An accurate estimation of GHG fluxes requires a gathering of more accurate data on GHG soil–atmosphere exchange rates for different ecosystems under different climatic conditions. Karst areas may play an important role in the entire GHG budget of the Earth, but related studies still overlook some aspects, such as GHG soil–atmosphere exchange studies and surveys. The karst mountain region of southwest China, one of the largest karst areas in the world (Yuan 1993), covers about 5,30,000 km^2. The karst ecosystem in southwest China is fragile (Yuan 2001), the rocky desertification area of which amounts to 1.05×10^5 km^2. Karst rocky desertification, as a typical type of land degradation, is characterized by soil erosion and bedrock exposure of large areas, often leading to low land productivity and fragile eco–geo environments (Jiang et al. 2009; Zhang et al. 2010). In order to better understand soil GHG dynamics in a karst area, this paper selected the central part of Guizhou Province, southwest China, as the study region.

The soil GHG surface fluxes and profile concentrations of the karst area in Guizhou Province were measured over 1 year. The main objectives of this paper were: (1) to detail the temporal variability of surface fluxes and concentrations of GHG in the soil of karst areas, (2) to explore the dependency of surface fluxes and profile concentrations of GHG on soil temperature and moisture, (3) to characterize the possible relationships between surface fluxes and profile concentrations of GHG.

Materials and methods

Site description

Study area (26°31′N, 106°20′E) is located at the karst peak cluster depression near the Wangjiazhai village, close to Qingzhen City, Guizhou Province, southwest China, representative of classic karst ecological environment (Fig. 1). Qingzhen covers about 1.49 km^2, and its karst area accounts for 85.62%. This area is influenced by subtropical humid monsoon climate with rainy seasons from May to October. The mean annual precipitation amounts to about 1,200 mm. The mean annual temperature at this location is 14.0°C, with January the coldest month and July the warmest. The exposed area of the carbonate rocks in the experimental plot is more than 70% of the overall land. Outcrops are dolomitic limestone with a bioclastic sparite to micrite texture, which belongs to Triassic Guanling formation. The soils developed on the carbonate rocks are discontinuously distributed in many points, classified as brown lime soil, and the depth is generally less than 30 cm. Vegetation coverage in this area is dominated by shrubs, such as *Rubus biflorus*, *Pyracantha fortuneana*, *Hypericum monogynum*, *Zanthoxylum planispinum*, *Rhamnus parvifolius* and *Rosa cymosa* (Ge and Wang 2008). The parameters of soil properties in the study site are listed in Table 1.

GHG sampling

The measurements were made monthly, from June 2006 to May 2007. The experimental plot was at a hillslope with gradient of 30°–35°. GHG were sampled using the static chamber technique. The static chamber assembly consisted of a permanently installed stainless steel base (25 cm × 25 cm × 10 cm) with a groove at the top edge to hold the PVC cover (25 cm × 25 cm × 50 cm) with a gas-sampling port. Three permanent bases were inserted into the soil below 5 cm, 2 weeks before the first measurement and left on sites for the whole observation time, with intervals longer than 2 m. Once the cover was placed onto the base, the groove was filled with water to a depth of 2 cm, which acted as an air seal. Gas samples were collected by five times sequentially at an interval of 3 min after closure and placed into 30-mL evacuated vials. GHG fluxes were calculated by regressing the linear changes in GHG concentrations within the chamber over time.

Soil profile gas samples were taken next to the sampling location using a multilevel sampling, which has been well

