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Exchange of carbonyl sulfide (COS) between the atmosphere and various soils in China

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Abstract

Using a dynamic enclosure, the exchange fluxes of carbonyl sulfide (COS) between the atmosphere and 18 soils from 10 provinces in China were investigated. The emission or uptake of COS from the soils was highly dependent on the soil type, soil temperature, soil moisture, and atmospheric COS mixing ratio. In general, with the only exception being paddy soils, the soils in this investigation acted as sinks for atmospheric COS under wide ranges of soil temperature and soil moisture. Two intensively investigated wheat soils and one forest soil, had optimal soil temperatures for COS uptake of around 15°C, and the optimal soil water content varied from 13 to 58%. The two paddy soils, exponentially COS emission fluxes increased with increasing soil temperature, and decreased COS emission fluxes with increased soil water content. However, negligible emission was found when the paddy soils were under waterlogging status. The observed compensation points for various soils were different and increased significantly with soil temperature. The laboratory simulation agreed with the preliminary field measurements for the paddy soil in Jiaxing, Zhejiang province.

1 Introduction

Carbonyl sulfide (COS), the most abundant and long-lived reduced sulphur gas in the troposphere, is an important precursor for the stratospheric sulfate aerosol layer (Crutzen, 1976; Hofmann, 1990; Engel and Schmidt, 1994) and thus has an impact on the earths radiation budget as well as on ozone destruction (Turco et al., 1980; Solomon et al., 1993; Roche et al., 1994; Andreae and Crutzen, 1997). Atmospheric sinks and sources of COS have aroused widely attention, and many studies have examined for atmospheric COS sinks and sources (Bartell et al., 1993; Kesselmeier and Merk, 1993; Kesselmeier et al., 1993; de Mello and Hines, 1994; Gries et al., 1994; Kuhn et al., 1999, 2000; Xu et al., 2002; Geng and Mu, 2004; Sandoval-Soto et al., 2005; Yi et al., 2007, 2008; Van Diest and Kesselmeier, 2008).

Soils were previously considered to represent one of the dominant sources for atmospheric COS (Khalil and Rasmussen, 1984; Chin and Davis, 1993). However, recently, field studies and laboratory simulations have presented convincing evidence that soils act more as a sink than as a source for COS (Castro and Galloway, 1991; Fried et al., 1993; de Mello and Hines, 1994; Kesselmeier et al., 1999; Kuhn et al., 1999; Geng and Mu, 2004; Yi et al., 2007, 2008; Van Diest and Kesselmeier, 2008). Earlier researchers investigating COS exchange usually used enclosure methods with COS-free sweep air (Aneja et al., 1979; Adams et al., 1981; Goldan et al., 1987; Lamb et al., 1987; MacTaggart et al., 1987), which masked the potential of soils to act as a sink for sulfur compounds. In contrast, some other researchers used very high concentration of COS to study the potential of soils to take up COS (Bremner and Banwart, 1976; Kluczewski et al., 1985; Lehmann and Conrad, 1996), which also generated artificial COS concentration gradients. Therefore, earlier data should be checked for artifacts due to the use of inappropriate air mixtures for flushing enclosures.

Watts (2000) estimated COS deposition and emission rates for two different types of soils as 0.92±0.78 $\mathrm{Tg\,a^{-1}}$ (sink, “oxic” soils) and 0.02±0.01 $\mathrm{Tg\,a^{-1}}$ (source, “anoxic” soils). However, the estimate was only based on a few studies with limited soil types, especially in the case of “oxic” soils (only two results from two types of soils were used as the basis for the estimation) and contained considerable uncertainty. Kesselmeier et al. (1999) were the first to parameterize the influencing factors of COS uptake by soil taken from arable land. Van Diest and Kesselmeier (2008) investigated COS exchanges between four kinds of soils (three arable soils from Germany, China, and Finland and one forest soil from Siberia) and the atmosphere for parameterization in relation to ambient COS concentration, soil water content, and temperature. They suggested that the uptake of COS depended on diffusivity, which was controlled by water-filled pore space (WFPS). The parameterization of COS uptake gave a clear clue as to how to reduce existing uncertainties in estimating COS uptake by different soils. Because COS exchange between soils and the atmosphere is largely dependent upon soil type, additional study is needed to re-assess the parameterization of different soil types using the enclosure method with ambient air (Kesselmeier et al., 1999; Watts, 2000; Sandoval-Soto et al., 2005; Van Diest and Kesselmeier, 2008).

