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Effect of fertilizer and water content on N_2O emission from three plantation soils in south China

LI Zhi-an, ZOU Bi, XIA Han-ping, DING Yong-zhen, TAN Wan-neng, MA Zhen-rong

(South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China. E-mail: lizan@scbg.ac.cn)

Abstract: The effects of fertilizers and water content on N_2O emission were studied using the three most typical plantation soils. Soil incubations were performed and fertilization and water content treatments were designed. At 25% of saturated water content(SWC), N_2O emissions from the soil treated with urea, KNO_3, $(NH_4)_2SO_4$ and KH_2PO_4 were compared at application rates of 0, 100, 200, 300 and 500 kg/hm^2. At 80% of SWC, similar experiments were carried out but at only one application rate(500 kg/hm^2). N_2O emissions at various water contents(20%, 35%, 50%, 65%, 80% and 100% of SWC) were studied. At low water content(25% of SWC), neither nitrogen nor phosphorus(or potassium) fertilizers led to a high level of N_2O emission, which generally ranged from 2.03 to 29.02 μg/(m^2·h). However, at high water content(80% SWC), the fertilizers resulted in much greater N_2O emission irregardless of soil tested. The highest N_2O emission rates after 24 h of water addition were 1233 μg/(m^2·h) for *S. superba* soil, 1507 μg/(m^2·h) for *P. elliottii* soil and 1869 μg/(m^2·h) for *A. mangium* soil respectively. N_2O emission from soils treated with urea, $(NH_4)_2SO_4$ and KH_2PO_4 immediately dropped to a low level but steadily increased to a very high level for the soil treated with KNO_3. High NO_3^- content was a basis of high level of N_2O emission. N_2O emission rates from soils peaked shortly after flooding, rapidly dropping to a very low level in soil from non-legume plantations, but lasting for a relatively long period in soil from legume plantations. When soil water content increased equaling to or higher than 65%, the accumulated N_2O emission over a period of 13 d ranged from 20.21—29.78 mg/m^2 for *S. superba*, 30.57—70.12 mg/m^2 for *P. elliottii* and 300.89—430.51 mg/m^2 for *A. mangium*. The critical water content was 50% of SWC, above which a high level of N_2O emission could be expected, and below which very little N_2O emissions were detected. The results suggest that, at low water content(< 50% of SWC), the fertilization practice is safe with regard to N_2O emissions, but at high water content(> 50% of SWC), nitrogen fertilizer in the form of nitrate could yield a 100-fold increase in N_2O emissions. Legume plantations like *A. mangium* should be avoided in low lands which could easily suffer from flooding or poor drainage.

Keywords: N_2O; plantation; south China; *Acacia mangium*; *Pinus elliottii*; *Schima superba*

Introduction

Nitrous oxide(N_2O) is one of the most important green house gases, which contributes to global warming and consumption of O_3 in the stratosphere (Breuer, 2000, Solomon, 1999). N_2O concentration increases at a rate of 0.25% per year, 57% of which is derived from the soil due to nitrification and denitrification by microbes (Firestone, 1989). As a result, N_2O emission from various sources has been a research focus in the field of global change for the last several decades. Agricultural soils have been well documented with regard to N_2O emission(Eichner, 1990), but forest soils draw far less attention. The magnitude of the contribution of forest ecosystems to the global sources of N_2O is based on a relatively small number of published data sets (Breuer, 2000).

Vast areas of plantation were established in South China during the last 20 years as part of the "Greening China" campaign, which increased forest cover from about 26% in the early 1980s to the current figure of about 52% (Ren, 2002). These plantations were grown on previously abandoned lands consisting of grasses and scattered shrubs. Parts of these plantations were cultivated as a source of raw materials such as pulpwood. Large scale fertilization was practiced. So far, there is no report on N_2O emissions from these plantations which constitute the major forest area in South China.

