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## Nitrous oxide emissions from the wheat-growing season in eighteen Chinese paddy soils: an outdoor pot experiment

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**Abstract** To identify the key soil parameters influencing N<sub>2</sub>O emission from the wheat-growing season, an outdoor pot experiment with a total of 18 fertilized Chinese soils planted with wheat was conducted in Nanjing, China during the 2000/2001 wheat-growing season. Average seasonal N<sub>2</sub>O-N emission for all 18 soils was 610 mg m<sup>-2</sup>, ranging from 193 to 1,204 mg m<sup>-2</sup>, approximately a 6.2-fold difference between the maximum and the minimum. Correlation analysis indicated that the seasonal N<sub>2</sub>O emission was negatively correlated with soil organic C ( $r^2=0.5567$ ,  $P<0.001$ ), soil total N ( $r^2=0.4684$ ,  $P<0.01$ ) and the C:N ratio ( $r^2=0.4530$ ,  $P<0.01$ ), respectively. A positive dependence of N<sub>2</sub>O emission on the soil pH ( $r^2=0.3525$ ,  $P<0.01$ ) was also observed. No clear relationships existed between N<sub>2</sub>O emission and soil texture, soil trace elements of Fe, Cu and Mg, and above-ground biomass of the wheat crop at harvest. A further investigation suggested that the seasonal N<sub>2</sub>O-N emission ( $E$ , mg m<sup>-2</sup>) can be quantitatively explained by  $E=1005-34.2\text{SOC}+4.1S_a$  ( $R^2=0.7703$ ,  $n=18$ ,  $P=0.0000$ ). SOC and  $S_a$  represent the soil organic C (g kg<sup>-1</sup>) and available S (mg kg<sup>-1</sup>), respectively.

**Keywords** N<sub>2</sub>O emission · Pot experiment · Soil properties · Wheat-growing season

### Introduction

Nitrous oxide (N<sub>2</sub>O) has a disproportionately large greenhouse effect, which makes it an important climate

change indicator. It is about 1,100 times less abundant than CO<sub>2</sub>, but is about 250 times more effective as a greenhouse gas absorber per molecule than CO<sub>2</sub>. Model calculations suggest that atmospheric N<sub>2</sub>O could approach a value ranging from 354 to 460 ppb by the year 2100, compared with the present concentration of 316 ppb (IPCC 2001). Annual anthropogenic emissions to the atmosphere are estimated at 3–8 Tg N and recent estimates suggest that agricultural systems contribute a large proportion of these anthropogenic emissions (Mosier and Kroeze 1998).

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification. A number of agricultural activities add N to soils, increasing the amount of N available for nitrification and denitrification, and ultimately the amount of N<sub>2</sub>O emitted. Major regulators of these processes are N supply (Bouwman 1996; Brown et al. 2000; Maggiotto et al. 2000), temperature (Goodroad and Keeney 1984; Zheng et al. 1997), pH (Daum and Schenk 1998; Mogge et al. 1999) and soil moisture content (Dobbie et al. 1999; Zheng et al. 2000). However, the role that soil physico-chemical properties play in N<sub>2</sub>O emission is still far from being understood. Because the interactions among the physical, chemical and biological variables that control N<sub>2</sub>O production are complex, N<sub>2</sub>O fluxes from agricultural systems are highly variable in both time and space (Smith 1990; McTaggart et al. 1994; Smith et al. 1999; Mosier and Kroeze 1999). As a result, measured N<sub>2</sub>O emissions associated with a unit of N application show a wide variation, with a range from the order of 0.1% to the order of 10% (IPCC 2000).