The objective of this study was to compare the exchange fluxes of COS between the atmosphere and different types of soils in China. The factors affecting the fluxes, i.e., temperature, soil moisture, and COS mixing ratio, were also investigated for five soils. Our results extend the data set and yield better insight into the role of different soils in the atmospheric COS budget.

2 Materials and methods

2.1 Sampling sites

Eighteen types of soil were sampled from 10 provinces in China (Fig. 1) covering about half of China's agricultural regions. Samples were taken from the top 5 cm of the soil profile and sieved to <2 mm using a stainless steel sieve.

The characteristics of the five most intensively investigated soils were determined, and these are listed in Table 1. Soil characteristics were determined at the Beijing Academy of Agriculture & Forestry Sciences using standard protocols (Liu, 1996). Samples were stored at 3°C prior to investigation.

2.2 Construction and performance of flux enclosure

A dynamic enclosure was used to measure the COS exchange flux from the different soils. The enclosure consisted of a stainless steel cylinder (20 cm high (H), 18 cm inner diameter (ID) and with a 9-L volume) with an inner surface covered by a Teflon film to prevent any effects from contamination or adsorption. An inlet (perforated stainless steel ring) that allowed gas with fixed COS concentration into the enclosure was located near the bottom of the cylinder. The investigated soil was put into a glass dish (ID, 15 cm) at the bottom of the enclosure. Soil temperature was controlled by putting the enclosure in a super-constant-temperature water boiler (CS501, Chongqing Testing Equipment Corporation, Chongqing, China). Total air-flow rate through the enclosure was kept at 0.7 $\mathrm{L\,min^{-1}}$ using a mass flow meter (SY-9506, Beijing Shengye Technologic Development Corporation, Beijing, China).

COS concentrations within the desired range were obtained by mixing compressed air (50 ppt COS) with high-concentration COS gas (500 ppb COS) from a glass flask (10 L). Before being introduced into the enclosure, the air was humidified by a water bubbler, which was also placed inside the water boiler. This prevented the soil samples from drying during the experiments.

The concnentration of COS was measured at the outlet of the enclosure every ten minutes after the introduction of air to the cylinder, and a relatively steady value (maximum 10% variation) was achieved after 30 min flushing. Then, all flux measurements were conducted under the condition of the dynamic equilibrium.

The COS exchange flux (F, $\mathrm{pmol\,m^{-2}\,s^{-1}}$ or $\mathrm{pmol\,g(dw)^{-1}\,h^{-1}}$) in the enclosure was calculated using the following equation:

$$F = (V/A) \times (C_{\mathrm{out}} - C_{\mathrm{in}}) \text{ or } F = (V/W) \times (C_{\mathrm{out}} - C_{\mathrm{in}}), \qquad (1)$$

where V ($\mathrm{m^3\,h^{-1}}$) is the steady flow rate of the flushing gas through the enclosure and A ($\mathrm{m^2}$) is the surface area of soil spread on the glass dish. W (g) is the dry weight of the applied soil, and C_{in} and C_{out} ($\mathrm{pmol\,m^{-3}}$) are the COS concentrations in the inlet and outlet of the enclosure, respectively.

The influence of the soil mass relative to surface area (i.e., soil column height inside the enclosure) on the COS exchange was tested incrementally up to 200 g of fresh soil. We found a linear correlation between the COS exchange flux and soil mass up to 100 g. This correlation shifted to a saturation-like exchange behavior with increased soil mass between 100 g and 200 g. Therefore, all experiments were performed using only 100 g of soil. Soil water content was varied by air-drying soils and re-moistening them with deionization water.

The control experiments for the dynamic enclosure, in which the steel cylinder containing no soil sample, were conducted between 10 and 40°C. Weak emissions of COS were found from the blank enclosure, especially when temperature was higher than 20°C (Fig. 2). To eliminate the background COS contribution, the blank COS flux was substracted from the total fluxes measured from the soil samples. To verify our laboratory simulation for paddy field soil,we carried out a brief set of field measurements in Jiaxing, Zhejiang province, the collection site for our paddy soil sample. A dynamic chamber method was also adopted for flux measurements. The dynamic chamber consists of a Polyvinylchlorid tube (30 cm (H)×20 cm (ID)) that has an inner surface covered by Teflon film (0.1 mm) and is mounted on a pedestal (15 cm (H)×20 cm (ID). Four inlets were evenly distributed in opposition at 5 cm above the bottom of the chamber. Four Teflon tubes were connected to the four inlets, and the other ends of the four tubes rose to 50 cm above ground. A mini-pump connected with an outlet at the top of the chamber was used to drive ambient air into the chamber. The flow rate was kept at 3.27 $\mathrm{L\,min^{-1}}$. The pedestal had a gutter around the outside of its upper rim that could be filled with water to make an airtight seal with the chamber during flux measurements. The pedestal was inserted 10 cm into the investigated soil for one day before the flux measurements. After flushing the chamber for 30 min with ambient air, air samples were collected into 2-L Teflon bags (0.1 mm film) and analyzed within 3 days after collection.