In a paddy field, N_2O emissions peaked at the beginning of the disappearance of floodwater(Cai, 1997) or in the transition period of change of soil water(Xu, 1999). A three- to six-fold higher rate of N_2O emission at soil water content of 54% was recorded over the figures at water contents of 18%—36% from a farm soil(Goodroad, 1984). Nitrogen fertilizers were responsible for the high N_2O emissions from many agricultural soils(Eichner, 1990). A percentage, 0.5% to 1.5%, of N fertilizer applied was estimated to be released as N_2O(McElroy, 1985; Eichner, 1990) contributing an average N_2O of 1.5 Tg N_2O-N/a to the atmosphere(Bolle, 1986; Eichner, 1990). These results suggest that, in the plantations of the region, wide variations in soil water content as a result of high rainfall(mostly from 1500 mm to 2000 mm) and frequent fertilization practices in afforested areas are among the environmental factors which most likely cause high N_2O emission. Unfortunately, rigorous data regarding the influence of the two factors on N_2O emission for forest soils is unavailable. As stated by Groffman and Tiedje (Groffman, 1989), factors controlling denitrification in forest soils are poorly understood. Such a fact makes us unable to mitigate N_2O emissions through the adjustment of afforestation practices including selecting the type of fertilizer and type of forest.

Inadequate knowledge of N_2O emission from these newly established plantations warrants a study combining the effect of fertilizer and water content. Our objectives were: to evaluate the effect of fertilizers including both nitrogen and non-nitrogen fertilizers on N_2O emission, to compare the difference of N_2O emission between legume plantations and non-legume plantations and to quantify the effect of water content of soils on N_2O emission.

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1 Materials and Methods

1.1 Site description and soil sampling

Soils were sampled from the Heshan Interdisciplinary Experimental Station(112°54′E, 22°41′N) of the Chinese Academy of Sciences in Guangdong Province, China. The topography of the experimental area is typical of the region with low hills(peak elevation of 98 m) and small catchments (each having an area of about 5—8 hm^2). The mean annual rainfall is about 1800 mm. The soil is an oxisol developed from sandstone, with a pH of about 4.2. In 1984, some adjacent catchments vegetated only with grasses were chosen for a scientific study based on their similarity. A different forest type was randomly allocated to each catchment and trees were planted on a 2.5 m × 3 m grid. Among them, 3 catchments are single species plantations of *Acacia mangium*, *Pinus elliottii* Engelm. and *Schima superba* Gardn. et Champ. *A. mangium* is an exotic species to south China, but very adaptive to this region. A twenty year stand of *A. mangium* has almost double the biomass of the other two species. Fast growth of the species is largely due to its nitrogen fixing ability since nitrogen is identified as the most important limiting factor for plant growth in this region. In the soil of *A. mangium* plantation at 20 years, a high nitrogen stock was established. *P. elliottii* plantations are widely established in this region because they are very adaptive and stress resistant, although it is not an environmentally beneficial species. As a coniferous species, its soil organic matter is regarded as low quality. *S. superba* is a native species, which often plays a co-dominant role in climax forest of the region. It grows slower than the other species but is more beneficial to the environment. This species has been planted on a large scale as an ecological forest during last several years.

Using steel cylinders of 5 cm diameter and 20 cm depth, we removed soil cores randomly from each of the 3 plantations. The soils were bulked, mixed, air-dried and milled to pass a 5 mm sieve. The plant residues were discarded and the soil was used for incubation experiments. An additional 6 soil samples were taken from each of the 3 plantations for chemical analysis. Each sample, consisting of 10 soil cores, was air-dried, milled to pass a 60 mesh sieve and analyzed for pH, organic matter, available phosphorus, available potassium and hydrolyzed nitrogen(Liu, 1996). The chemical properties are listed in Table 1. The saturated water content(SWC) was also determined(Nanjing Institute of Soil, 1978).