Over 250 estimates of direct N<sub>2</sub>O emission from agricultural fields, Bouwman (1996) addressed what type of agricultural systems emit large amounts of N<sub>2</sub>O, but was unable to establish systematic patterns of N<sub>2</sub>O flux with soil texture, soil pH, soil drainage, crop type, or residue management. The analysis of 11 German forest sites conducted by Brumme et al. (1999) found very poor relationships between annual N<sub>2</sub>O flux and a set of long-term ecosystem-scale “state variables” including soil

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organic C, N leaching, bulk density, annual temperature and precipitation. These reports encourage us to pay careful attention to the effect of soil physico-chemical properties on N<sub>2</sub>O emission, especially how to eliminate the impacts of climate and agricultural management on the emission when an experiment is carried out with various soils. In this paper, we presented results of N<sub>2</sub>O emissions from wheat-growing season with various Chinese soils in an outdoor pot experiment. The major objectives of this study were to quantitatively identify the key soil parameters influencing N<sub>2</sub>O emission under similar weather conditions and agricultural management and to develop a soil-specific scaling factor for estimating N<sub>2</sub>O emission.

## Material and methods

Wheat cultivation, representing some 26.2% of the total national food crop growing area in China and some 13.4% of the international wheat cropping acreage (FAO, <http://apps.fao.org/>), is widely distributed in various agricultural soils. A rice-wheat rotation system is the dominant cropping system in China. In accordance with the cropping system, an outdoor pot cultivation experiment with 18 Chinese soils was conducted at Nanjing Agricultural University, Nanjing, Jiangsu province of China, during the 2000/2001 wheat-growing season, following a rice-growing season from June to October 2000 for a CH<sub>4</sub> emission study (Huang et al. 2002). During the winter season in 1999, soil samples were collected from approximately 0–20 cm depths of rice paddies in the region of latitude between 31°20' N and 33°20' N, longitude between 118°50' E and 120°10' E, Jiangsu province. Physico-chemical properties of the soil samples (Table 1) were determined according to the Chinese Soil Society guidelines (Liu 1996) for soil analysis. An atomic absorption spectrometer was employed to determine the amounts of available and total Fe, Cu, the amounts of exchangeable and total Mn, and Mg. A wide variation in physico-chemical properties was documented among the soils (Table 1). The coefficient of variation (CV), a measure of relative variation, ranged from 13.4 to 158.4% for all the measured properties except the pH value.

Pots made of pottery clay were 22 cm high with an inside diameter of 20 cm. The top edge of the pot had a groove for filling water to seal the rim of the gas-collecting chamber. The bottom of the pot had a hole with a 2 cm diameter for percolating the rainfall.

**Table 1** Physico-chemical properties of air-dried soil

Physico-chemical properties	Minimum	Maximum	Mean	CV(%)
Clay <0.002 mm (%)	4.3	60.6	34.9	47.7
Silt 0.002–0.05 mm (%)	24.2	81.5	42.5	32.0
Sand >0.05 mm (%)	3.5	70.3	22.5	81.6
pH (H <sub>2</sub> O)	5.6	8.6	7.3	10.8
Organic C (g.kg <sup>-1</sup> )	5.2	39.4	16.2	48.2
Total N (g.kg <sup>-1</sup> )	0.7	3.4	1.6	40.8
C:N ratio	7.0	11.7	9.7	13.4
Total P (g.kg <sup>-1</sup> )	0.86	2.51	1.5	28.1
Available K (mg.kg <sup>-1</sup> )	26	283	113	51.3
Available S (mg.kg <sup>-1</sup> )	3.0	138.1	38.4	111.9
Total S (g.kg <sup>-1</sup> )	0.304	1.203	0.489	47.8
Available Fe (mg.kg <sup>-1</sup> )	20.4	632.0	91.0	158.4
Total Fe (g.kg <sup>-1</sup> )	16.0	35.0	26.3	19.8
Available Cu (mg.kg <sup>-1</sup> )	1.0	5.3	3.0	42.3
Total Cu (g.kg <sup>-1</sup> )	0.020	0.070	0.035	35.5
Exchangeable Mn (mg.kg <sup>-1</sup> )	3.1	50.6	24.8	65.3
Total Mn (g.kg <sup>-1</sup> )	0.135	0.729	0.477	33.0
Exchangeable Mg (mg.kg <sup>-1</sup> )	43.1	988.8	564.5	42.8
Total Mg (g.kg <sup>-1</sup> )	1.3	12.0	4.5	68.5

Four kilograms of air-dried soil was placed in each pot before rice transplanting, yielding approximately 15 cm depth of soil. To reduce the potential unevenness of temperature distribution among pots, about four-fifths of the height of the pot was buried in soil. Three pots for each soil were employed as replicates.