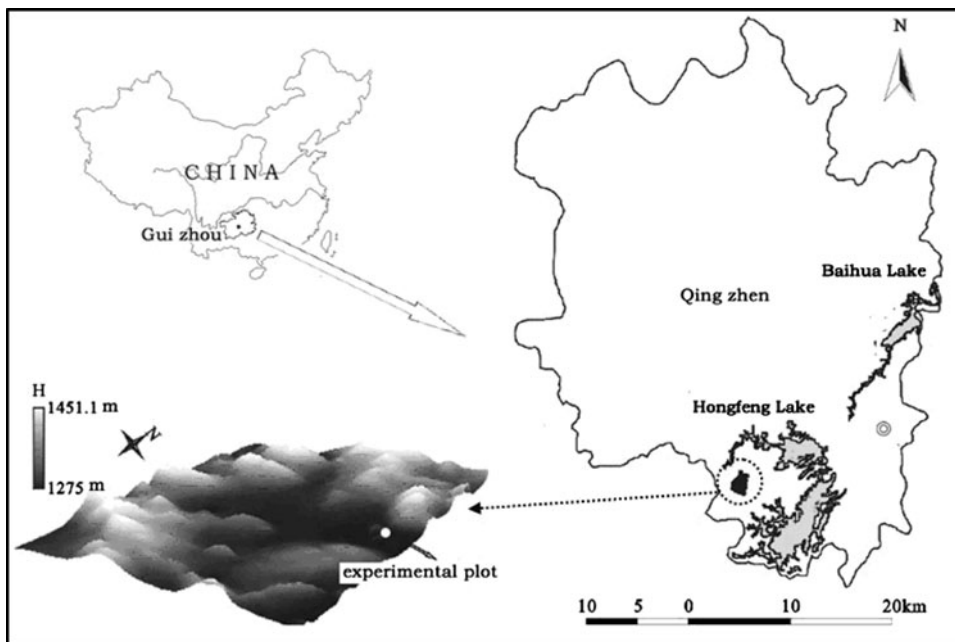**Fig. 1** Map showing the location and landform of the experiment site

Table 1 Physical and chemical characteristics of profile soils

Depth (cm)	Organic C (%)	Total N (%)	pH	Particle-size distribution (%)		
				Clay	Silt	Sand
0–5	4.416	0.369	6.33	43.6	41.0	15.4
5–10	4.542	0.361	6.42	40.6	30.0	29.4
10–15	3.255	0.266	6.44	42.6	22.0	35.4
15–20	2.296	0.214	6.46	11.6	3.0	85.4
20–25	1.494	0.144	6.45	45.6	26.0	28.4
25–30	1.355	0.125	6.51	46.5	29.0	24.5

described by Burton and Beauchamp (1994). The shaft of the sampler was constructed of long polyvinylchloride (PVC) tubes with an inner diameter of 1.2 cm. Sampling wells were positioned on the side of the tubing at 5, 10, 15, 20, 25 and 30 cm below the soil surface. The sampling wells were constructed with 1-mL disposable syringes and connected with a tube to the inner diameter of 3 mm. The syringe barrels were inserted in holes drilled on the side of the PVC shaft. The tube was connected with a needle at the soil surface. Gas samples were collected from the well and preserved in 5-mL evacuated tubes. Soil temperature data were simultaneously recorded during sampling. All measurements were performed between 9 and 10 a.m. of the 15th of each month.

GHG analysis

The gas samples were taken back to the laboratory and analyzed for N_2O, CH_4 and CO_2 within 48 h using HP 6890 gas chromatograph equipped with electron capture detector (ECD), flame ionization detector (FID) and a nickel catalyst for converting CO_2 to CH_4 at 375°C. The gas samples were injected into the GC by a 1-mL loop fitted to an automatic input port valve, separated with a 3-m, 2-mm i.d. Porapak Q (60/80 mesh) stainless steel column at 50°C. ECD worked at 320°C using a mixture of argon (95%) and methane (5%) as the carrier gas with flow speed of 20 mL min^{-1}. FID was set at 250°C using high-purity nitrogen as the carrier gas with flow speed of 20 mL min^{-1}.

Soil parameters analysis

Soil samples at various depths were taken with an auger and physicochemical properties were analyzed as described by Zhu and Liu (2006). Particle-size fractionation was done on <2 mm material (bulk soil). The sand fraction (2,000–53 μm) was isolated by wet sieving. The silt fraction (53–2 μm) was separated from the clay fraction (<2 μm) by centrifugation after ultrasonic dispersion. Soil pH was measured with a glass electrode in a 1:2.5 soil to water suspension. Organic carbon and total nitrogen contents were analyzed by using an elemental analyzer after treatment with 0.5 mol L^{-1} HCl to remove carbonates, and the analytical precision was better than 5%. Soil water content was determined by weighing field-moist samples before and after oven drying at 105°C.

Statistic analysis of data

All statistical analyses were performed using the SPSS software package. Effects of soil temperature and moisture

on GHG, and relationships between soil profile concentrations of GHG were analyzed with correlation analysis. A p value is the lowest level at which the observed value of the test statistic is significant. A P value less than the level of significance of 0.5 indicates that the null hypothesis is false and the attributes are, in fact, correlated.