2.3 COS analysis

COS was sampled by cryogenic trapping and analyzed by means of a gas chromatograph (GC) equipped with a flame photometric detector (FPD) according to Hofmann et al. (1992). Detailed description of the method can be found in Mu et al. (2002, 2004). The detection limit for COS was approximately 0.88 $\mathrm{pmol\,L^{-1}}$ (800 mL gas sample). The relative precision of the method for COS was less than 6%, and the recovery efficiency of COS was about 94% (Mu et al., 2002, 2004).

The following assumptions were made in calculating the errors of the exchange rates: 10% error for the COS measurements at the enclosure inlet (σ_{in}) and the enclosure outlet (σ_{out}), 5% error in the enclosure flow measurement (σ_Q), and 1% error in the surface area determination or the soil mass determination ($\sigma_{A/W}$). The total flux error (σ_F) can be obtained by using the error propagation method according to Doerffel (1984):

$$\sigma_F = \sqrt{\frac{[(C_{\text{in}}\sigma_{\text{in}})^2 + (C_{\text{out}}\sigma_{\text{out}})^2]}{(C_{\text{out}} - C_{\text{in}})^2} + \sigma_Q^2 + \sigma_{A/W}^2}. \qquad (2)$$

3 Results

For all soil samples, we investigated COS fluxes at the original moisture level and at two different temperature: 17°C and 25°C. COS concnentration was kept at around 500±80 ppt. We derived COS deposition velocities for each soil sample using the measured fluxes and the COS concnentration.

Table 2 gives an overview of the flux and deposition velocity measured at 17°C and 25°C at original moisture levels for each of the investigated soils. It is evident that large difference in COS flux and deposition velocity exist among the different soil types. The maximal emission and uptake fluxes were 12.90 $\text{pmol m}^{-2}\,\text{s}^{-1}$ at 25°C (paddy soil) and -4.90 $\text{pmol m}^{-2}\,\text{s}^{-1}$ at 17°C (lawn soil).

Three of the paddy soil samples acted as COS sources at both 17°C and 25°C, whereas two acted as COS sinks. COS uptake (sink) was observed at 17°C for the paddy soil from Jishui (Jiangxi province), although a weak emission (source) was observed at 25°C. The same behavior was observed for the paddy soil from Zhumadian (Henan province), where wheat and rice are cultivated in rotation. In contrast to the paddy soils, all other soils acted as COS sinks.

To investigate the influence of COS concnentration, soil temperature, and moisture on COS exchange, we focused on five soil samples. Two of these were from northern wheat land soils: Beijing (W1) and Zibo (Shandong province) (W2); two were from southern paddy-field soils: Jiaxing (Zhejiang province) (P1) and Guangzhou (Guangdong province) (P2); and one was from northern forest (larch)-land soil: Beijing (Lingshan) (F).

3.1 COS fluxes under varying COS concentrations

The exchange of COS flux and its dominant direction are recognized to strongly depend upon ambient COS concentration (Conrad, 1994; Lehmann and Conrad, 1996; Kesselmeier et al., 1999) and a so-called compensation point (under a typical ambient concentration, the consumption and production balance each other, and the net flux is zero; Kesselmeier et al., 1999). When the ambient concentration is above the compensation point, net deposition occurs. Whereas when concentrations are below the compensation point, net emission occurs. The compensation point, therefore, is an important parameter in judging flux direction. To obtain the compensation points for the different soils in this study, the fluxes from the investigated soils were measured under varying COS concnentrations, from 50 ppt to 1500 ppt, at 17°C and 25°C. Linear correlations between COS flux and COS concnentration were found for all investigated soil samples. The compensation points for the five soils were determined by the linear regression as the abscissa intercept of the regression line (Kesselmeier et al., 1999), and are listed in Table 3, together with the values reported in the literature for other soils.