Following the harvest of the rice crop on 18 October 2000, wheat seeds were planted on 8 November 2000 and emergence occurred about 10 days later. Plant heading occurred on 15 April and plants were harvested on 20 May 2001. Nitrogen fertilization as urea was applied at the rates of 0.59, 0.15, 0.15 and 0.15 g N per pot on 7 and 22 November 2000 and on 22 February and 20 March 2001, respectively. Phosphorus (total of 1.33 g KH<sub>2</sub>PO<sub>4</sub> per pot) and potassium (total of 1.55 g K<sub>2</sub>SO<sub>4</sub> per pot) were applied in the proportions of 60, 14, 13 and 13% of the total, respectively, when the N was applied. No additional organic fertilizer was incorporated to the soils in the experiment.

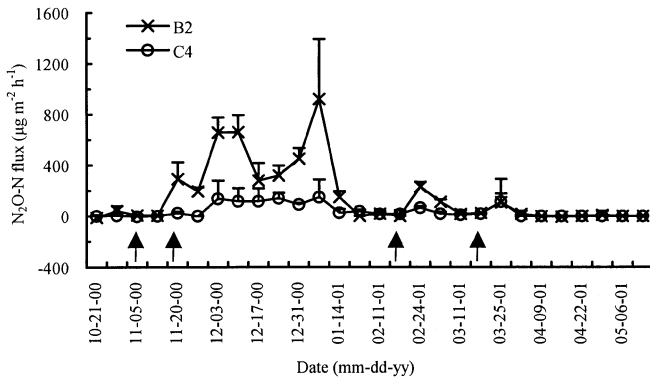
Nitrous oxide measurements were taken once a week between local time 1400 and 1600 hours, by taking samples of the headspace gas in an open-bottomed cylindrical chamber. The chamber was 100 cm high and wrapped in a layer of sponge and aluminum foil to minimize temperature changes during the period of sampling. While taking gas samples, the chamber was placed over the vegetation with the rim of the chamber fitted into the groove of the pot. Nitrous oxide mixing ratios were obtained by gas chromatography (Shimadzu, GC 14-A) with an electron capture detector. The emission was determined from the slope of the mixing ratio change in the three samples, taken at 0, 10 and 20 min. Rates of N<sub>2</sub>O emission were determined from an average of three replicates. Chamber air temperature was recorded with each set of emission measurements.

## Results and discussion

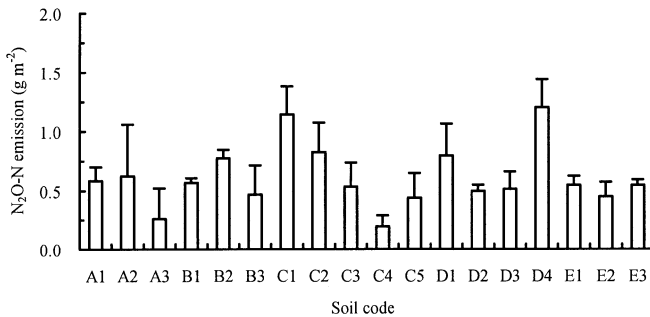
### Variation in N<sub>2</sub>O emission among soils

Figure 1 shows representative seasonal patterns of N<sub>2</sub>O-N emission from two soils typical of lower and higher emissions. As shown in Fig. 1, N<sub>2</sub>O-N fluxes from the B2 soil were generally higher than those from the C4 soil. Higher emissions usually occurred during the period from planting to mid-February when the crop lay in seedling stage through the winter season.