Results

Seasonal changes of GHG

As seen from Table 2, the annual GHG fluxes showed high variability. The fluxes of CO_2 and N_2O varied in the range of 460.9–1,281.2 mg m^{-2} h^{-1} and −25.4–81.5 μg m^{-2} h^{-1}, respectively. CO_2 fluxes were higher and more variable in summer and autumn, and the highest emission was observed in September. From October to March, the fluxes of CO_2 were lower and less variable. N_2O fluxes displayed a different pattern from CO_2 fluxes in summer, the highest being in July and decreasing later in autumn and winter. Uptake of atmospheric N_2O by the soil was observed in September, November and December. CH_4 fluxes were negative, ranging between −28.7 and −274.9 μg m^{-2} h^{-1}, with the highest value in January, lowest in October and varying inconspicuously between seasons.

Variations of GHG profile concentrations

For the entire measurement period, variations of GHG concentrations in soil profile were significantly large. Concentrations of CO_2, N_2O and CH_4 varied in the ranges of 0.5–31.5 mL L^{-1}, 0.273–0.734 and 0.1–3.5 μL L^{-1}, respectively (Table 2). CO_2 concentrations were the highest in summer, especially in June, and higher than 10 mL L^{-1} below the 10-cm depth was observed. In general, CO_2 concentrations increased with increase in depth. However, when light rain events of long duration occurred in the cold season, CO_2 concentrations decreased with depth below 15 cm. For instance, CO_2 concentrations decreased from 17.5 mL L^{-1} at 15 cm to 3.3 mL L^{-1} at 30 cm in October when rainfall was 153.88 mm in 18 days. In November and January, rainfall reached 28.3 mm in 7 days and 55.4 mm in 9 days, while CO_2 concentrations decreased from 10.3 to 3.6 mL L^{-1} and from 4.2 to 0.6 mL L^{-1} between 15- and 30-cm depth, respectively. N_2O concentration did not show seasonal variations, and its spatial variations along the soil profile were similar to that of CO_2, increasing along with depth. We also found that N_2O decreased with depth below 15 cm in October, November and January. In contrast, CH_4 concentrations between 5- and 15-cm depth decreased with the increase of depth. From 20- to 30-cm depth, CH_4

concentrations increased along with depth in some months, such as in July, August, October, January and April.

Discussions

Surface fluxes of GHG

The studied soil dominantly functioned as sources of atmospheric N_2O and CO_2 (Table 2). The CO_2 fluxes varied considerably in summer and autumn. During winter and early spring, the CO_2 fluxes were lower because of the lower soil respiration under lower temperature. The N_2O fluxes were higher in June and July during the year, and showed a decrease to a steady minimum in winter when rainfall event occurred with long duration. Moreover, uptake of atmospheric N_2O by soil was observed at some periods. It seemed that the heavy rainfall in summer could promote N_2O fluxes by stimulating nitrification and denitrification rate. However, continuous rainfall in winter sealed the surface of the soil, preventing mass transfer between the air filling the pores of the soil and the atmosphere. Highly soluble N_2O could not be emitted easily to the atmosphere while it was further denitrified to N_2, and the soil released lower N_2O or even acted as a sink for atmospheric N_2O. A similar phenomenon has been observed in tropical peatlands (Inubushi et al. 2003) and temperate paddy fields (Minami 1997). The soil acted as net sink for atmospheric CH_4. The maximum uptake rate occurred in January. This can be explained by the slow recovery of the microbial activity from water stress (Wu et al. 2010).

Variations in profile concentrations of GHG

It is well known that biogenic CO_2 in soil is an important agent in the chemical weathering of limestone. Several studies have evaluated the magnitude of spatial variability of soil CO_2 concentration in the karst areas. CO_2 profile concentrations varied from 0.53 to 31.5 mL L^{-1} depending on the seasons and soil depth in our research. These values are consistent with the values reported by previous studies in the karst region of southwest China (Zheng 1998; Li et al. 2002; Zhang et al. 2005). In tropical karst soils of the Malay Peninsula, concentrations of soil CO_2 range from 1.5 to 15.8 mL L^{-1} at 15-cm depth and 2.7 to 32.6 mL L^{-1} at 30-cm depth (Crowther 1983). The soil air CO_2 content measured in a Mediterranean karst yields an average value of 1.3 mL L^{-1} overall, the minimum value is 0.34 mL L^{-1}, and the maximum is nearly 6.9 mL L^{-1} (Benavente et al. 2010). In tundra soils on limestone of Spitsbergen, the maximal CO_2 concentration is 3.0 mL L^{-1} at a depth of 10–60 cm (Pulina et al. 2003). It