For the paddy soils, P1 and P2, the compensation points were around the global average concentration of 500 ppt at 17°C, but were much greater at 25°C. These soils can be considered as COS sources, especially when their temperature is above 17°C.

For other soils (W1, W2, and F), the compensation points were found to be below the global average COS concentration at 17°C and 25°C. As for the forest soil (F), the compensation point was 80 ppt at 17°C, similar to the data obtained during field measurements on an oak woodland soil in California (Kuhn et al., 1999). Consequently, these soils should act as COS sinks under natural conditions. Additionally, the compensation points for the five soil types were higher at 25°C than they were at 17°C, indicating that an increase in temperature may favor the production of COS.

3.2 COS fluxes under varying temperatures

Temperature has been shown to be an important factor governing sulfur emission as microorganism activity is enhanced (Hill et al., 1978; Adams et al., 1981; MacTaggart et al., 1987; Kesselmeier et al., 1999). Therefore, we investigated COS exchange between the soil and the atmosphere under varying temperatures (1°C to 40°C). Figure 3 shows the result of COS fluxes from the five soils under different temperatures at constant pressure and with a concnentration of 500 ppt COS in the air used to flush the enclosure. The wheat (W1 and W2) and forest (F) soils showed increased uptake (sink) with increasing temperature to an optimum at 15–20°C, followed by a sharp decrease at higher temperatures. These results support the data obtained by Kesselmeier et al. (1999), who found an optimum temperature between 16 and 20°C for COS uptake. When the soil temperature was above 25°C, weak emissions were measured from the W1 and F soils, whereas W2 remained negative (uptake).

Carbonic anhydrase (CA) has been recognized as the key enzyme for the uptake of COS by different biological organisms (Chengelis and Neal, 1979, 1980; Miller et al., 1989; Badger and Price, 1990; Protoschill-Krebs and Kesselmeier, 1992; Protoschill-Krebs et al., 1995, 1996; Kesselmeier et al., 1999). As mentioned by Kesselmeier et al. (1999), the activity of the enzyme should be responsible for the variation of COS fluxes under different temperatures. de Mello (1992) found that the net consumption rate of COS in Sallie's Fen decreased from ~50 to 15 $\mathrm{nmol\,m^{-2}\,h^{-1}}$ (13.89–4.17 $\mathrm{pmol\,m^{-2}\,s^{-1}}$) as temperature increased from ~16 to 30°C.

For paddy soils (P1 and P2), the flux of COS was around 0 at low temperatures (for P1 below 15°C, for P2 below 10°C), whereas at higher temperatures, the emission was obvious and increased exponentially with increasing temperature. The relationships between COS emission flux (F) and temperature (T, °C) for the paddy soils of P1 and P2 under the experimental soil moistures fitted the following equations:

$$F_{\mathrm{P1}} = \exp(0.138 \times T - 3.20),\ R^2 = 0.99 \tag{3}$$

$$F_{\mathrm{P2}} = \exp(0.0964 \times T - 0.460),\ R^2 = 0.98. \tag{4}$$

3.3 COS fluxes under varying soil moistures

Soil water content is also a critical parameter controlling the exchange of trace gases (Conrad and Smith, 1995; Meixner et al., 1997; Kesselmeier et al., 1999), because it influences chemical, physical, and biological processes. The optimal activity of certain sulfur-producing bacteria is in a narrow range of the soil's water-holding capacity. The exchange fluxes of COS under varying soil water contents were also determined in this study under the optimal temperature at 17°C. A cool environment allowed for several repetitions of the measurements with negligible water loss (0.3–0.8%). Again, we used air with a COS concentration of 500 ppt, and the results are shown in Fig. 4.

Of the two wheat soils (W1 and W2), only W1 acted as a sink for atmospheric COS at low moisture contents (5.66%). Optimum water contents for W1 and W2 were found to be 13% and 23%, respectively. The maximum uptake rate for W2 was hifger by a factor of 5 than that for W1. As for the forest soil (F), net emission was observed when soil water content was below 20%, whereas uptake increased with increasing soil water content, up to optimum at 58% water content.