A wide variation in seasonal N<sub>2</sub>O-N emission was observed among the soils (Fig. 2). The highest emission came from soil D4 with a value of 1,204 mg m<sup>-2</sup> and the



**Fig. 1** Seasonal pattern of  $\text{N}_2\text{O}$ -N emissions from wheat-cultivated soil samples at sites B2 and C4. The vertical bars are standard deviations from triple replicates. Arrows show the date of fertilization



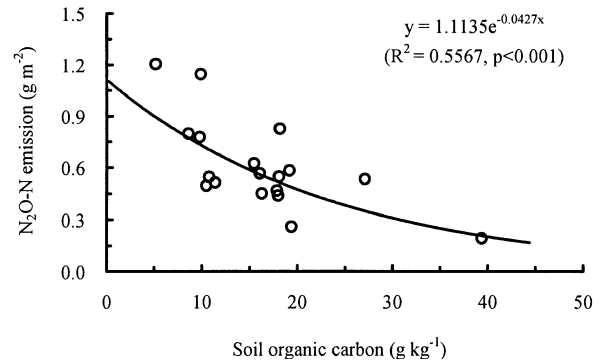
**Fig. 2** Seasonal total of  $\text{N}_2\text{O}$ -N emission from various wheat-cultivated soil samples. The vertical bars are standard deviations from triple replicates

lowest was from soil C4 with a value of  $193 \text{ mg m}^{-2}$ , approximately a 6.2-fold difference between the highest and the lowest. The average of the seasonal  $\text{N}_2\text{O}$ -N emission for all 18 soils was  $610 \text{ mg m}^{-2}$  with a standard deviation of  $261 \text{ mg m}^{-2}$ . These values were comparable with those reported by Kaiser and Ruser (2000) and Bouwman (1990). The former summarized  $\text{N}_2\text{O}$  emissions from 99 arable soils from six long-term field experiments in Germany and gave a range of  $0.5\text{--}16.8 \text{ kg N}_2\text{O-N ha}^{-1} \text{ a}^{-1}$  (Kaiser and Ruser 2000). The latter reported that the  $\text{N}_2\text{O}$  emissions had a range of  $-0.6$  to  $41.8 \text{ kg N}_2\text{O-N ha}^{-1} \text{ a}^{-1}$  for mineral soils (Bouwman 1990). Analysis of variance for the present  $\text{N}_2\text{O}$ -N emissions indicated that the variation among soils was statistically significant ( $F=5.06$ ,  $P=0.0000$ ).

#### Soil parameters influencing $\text{N}_2\text{O}$ emission

##### Carbon

Several investigators reported that  $\text{N}_2\text{O}$  production derived from denitrification in various soils showed a positive correlation with soil organic C content (Arcara et al. 1985; Eaton and Patriquin 1989; Iqbal 1992). A



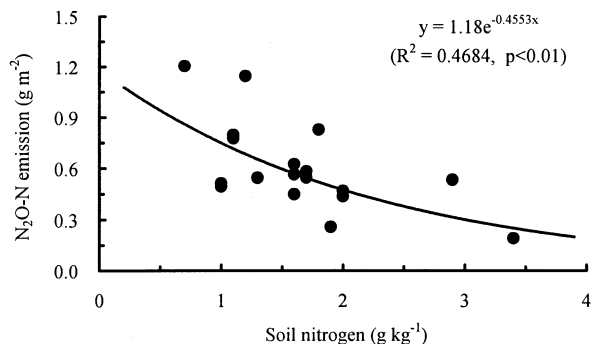
**Fig. 3** Correlation of  $\text{N}_2\text{O}$ -N emission with soil organic C in a pot experiment with wheat-planted soil samples

general understanding is that soils with high levels of organic C content have a greater propensity for  $\text{N}_2\text{O}$  formation than soils with low levels, notably after N application (Granli and Bøckman 1994). However, observations from this experiment showed the opposite behavior. Plotting seasonal  $\text{N}_2\text{O}$  emission against soil organic C content gave a negative nonlinear relationship (Fig. 3), suggesting that agricultural soils with higher organic C yield lower  $\text{N}_2\text{O}$  emissions. A possible explanation might be that higher C in soils would positively influence the reduction of  $\text{N}_2\text{O}$  to  $\text{N}_2$  in consequence of a higher content of electron donors.