Table 2 Fluxes and profile concentrations of CO_2, N_2O and CH_4 in a soil of karst area in Guizhou, China

Year:	2006							2007				
Month:	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
CO_2 flux (mg m^{-2} h^{-1})	959.8	491.7	911.7	1,281.2	857.5	460.9	571.0	578.1	483.4	468.8	802.0	836.4
N_2O flux (µg m^{-2} h^{-1})	47.4	66.7	28.3	−25.4	24.9	−8.9	−11.1	40.9	23.4	12.3	37.9	81.5
CH_4 flux (µg m^{-2} h^{-1})	−203.9	−238.6	−199.9	−203.9	−28.7	−141.2	−195.7	−274.9	−68.0	−62.8	−253.8	−62.6
CO_2 profile concentrations (mL L^{-1})												
5-cm deep	4.9	2.9	2.0	1.3	0.5	6.8	1.1	0.8	0.8	0.8	1.0	1.6
10-cm deep	17.6	14.5	2.3	10.4	11.8	11.2	3.9	3.5	4.0	2.1	5.1	2.8
15-cm deep	23.4	15.6	2.4	12.4	17.5	10.3	4.5	4.2	5.0	2.4	6.7	5.3
20-cm deep	28.6	17.6	6.5	13.6	12.5	7.9	3.5	2.7	5.5	2.5	7.4	10.1
25-cm deep	31.5	16.5	8.0	13.7	15.3	11.0	5.5	1.0	6.4	2.6	7.6	10.0
30-cm deep	29.6	17.9	9.6	13.7	3.3	3.6	5.6	0.6	6.7	3.2	7.8	9.1
N_2O profile concentrations (µL L^{-1})												
5-cm deep	0.335	0.367	0.339	0.336	0.338	0.370	0.312	0.433	0.332	0.344	0.316	0.357
10-cm deep	0.349	0.434	0.338	0.351	0.430	0.404	0.314	0.616	0.317	0.354	0.331	0.372
15-cm deep	0.346	0.466	0.340	0.362	0.458	0.404	0.320	0.667	0.350	0.353	0.273	0.431
20-cm deep	0.354	0.500	0.380	0.374	0.425	0.385	0.324	0.472	0.357	0.353	0.471	0.629
25-cm deep	0.368	0.466	0.410	0.371	0.446	0.424	0.321	0.358	0.366	0.355	0.362	0.717
30-cm deep	0.359	0.474	0.418	0.376	0.363	0.367	0.322	0.339	0.369	0.351	0.375	0.734
CH_4 profile concentrations (µL L^{-1})												
5-cm deep	1.9	1.9	2.7	2.1	1.9	1.6	1.6	1.7	1.9	2.0	2.2	2.1
10-cm deep	1.3	1.8	1.7	1.4	1.5	1.2	1.2	1.6	1.4	1.6	1.9	2.1
15-cm deep	1.0	1.7	1.9	1.2	1.0	1.0	0.7	0.9	1.3	1.2	2.1	2.8
20-cm deep	0.9	1.0	1.5	1.1	1.4	1.4	0.6	1.3	1.1	1.0	1.6	2.0
25-cm deep	0.7	1.6	1.5	0.9	1.2	0.4	0.1	1.9	0.6	1.0	3.6	0.7
30-cm deep	0.8	2.8	2.0	0.7	1.9	1.6	–	2.0	0.5	0.5	3.2	0.6

is ten times lower than that in karst areas of southwest China. Concentrations of soil CO_2 in subtropical karst areas is within the range in tropical karst areas, and higher than that in other climatic zones.