The two paddy soils (P1 and P2) showed decreasing COS emission with increasing soil water content untill the fluxes reached a steady state when soil water content was above 20%. For P1, the steady flux was about 0 pmol$\,$m^{-2}s^{-1}, and for P2, the steady flux was about 6 pmol$\,$m^{-2}s^{-1}. Paddy soils are constantly waterlogged during rice growing season, The effects of waterlogging on COS fluxes from the paddy soils were also investigated. No evident COS exchange was found after watering the paddy soils of P1 and P2 with de-ionized water to full saturation (soil surface covered with a water film), indicating that water cover prevents gas exchange with the atmosphere. It should be noted that the incubation of the soils under this condition lasted for less than 2 h. Therefore, the zero flux observed in this study might be due to the non-equilibrium of COS between the soils and the water.

COS exchange fluxes were also investigated in the paddy field of Jiaxing, Zhejiang province. The measured fluxes, soil temperatures, and water contents for three patches are listed in Table 4. In general, the field measurements agreed with the laboratory simulation. As shown in Table 4, COS exchange flux and its direction on the paddy soil strongly depend on ambient COS concentration. The strength of COS emission was much higher at 26°C than at 22°C, although the water content was greater in the patch with 26°C soil temperature than the patch with 22°C soil temperature. COS exchange fluxes under waterlogged conditions are also close to zero. The compensation point for the paddy soil from Jiaxing obtained by laboratory simulation was about 765 ppt at 25°C (Table 3). However, obvious emission was observed by field measurements when ambient COS concentration was around 1500 ppt. The disturbance of the soil due to sample collection, storage, and disposal may be responsible for this difference. In addition, the small negative pressure caused by the pump drawing air through the chamber for the field measurements might favor COS emission.

It should be mentioned that the ambient COS concentration in Jiaxing was extremely high; it was higher than the background COS concentration by a factor of 3. The memory effect of the Teflon bags was checked by using the ambient air of Beijing three times, and an increment in COS concentration of about 10% was found during three days' storage. The high COS concentration in the field may be ascribed to the direct sources from a power plant about 1 km away and a pig factory nearby the field.

4 Discussion

Paddy soils, which are always in a waterlogged condition, tend toward "anoxic" conditions. COS emission from these types of soil have been recognized previously (Devai and Delaune, 1995; Kanda et al., 1995; Yang et al., 1996; Yi et al., 2008). The laboratory simulation and short-term field measurements in this study further confirmed that most paddy soils act as sources of atmospheric COS. The exponential dependence of COS emission from paddy soils on temperature might be useful quantitatively in predicting COS emission flux from paddy soils in the short term, when soil water content is kept relatively constant. The emission fluxes from the two paddy soils investigated in this study decreased significantly as the soils' water content increased, especially when the soils were waterlogged. Field measurements in this study for the paddy soil in Jiaxing also yield no COS emission under waterlogged conditions. The phenomenon observed in this study is contrary to recently field measurements by Yi et al. (2008). They found obvious COS uptake by the dry paddy soil and significant emission from the waterlogged soil. It should be noted that the paddy soil in the present study (P2) was from the same field as that used in their study. The conflicting results between our two laboratories might be due to the disturbance of the soil during sample collection, storage, and disposal. In addition, the photochemical production of COS in water covered by their transparent static chambers made of Teflon film may also result in strong COS emission for the waterlogged soil because a large quantity of COS precursor(s), which is/are easily converted to COS under sunlight, existed in water system (Andreae and Ferek, 1992; Mu et al., 2004).

With the exception of paddy soils, all soils investigated in this study acted as sinks for atmospheric COS, which agrees with field experiments: 0–(−6.52) $\text{pmol m}^{-2}\,\text{s}^{-1}$ (Geng and Mu, 2004) for lawn soil in Beijing, China; −1.4–(−8.4) $\text{pmol m}^{-2}\,\text{s}^{-1}$ for unvegetated forest soil (Castro and Galloway, 1991); and −1.5–(−10.3) $\text{pmol m}^{-2}\,\text{s}^{-1}$ for arable soil (Kesselmeier et al., 1999). The large difference for COS fluxes among different soils as well as the complicated influencing factors indicated that the estimations of COS emission from "oxic" soils based on only two types of soils must be made with caution (Watts, 2000).

Van Diest and Kesselmeier (2008) investigated COS exchanges between four kinds of soils and the atmosphere and found the same optimal COS uptake at 19% WFPS for the three different boreal soils (two arable soils from China and Finland and one forest soil from Siberia). Although we did not measure the bulk densities for the investigated soils, the optimal soil WFPS for COS uptake from the investigated boreal soils in this study must be greater than 19%, especially for the soil from the forest.