Similarly, field measurements in Germany by Teepe et al. (2000) show that a total of 2.0, 1.6 and  $0.7 \text{ kg N}_2\text{O-N ha}^{-1}$  was released, respectively, from an agricultural, a fallow and a forest system during the vegetation period. The organic C of these soils was 1.1, 1.5 and 8.1%, respectively. Benckiser et al. (1996) reported that the  $\text{N}_2\text{O}$  emission was positively correlated with  $\text{NO}_3^-$  concentrations in the field plots which received no N fertilizer, while  $\text{N}_2\text{O}$  emission from the soil fertilized with  $80 \text{ kg N ha}^{-1}$  per year was negatively correlated with available C. Nevertheless, combining  $\text{N}_2\text{O}$  flux and soil organic C data from several temperate forest studies shows that soil organic C, ranging from 2 to 14%, is not a strong predictor of annual  $\text{N}_2\text{O}$  emissions (Groffman et al. 2000).

##### Nitrogen

Figure 4 shows the relationship between  $\text{N}_2\text{O}$  emission and soil total N content. This relationship is similar to that with soil organic C content (Fig. 3), because  $\text{N}_2\text{O}$  emission decreased exponentially with an increment in the soil N content. This is not surprising because the soil total N content is generally proportional to the soil C content. When the total N (TN) was plotted against the total organic C (TOC), a linear relationship of  $\text{TN}=0.084\text{TOC}+0.291$  ( $r^2=0.9466$ ,  $n=18$ ,  $P=0.0000$ ) was obtained. An incubation experiment with 20 nonfertilized soils at constant temperature and moisture by Gödde and Conrad (2000) showed that soils with the low contents of total and inorganic N produced the lowest amounts of NO



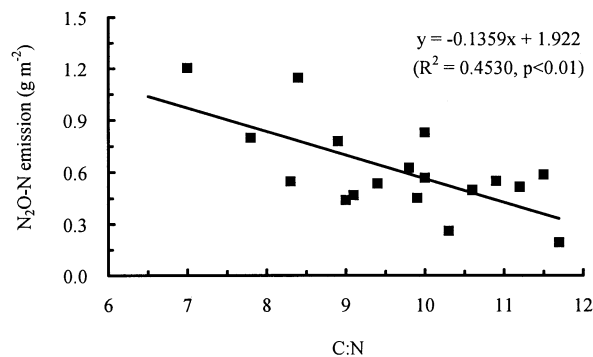
**Fig. 4** Correlation of N<sub>2</sub>O-N emission with soil total N in a pot experiment with wheat-planted soil samples

and N<sub>2</sub>O as compared to soils richer in organic and inorganic N. This may depend on the lower amounts of substrate N for mineralization. It may be postulated that the mineralization of soil N is the unique N source for microbes in unfertilized soils.

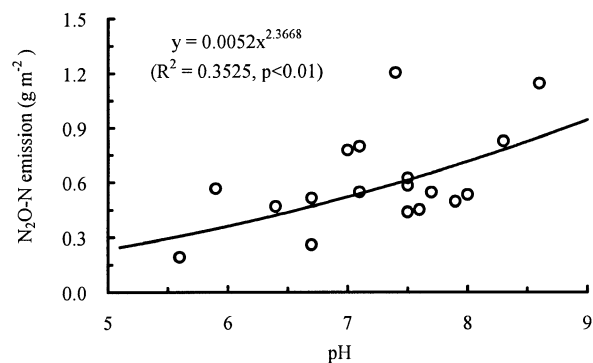
#### Ratio of carbon to nitrogen

The optimum C:N ratio for soil microbial activities is thought to range from 25 to 30. Stevenson (after Chen 1990) concluded that the mineralization will occur for organic compounds with C:N ratios lower than 20, neither mineralization nor immobilization will prevail for C:N ratios between 25 and 30, and microbes will immobilize inorganic N when C:N ratio is higher than 30. The microbial immobilization will decrease the concentration of NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> which are N<sub>2</sub>O precursors and thus both N<sub>2</sub>O production and emission will be reduced. It is expected that soils with lower C:N ratios would release more N<sub>2</sub>O than those with higher C:N ratios, and that the N<sub>2</sub>O emission would be markedly reduced when the C:N ratio approaches 20. The C:N ratios of our soils are reported in Table 1. A negative linear relationship was observed by plotting total N<sub>2</sub>O emission against the C:N ratio (Fig. 5). Similarly, Erickson et al. (2001) reported that the annual emission of N oxides was positively correlated with leaf litter N and negatively correlated with the leaf litter C:N ratio, when they related emissions of N<sub>2</sub>O and NO to forest composition, litterfall and soil N pools in a subtropical wet region of Puerto Rico.