In general, CO_2 and N_2O concentrations increased, while CH_4 concentrations decreased with increasing depth of soil profile. Concentrations of GHG at a given depth were determined by the relative strength of production/consumption and transport (Oh et al. 2005). There are two reasons for the greatest soil–atmosphere exchange rate in the uppermost horizons. First, the flow paths for gas transfer between the soil and the atmosphere are shorter. Secondly, the soils at horizon are often enriched in organic material, and generally have high porosity, which will result in high gas diffusion (Bekele et al. 2007; Crowther 1983). The rapid soil–atmosphere exchange impeded the accumulation of CO_2 and N_2O, and the CH_4 consumption exceeded those in the near-surface soil. In October, November and January, when rainfall with long duration gave rise to higher moisture level in deep soil horizon, CO_2 and N_2O concentrations decreased with increasing depth below 15-cm depth. According to the studies carried out in the peak cluster karst areas of southwest China (Liu et al. 2004), at least two key processes controlled hydrochemical variations during rainy season, that is, dilution by precipitation and water–rock–gas interactions. The latter may be more important. During flood periods, soil gas with CO_2 dissolves in water and enters the fracture system, and the water in turn will become more highly undersaturated, which then will dissolve more limestone. Zhang (2011) suggested that CO_2 from soil may be involved actively in carbonate weathering processes in karst regions, and these processes are generally dependent on precipitation, rather than temperature. The higher the precipitation, the higher will be the dissolution rate. The decrease of N_2O concentrations in the deep soil horizon may lead to indirect losses of dissolved N_2O through drainage water (Reay et al. 2003) or by further reduction to N_2 before it escapes (Schmid et al. 2001; Elmi et al. 2003). CH_4 had an inverse trend in subsoil, unlike CO_2 and N_2O. Occasionally, CH_4 production may balance or even exceed CH_4 oxidation due to limited soil aeration, which can be supported by the fact that CH_4 concentrations increase with depth in deep soil layer.

The relationships between soil GHG concentrations

CO_2 concentrations in the soil profiles were positively correlated with N_2O, with different slopes in different months, as shown by different correlations *a*, *b* and *c* in Fig. 2. Increase of carbon supply or anaerobicity via soil respiration is frequently considered as the dominant force causing higher N_2O production by denitrification under
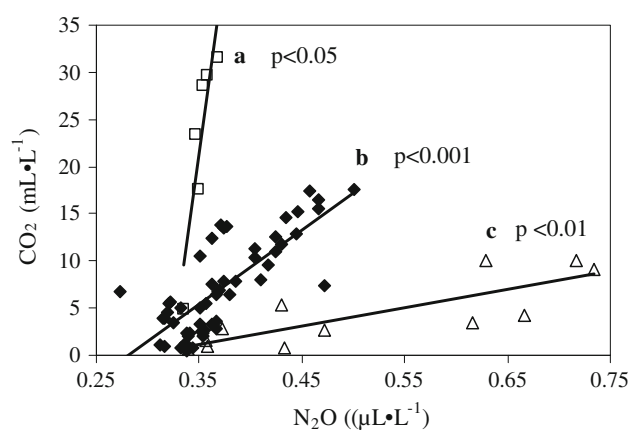

Fig. 2 Relativity between concentration of CO_2 and N_2O in the soil profile from June 2006 to May 2007. *a* in June 2006, *b* in July–December of 2006 and February–April of 2007, *c* in January and May of 2007
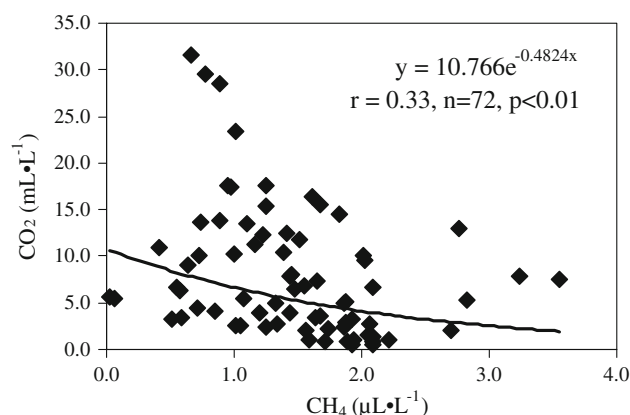

Fig. 3 Relativity between concentration of CO_2 and CH_4 in the soil profile from June 2006 to May 2007

elevated CO_2 (Baggs and Blum 2004; Kettunen et al. 2007; Kammann et al. 2008). Moreover, increase or decrease of CO_2 availability will also influence the process of nitrification (Kinsbursky and Saltzman 1990; Azam et al. 2004a, b). Significant correlation was found between CO_2 and CH_4 in soil profile (Fig. 3). The production and consumption of CO_2 and CH_4 involves transformation processes of soil carbon. Both of them can act as reciprocal origins under certain soil environment. In aerobic environments, methanotrophs can use CH_4 as only a carbon energy source to produce CO_2 (Einola et al. 2007), whereas in most anaerobic environments, CO_2 reduction by H_2 is one of the important pathways for CH_4 production (Mer and Roger 2001). Moreover, the correlation between CO_2 and CH_4 in soil profile followed the exponential relationship in the present study. Some studies suggested that less CO_2 was produced than CH_4 consumed at all studied temperature and water content (e.g., Megraw and Knowles 1987; Börjesson et al. 1998, 2001; Einola et al. 2007). Further studies

are required to identify the internal mechanism of the relevancy between CO_2 and CH_4 in karst soil carbon cycling.