Table 1 Characteristics of plantation soils tested

Plantation	pH(1 mg/L KCl)	OM, g/kg	Avail. P, mg/kg	Avail. K, mg/kg	Hydrolyzed N, mg/kg
A. mangium	3.68 ± 0.04	35.14 ± 3.68	2.18 ± 0.35	37.01 ± 3.64	110.9 ± 8.4
S. superba	4.13 ± 0.03	23.36 ± 2.33	2.08 ± 0.21	59.40 ± 6.99	94.6 ± 5.1
P. elliottii	3.93 ± 0.07	28.88 ± 3.44	3.47 ± 0.70	40.46 ± 3.61	100.8 ± 11.6

1.2 Experiment design

1.2.1 Effect of fertilizers on N_2O emission at low water content

A sample of 1.5 kg soil from *A. mangium* was added to a PVC cylinder of 10.6 cm diameter and 35 cm height for incubation. The bottom of the cylinder was sealed with a PVC cover and the top covered with removable lips. Two holes of 2 mm diameter were drilled on opposite walls of the cylinder at 10 cm from the top. Fertilizer solution was added to the soil at rates equivalent to 0, 100, 200, 300 and 500 kg/hm^2 of nitrogen or phosphorus. KNO_3, urea and $(NH_4)_2SO_4$ as nitrogen fertilizer and KH_2PO_4 as phosphorus fertilizer were employed. The fertilizers and the application rates were often used in forest management practices of the region. Complete randomized design was used. Combined with the nutrient solution, total water content of the soil was adjusted to 25% of SWC and readjusted daily. This water content most likely occurs under natural soil conditions(Li, 1995).

Every 3 to 5 d an air sample was collected. Each sampling day, fresh air was pumped into each of the cylinders for about 20 s. Fresh air, 100 ml, was drawn with a syringe from the outlet of the pump and injected into an air bag which had been pre-vacuumized. The initial air served as the T0 sample. The cylinders were then covered with lip and the holes on the wall were sealed with tape. One hour later, another 100 ml of air(T1 sample) was sampled through the hole with a syringe. During sampling, the other hole in the wall was opened to balance the air pressure inside the cylinder. Samples were analyzed for N_2O by a gas chromatograph(HP 5890). The difference in N_2O concentration between T1 and T0 was attributed to the N_2O emission from the soil. The experiment were conducted in a room of constant temperature(25℃). All treatments were replicated 4 times.

N_2O analysis: All gas samples were analyzed for N_2O by a 2 column GC system(Wang, 2003). The first column (Stainless steel: 1 m × 2 mm × Porapak Q(80—100 mesh)) separated and removed moisture, CO_2, CFC from the sample. The second column(Stainless steel: 3 m × 2 mm × Porapak Q(80—100 mesh)) removed O_2 from the sample. The N_2O signal was finally recorded by an ECD detector. The carrier gas was pure N_2 at a flow rate of 25 cm^3/min. Operating temperatures of the detector and column were 330℃ and 55℃ respectively. A nitrous oxide standard(482 ppbv in N_2) were injected into the system periodically.

The soils from *S. superba* and *P. elliottii* were also incubated with no fertilizers added. Four cylinders of each of the soils were used for N_2O measurement and the other 4 for NH_4^+-N and NO_3^--N measurement. About 20 g of soil from the latter 4 cylinders were transferred to plastic bottles. A KCl solution of 2 mol/L was added at a soil: solution ratio of 1:10. The samples were shaken for 1 h in a reciprocal shaker and filtered. The filtrates were analyzed for NH_4^+-N and NO_3^--N colorimetrically by an Autoanalyzer(Lachat).

1.2.2 Effect of fertilizers on N_2O emission at high water content

This experiment was carried out in a similar manner with the previous one. In brief, the soils from 3 plantations were incubated in PVC cylinders. Different fertilizers were applied. The gas was sampled periodically and analyzed for

N_2O. In this experiment, KNO_3, urea and $(NH_4)_2SO_4$ as nitrogen fertilizer and KH_2PO_4 as phosphorus fertilizer were tested again, but at a rate of 500 kg/hm^2 only. Water content of soil was adjusted to 80% of SWC. Following exactly the same procedure, a parallel experiment was conducted for soil NH_4^+-N and NO_3^--N analysis. Sampling and measurements were made on the day 3 and 5.