The fact that N<sub>2</sub>O emission is negatively correlated with soil organic C (Fig. 3), total N (Fig. 4) and the ratio of C:N (Fig. 5) opens the question of how the soil C and N contribute to the production and emission of N<sub>2</sub>O. Nitrogen mineralization and immobilization and the amount of available N are intimately linked to the C cycle; both C and N should be considered together to more accurately determine the N<sub>2</sub>O emission. A further investigation is required to study which fractions of the organic C and total N regulate the N<sub>2</sub>O emission.



**Fig. 5** Correlation of N<sub>2</sub>O-N emission with soil C:N from soil samples in a pot experiment



**Fig. 6** Correlation of N<sub>2</sub>O-N emission with soil pH from soil samples in a pot experiment

**Table 2** Pearson correlation coefficients of N<sub>2</sub>O emission in pot experiment against soil physico-chemical properties

Soil parameter	<i>r</i>
Clay	-0.062
Silt	-0.118
Sand	0.143
pH (H <sub>2</sub> O)	0.526*
Total organic C	-0.661**
Total N	-0.613**
C:N ratio	-0.673**
Total P	0.169
Available K	0.182
Available S	0.138
Total S	-0.050
Available Fe	0.074
Total Fe	-0.099
Available Cu	-0.144
Total Cu	-0.308
Exchangeable Mn	0.111
Total Mn	0.501*
Exchangeable Mg	-0.248
Total Mg	0.429

\*, \*\* Significant at probability levels of 5% and 1%, respectively

## pH

It has been well recognized that the optimum pH value for nitrification and denitrification ranges from 7 to 9 (Chen 1990). When the total N<sub>2</sub>O emission was plotted against soil pH, a positive relationship between these parameters was observed (Fig. 6). Data sets from Sahrawat (1982) indicated that the nitrification is positively related to soil pH within the values between 3.4 and 8.6. A significant linear relationship was also found between nitrification rate and soil pH by Zhu and Wen (1992). Results of Fig. 6 confirm the responses to liming observed in the German studies; that is, the rates of N cycling and loss increase by increasing pH (Nagele and Conrad 1990; Nodar et al. 1992; Papen et al. 1993). On the other hand, other studies showed that soil liming significantly reduced N<sub>2</sub>O emissions in different soils (Brumme and Beese 1992; Borken and Brumme 1997). These reports suggest that the effect of soil pH on N<sub>2</sub>O emission can be complex, depending on which microbial process is dominant, nitrification or denitrification.

## Other soil parameters

Table 2 shows the Pearson correlation coefficients of N<sub>2</sub>O emission against various soil physico-chemical properties shown in Table 1. As already observed (Figs. 3, 4 and 6), total N<sub>2</sub>O emission was negatively correlated with soil organic C and total N, respectively, and positively correlated with soil pH. In addition, the emission was positively related to the total Mn content of the soil (Table 2), whereas the total Mn content was significantly correlated with soil pH ( $r=0.622$ ,  $P<0.01$ ). Probably it is the soil pH rather than the Mn content parameter that is responsible for the N<sub>2</sub>O emission. Texture, available K, total P, S, Fe, Cu, exchangeable Mn and Mg were not significantly correlated with N<sub>2</sub>O emission (Table 2).

## N<sub>2</sub>O emission with wheat production

Above-ground biomass of the wheat crop measured as dry weight at harvest was significantly affected by soil, with a  $F$  ratio of 4.669 and a  $P$  value of 0.0001. However, no significant relationship between the total N<sub>2</sub>O emission and the above-ground biomass was observed (Fig. 7), suggesting that the wheat production is not responsible for the N<sub>2</sub>O emission when various soils are compared.