5 Conclusions

Large differences in COS exchange were observed among the 18 types of soil samples from 10 provinces in China investigated in this study. Soil temperature, soil water content, and COS concentration are important influencing factors for the direction and the magnitude of COS exchange. The compensation points for various soils were significantly different and were strongly dependent upon soil temperature. Most agricultural soils, except for paddy soils, should be considered as COS sinks under natural conditions.

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Table 1. The characteristics of five soil samples (W1: wheat soil in Beijing; W2: wheat soil in Zibo (Shandong Province); P1: Paddy soil in Jiaxing (Zhejiang Province); P2: Paddy soil in Guangzhou (Guangdong Province); F: forest soil in Beijing).

Soil	pH	$C_{organic}$ g/kg	OM[a] g/kg	N_{total} g/kg	P_{total} g/kg	S_{total} g/kg	S_{effect} mg/kg
W1	6.31	8.24	14.2	0.92	0.618	0.12	25.0
W2	7.74	15.1	26.0	1.13	0.783	0.40	94.8
P1	6.14	24.5	42.3	2.26	0.579	0.45	31.5
P2	6.42	29.1	50.1	2.42	0.860	0.65	56.2
F	6.44	61.5	106	4.94	0.967	0.90	21.2

[a] OM: organic matter

Table 2. COS fluxes and deposition velocities of various soils in China.

Site	Plant type	Parent material	Soil moisture %	Flux (17°C) pmolm^{-2}s^{-1}	Flux (25°C) pmolm^{-2}s^{-1}	Flux (17°C) pmolg^{-1}h^{-1}	Flux (25°C) pmolg^{-1}h^{-1}	Deposition velocity mms^{-1} (17°C)	Deposition velocity mms^{-1} (25°C)
Beijing	wheat	Drab soil	8.00	−1.04	−0.73	−0.69	−0.44	0.05	0.03
Zibo, Shandong	wheat	Burozem	17.15	−4.32	−2.73	−2.80	−1.66	0.14	0.11
Jiaxing, Zhejiang	paddy	Drab soil	20.70	0.44	1.19	0.27	0.63	–	–
Guangzhou	paddy	Paddy soil	19.37	0.69	12.89	0.46	8.56	–	–
Beijing	forest	Drab soil	43.90	−4.05	−0.83	−3.21	−0.81	0.13	0.04
Zhumadian, Henan	wheat/paddy	Yellow-brown	13.11	−0.77	0.02	−0.48	0.03	0.04	–
Liaocheng, Shandong	cotton	Fluvo-aquic soil	16.50	−1.32	−1.10	−0.84	−0.69	0.07	0.05
	maize	Fluvo-aquic soil	18.89	−2.17	−1.41	−1.42	−0.90	0.09	0.07
Jinchun, Hubei	paddy	Red earth	23.20	0.57	2.00	0.40	1.34	–	–
Yancheng, Jiangsu	paddy	Solonchak soil	19.69	−0.41	−0.10	−0.27	−0.04	0.02	0.004
	cotton	Solonchak soil	17.77	−0.49	−0.11	−0.31	−0.05	0.02	0.005
Lanzhou, Gansu	plum blossom	Grey-drab soil	10.68	−2.46	−2.18	−1.51	−1.32	0.10	0.08
Dalian, Liaoning	wheat	Burozem	9.13	−2.10	−2.76	−1.26	−1.66	0.08	0.14
Jishui, Jiangxi	paddy	Red earth	18.75	−2.04	0.29	−1.33	0.22	0.07	–
Jinxian, Jiangxi	badlands	Red earth	19.02	0	−2.84	0	−1.84	0	0.10
Huangping, Guizhou	paddy	Yellow earth	27.78	−3.20	−3.56	−2.25	−2.15	0.13	0.16
Waliguan, Qinghai	grass	Chestnut soil	9.77	−3.76	−2.69	−2.28	−1.62	0.17	0.13
Beijing	lawn	Drab soil	8.35	−4.90	−4.83	−3.00	−3.08	0.17	0.19

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Table 3. COS compensation point in this study compared with other studies (P1: Paddy soil in Jiaxing (Zhejiang Province); P2: Paddy soil in Guangzhou (Guangdong Province); W1: wheat soil in Beijing; W2: wheat soil in Zibo (Shandong Province); F: forest soil in Beijing).