1.2.3 Effect of water content on N_2O emission

The soils from 3 plantations were incubated at water contents of 25%, 35%, 50%, 65%, 80%, and 100% of SWC. Every 2 d, gas was sampled and analyzed for N_2O content. Sampling was conducted over 13 d for *A. mangium* soil, but only 9 d for *P. elliottii* and *S. superba* soils since N_2O concentration dropped to a very low level on the day 7 and had almost no change until the day 9. Soil water content was readjusted every day.

1.3 Statistics

Anova was conducted for NH_4^+-N and NO_3^--N data. Residual plots and Levene tests indicated the data meet the anova basic assumption of variance homogeneity and normality of the data(Kuehl, 2000).

2 Results

2.1 N_2O emission from the fertilized *A. mangium* soil at low water content

The effect of fertilizers on N_2O emission is illustrated in Fig.1. All treatments, including controls, had a peak at the day 11. A few peaks lasted until the next measurement at the day 16; for instance, KNO_3 sustained at a rate of 20 g/m^2 and $(NH_4)_2SO_4$ at a rate of 50 g/m^2. The KNO_3 treatment resulted in higher N_2O emissions than other fertilizer treatments. The highest values recorded were 55.8 and 55.1 $\mu g\ N_2O/(m^2 \cdot h)$ for KNO_3 at an application rate of 20 g/m^2 on the day 11 and 16 respectively. The corresponding second highest values were 42.8 and 29.0 $\mu g\ N_2O/(m^2 \cdot h)$ for KNO_3 at an application rate of 50 g/m^2. For $(NH_4)_2SO_4$, all treatments except the application rate of 50 g/m^2 had N_2O emissions below the control. For urea, all treatments had similar N_2O emissions except for treatments of 10 and 50 g/m^2, which emitted more N_2O than others at the peak time on the day 11. The N_2O emission pattern in KH_2PO_4 treatment was very similar to that of urea, with higher N_2O emissions for application rates of 10 and 50 g/m^2 on day 11. As a whole, N_2O emissions remained low and relatively constant during the incubation period, except for the emissions peak on the day 11 or 16.