Soil temperature and moisture controls on GHG concentrations and fluxes

Annual soil temperature decreased with depth, varying from 6.5 to 30.0°C at 5-cm depth to 4.2–27.0°C at 30-cm depth, showing distinctly similar trend at all depths (Fig. 4). In contrast, soil water contents showed a reverse seasonal pattern to soil temperature, maintaining moisture in winter due to light rain events of long duration. Neither soil temperature nor moisture was significantly correlated with the seasonal pattern of GHG fluxes. However, as plotted in Figs. 5, 6 and 7, correlation analysis revealed strong dependency of GHG profile concentrations on variations of soil temperature or water content. There was exponential correlation between CO_2 concentrations and soil temperature (Fig. 5). The relationships between N_2O concentrations and soil water content, CH_4 concentrations and soil temperature were significant only at 5–20 cm depth (Figs. 5, 7). At $p < 0.05$, no dependence of N_2O and CH_4 concentrations on soil temperature or moisture is recognizable in deep soil horizon.
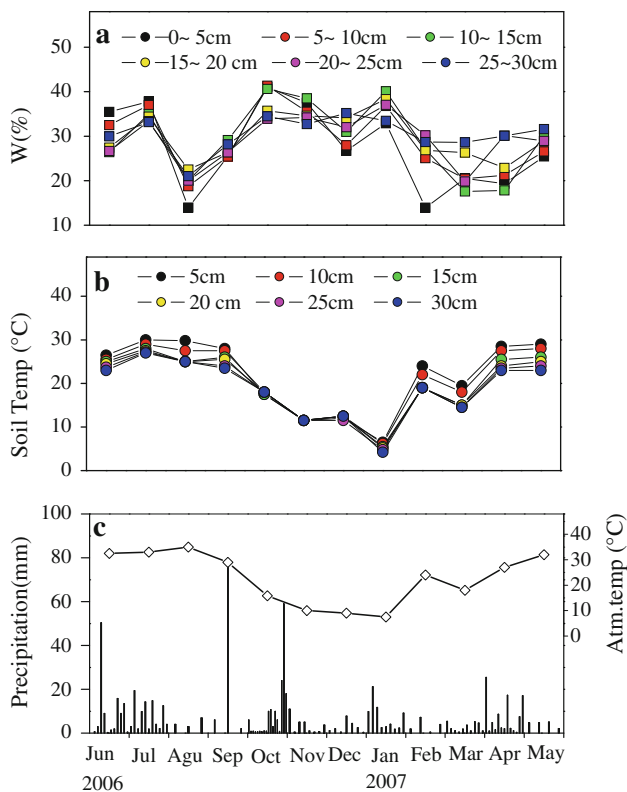

Fig. 4 Seasonal variations of water content in soil profile (**a**), soil temperature in soil profile (**b**), and precipitation and atmospheric temperature during the experimental period (**c**)
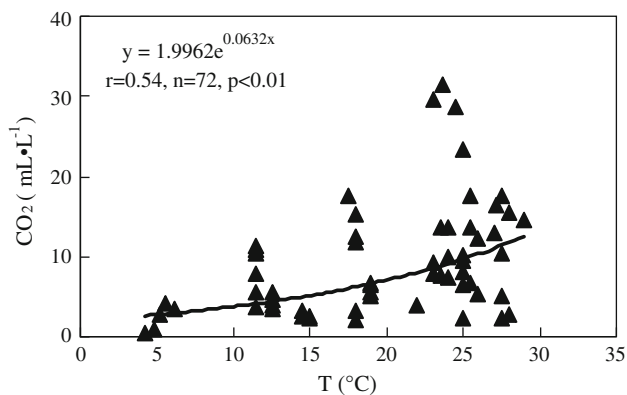