Soil	Water content %	Compensation point, ppt (17°C)	Compensation point, ppt (25°C)	Reference
P1	20.7	491	765	This study (laboratory)
P2	19.37	572	780	This study (laboratory)
W1	8.0	255	267	This study (laboratory)
W2	17.5	120	149	This study (laboratory)
F	43.9	80	225	This study (laboratory)
Oak woodland		<100		Kuhn et al. (1999) (field)
Sandy clay soil		∼53		Kesselmeier et al. (1999) (laboratory)

Table 4. Field measurements for COS exchange fluxes from the paddy soil in Jiaxing, Zhejiang province.

Patch	Soil temperature (°C)	Soil water content (%)	Ambient COS concentration (ppt)	Flux (pmol m^{-2} s^{-1})
1	22	19.6	3008	–57.9 (sink)
			1390	19.6 (source)
2	26	25.3	1695	26.8 (source)
			1866	18.0 (source)
3	24	31.0	1764	–2.11 (sink)
		(under waterlogging)	1762	0

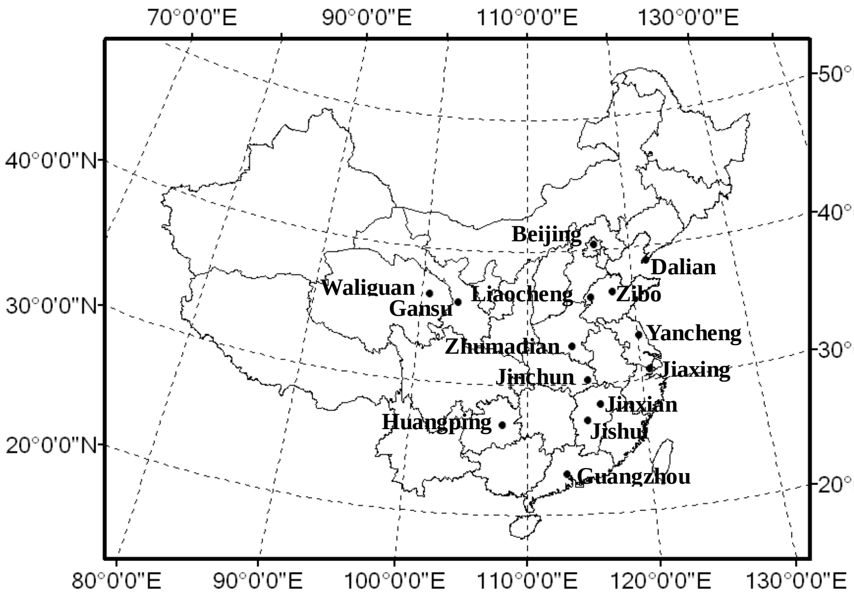

Fig. 1. Locations of sampling sites in this study.

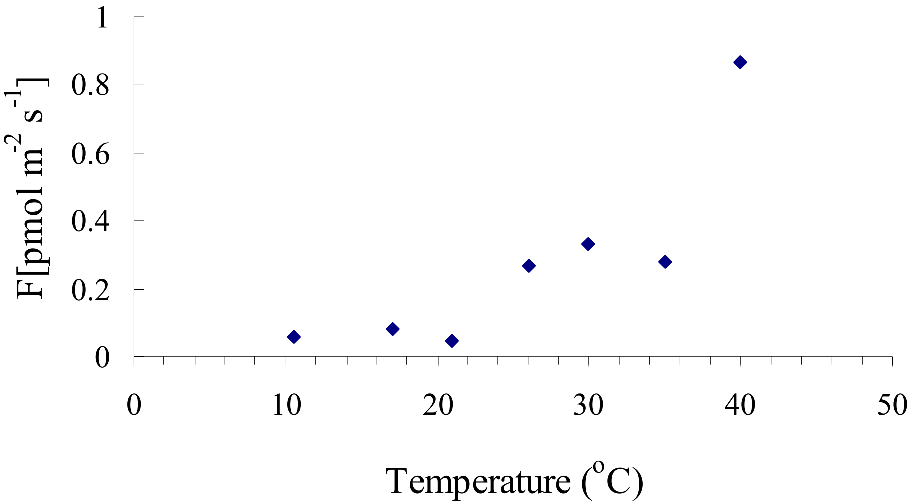

Fig. 2. COS fluxes of the blank enclosure system (with glass dish) in relation to the temperature.