## Integrative effect of soil parameters on N<sub>2</sub>O emission

In order to determine the integrative effect of soil parameters on the N<sub>2</sub>O emission, we applied a stepwise regression method (SPSS) to relate the emission to soil properties. Analysis of the stepwise regression indicated that the seasonal emission can be quantitatively described by a linear combination of soil organic C (SOC) and

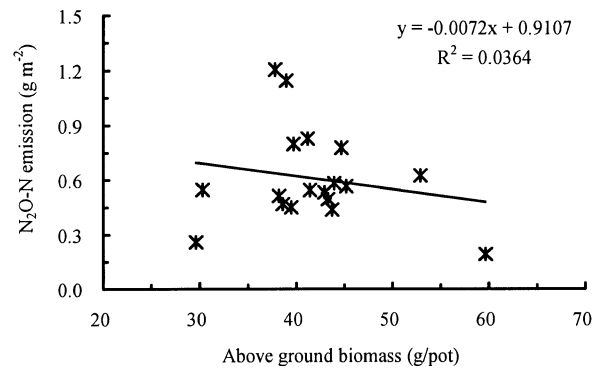


Fig. 7 Correlation of N<sub>2</sub>O-N emission from soil samples with above-ground biomass of the wheat crop at harvest

available S ( $S_a$ ), as expressed by the following relationship:

$$E = 1005 - 34.2\text{SOC} + 4.1S_a \quad (R^2 = 0.7703, n = 18, P = 0.0000) \quad (1)$$

Soil organic C and available S are expressed as  $\text{g kg}^{-1}$  and  $\text{mg kg}^{-1}$ , respectively. The  $R^2$  of 0.7703 indicates that approximately 77% of the variability in the emission can be explained by these two soil parameters. The coefficient of  $-34.2$ , on the other hand, suggests that the emission will be reduced by  $34.2 \text{ mg N}_2\text{O-N m}^{-2}$  by an increment of organic C of  $0.1\%$ . However, to note that there is a weak correlation of N<sub>2</sub>O emission with a single soil parameter does not mean that this parameter is not responsible for the emission. For example, the available S was not found to significantly correlate with total N<sub>2</sub>O emission (Table 2) while it was singled out in a linear combination, as in Eq. 1, with a two-tailed probability level of 0.0000. The dependence of N<sub>2</sub>O emission on soil available S, when the one-to-one correlation was calculated (Table 2), might be overlapped by some other soil parameters that are significant to N<sub>2</sub>O emission.

According to Bouwman (1996), the Intergovernmental Panel on Climate Change methodology (IPCC 2000) assumes an emission factor, defined as the N<sub>2</sub>O-N emissions per unit N input, of  $1.25 \pm 1\%$  for estimating direct N<sub>2</sub>O emission from synthetic fertilizer N applied to agricultural soils. Results from this study strongly suggest that the emission is dependent upon soil properties. However, we did not calculate the emission factor since N<sub>2</sub>O emissions from the unfertilized soils were not measured in this study. Up until now the soil parameters have not been taken into account in the IPCC guidelines because available data on N<sub>2</sub>O emissions from various soils were limited. It would further improve accuracy for estimating N<sub>2</sub>O emission from applied N if a more reliable soil-specific scaling factor, as shown in this study, could be derived from a variety of soils.

## Conclusions

Under similar agricultural management and weather conditions, N<sub>2</sub>O emission from the wheat-growing season was greatly dependent on soil properties. Significant negative relationships existed between the seasonal N<sub>2</sub>O emission and the soil organic C, total N, and the ratio of C:N, respectively. In addition, the emission was positively correlated with soil pH. Soil texture, and trace elements of Fe, Cu and Mg did not significantly affect N<sub>2</sub>O emission. No clear relationship existed between N<sub>2</sub>O emission and above-ground biomass of the wheat crop at harvest. A further conclusion is that approximately 77% of the variability in the N<sub>2</sub>O emission from this study can be quantitatively expressed by a linear combination of soil organic C and available S.

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