Fig. 5 CO_2 concentrations versus soil temperature in the soil profile
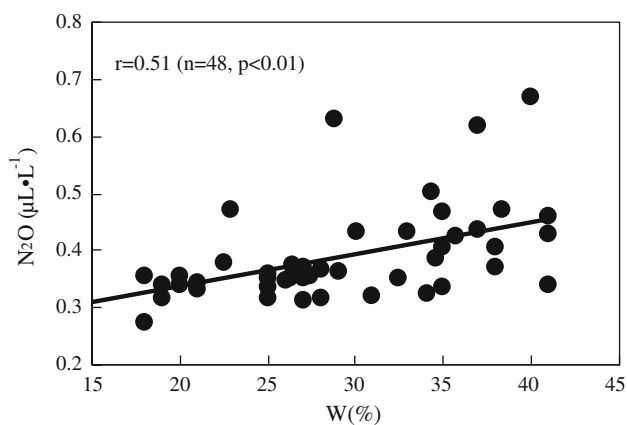

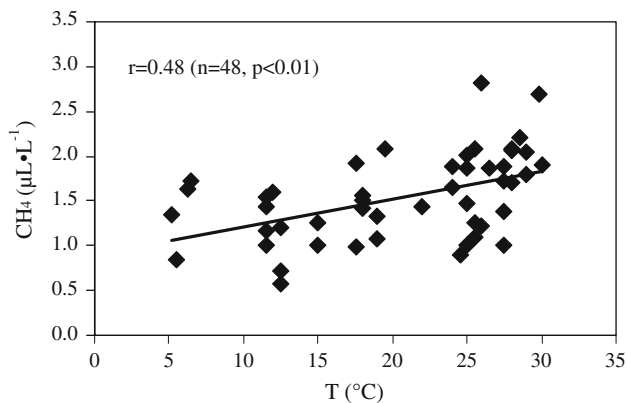**Fig. 6** N_2O concentrations versus soil water content at 5–20 cm depth

Fig. 7 CH_4 concentrations versus soil temperature at 5–20 cm depth

The relative importance of soil temperature and water content on GHG fluxes has been extensively discussed (e.g., Certini et al. 2003; Nakano et al. 2004; Guay et al. 2006; Almagro et al. 2009). These two parameters are generally considered as independent or confounded factors to control GHG fluxes. In our study, the correlation

analysis has shown that relationships between GHG fluxes and temperature or water content were weak ($p > 0.05$), while soil temperature and water content imposed more influence on GHG profile concentrations relative to GHG fluxes. Variations of CO_2 profile concentration were consistent with those of soil temperature. Several studies of different ecosystems have reported that CO_2 production increased with increasing soil temperature (Risk et al. 2002; Hashimoto and Komatsu 2006). A significant dependency between increase in temperature and CH_4 concentrations could be found at 5–20 cm depth. The dependency of N_2O concentrations on soil water content was also observed at these depths. Increasing soil moisture is beneficial to N_2O accumulation in the upper layers of the soil profile. Though statistical analysis failed to reveal a significant effect of water content on GHG concentrations at 20–30 cm depths, high moisture content might stimulate the consumption of CO_2 and N_2O, and the production of CH_4 in deep soil when rainfall of long duration occurred in some months.

Conclusions

With the increment of depth, concentrations of CO_2 and N_2O increased while CH_4 decreased, except in some humid months when a reversal pattern of GHG concentrations was observed below 15-cm depth of the soil profile. The fluxes of CO_2 and N_2O varied in the range of 460.9–1,281.2 mg m^{-2} h^{-1} and −25.4 to 81.5 μg m^{-2} h^{-1}, respectively. CH_4 fluxes were negative, ranging between −28.7 and −274.9 μg m^{-2} h^{-1}, with the highest value in January, lowest in October and varied inconspicuously between seasons.

Temporal variations of surface fluxes and profile concentrations of GHG did not show obvious seasonal trend. Correlation analysis showed that neither soil temperature nor moisture dominates seasonal variations of GHG fluxes, but these two factors have more influence on GHG concentrations in the soil profile. Though the interrelations among the fluxes of GHG were not obviously existent, variations of CO_2 within the soil profile were positively correlated with those of N_2O ($p < 0.05$–0.001) and negatively with those of CH_4 ($p < 0.01$). Such interrelationships among GHG in karst soil suggest that there may be some relationships between N and soil C dynamics in soil, and further research in future would be needed for documenting the relationships.

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