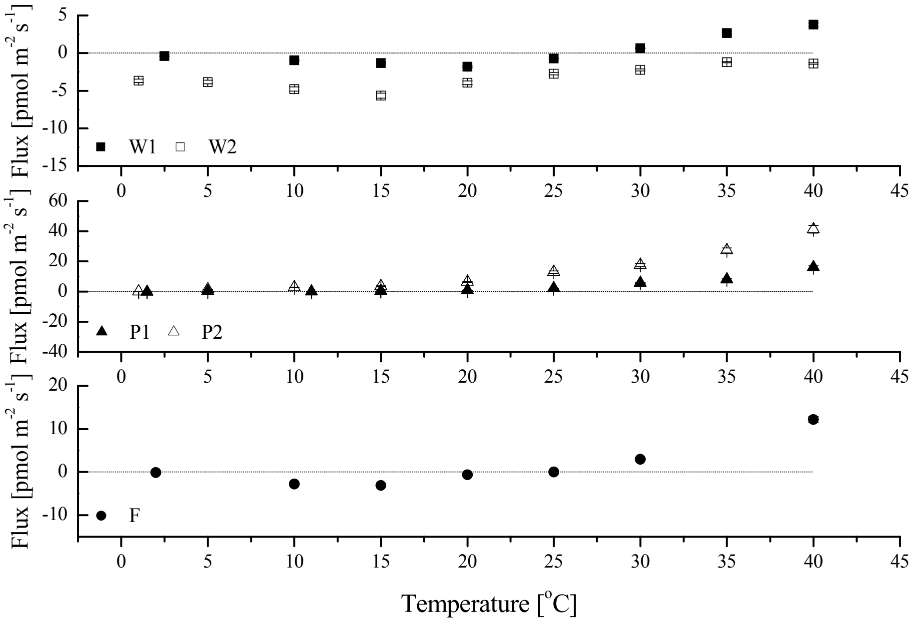

Fig. 3. COS fluxes in relation to the temperatures. (W1: wheat soil in Beijing, 8.00% moisture; W2: wheat soil in Zibo (Shandong Province), 17.15% moisture; P1: Paddy soil in Jiaxing (Zhejiang Province), 20.70% moisture; P2: Paddy soil in Guangzhou (Guangdong Province), 19.37% moisture; F: forest soil in Beijing, 43.90% moisture). The error bars are calculated from formula (2); each flux measurement was conducted twice.

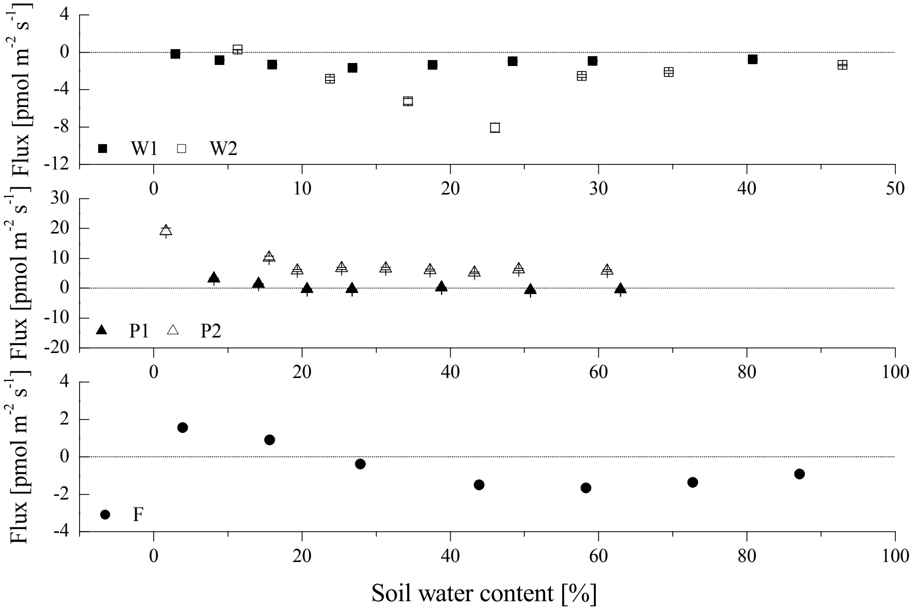

Fig. 4. COS fluxes in relation to soil water content at 17°C. (W1: wheat soil in Beijing; W2: wheat soil in Zibo (Shandong Province); P1: Paddy soil in Jiaxing (Zhejiang Province); P2: Paddy soil in Guangzhou (Guangdong Province); F: forest soil in Beijing). The error bars are calculated from formula (2); each flux measurement was conducted twice.