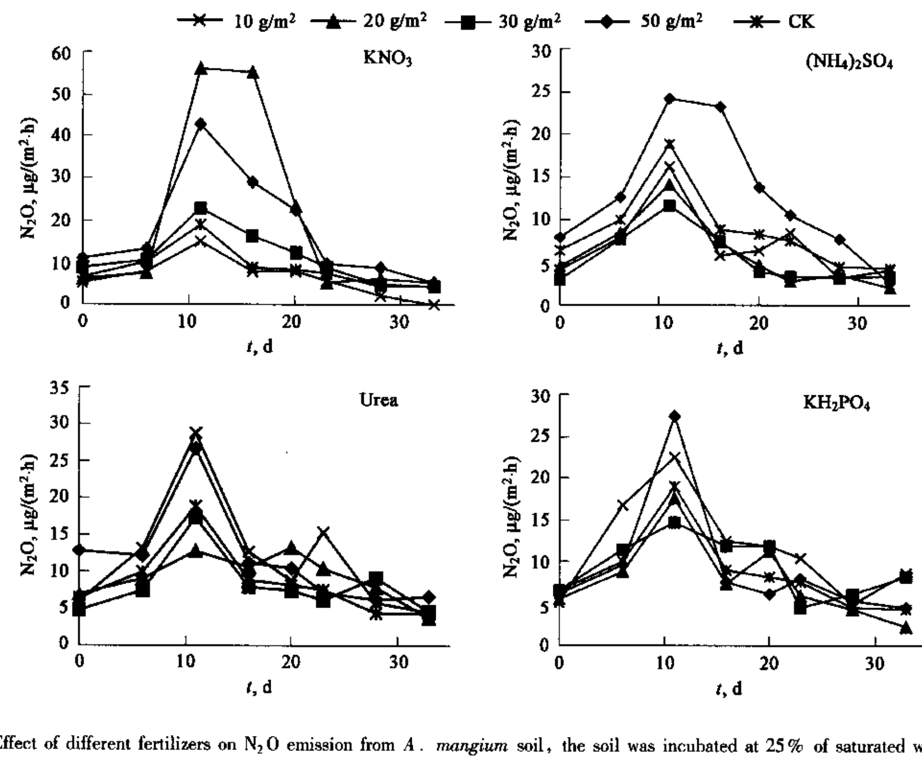

Fig.1 Effect of different fertilizers on N_2O emission from *A. mangium* soil, the soil was incubated at 25% of saturated water content

Fig. 2 shows the dynamics of NH_4^+-N, NO_3^--N, and N_2O in the unfertilized soils at 25% SWC. In *A. mangium* soil, NO_3^--N steadily increased while NH_4^+-N stayed constant at low level. In *S. superba* soil, NO_3^--N stayed nearly unchanged at about 50 mg/kg. By contrast, NH_4^+-N remained low with only a slight increase over the last two measurements. In *P. elliottii* soil, NO_3^--N and NH_4^+-N had converse relationships. NO_3^--N increased when NH_4^+-N decreased over the first three measurements. The last two measurements had opposite trends for both NO_3^--N and NH_4^+-N. The pattern of N_2O emission from all 3 soils was the same; N_2O immediately increased to a high level in the second measurement and then decreased steadily. N_2O emission followed the order of *P. elliottii* > *S. superba* > *A. mangium* in the first two measurements, but became nearly the same in later measurements.

2.2 N_2O emission from 3 fertilized plantation soils at high water content

N_2O emission rates of 3 soils with added fertilizers at

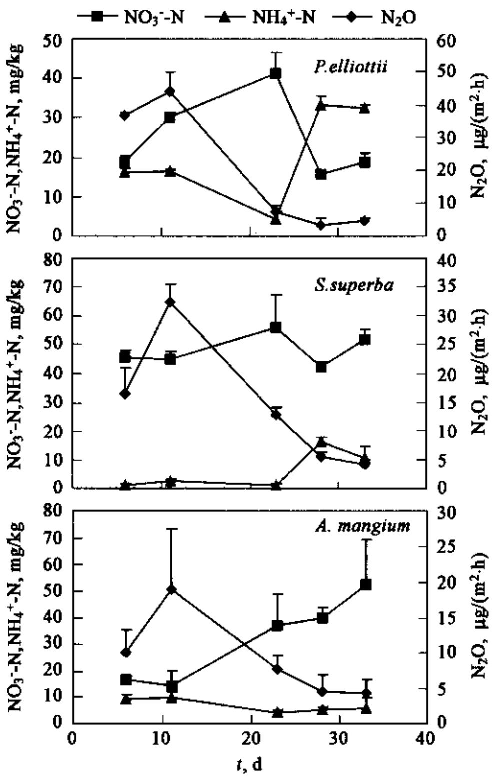

Fig. 2 Dynamics of nitrate-N, ammonium-N and N_2O of 3 plantation soils without any treatments, the soils were incubated at 25% saturated water content

high water content (80% SWC) are shown in Fig. 3. No matter what treatment, all soils had very high N_2O emissions after 24 h incubation, ranging from 1409 to 1869 μg/(m^2·h) for *A. mangium* soil, from 550 to 1233 μg/(m^2·h) for *S. superba* soil and from 890 to 1507 μg/(m^2·h) for *P. elliottii* soil. From the second day on, N_2O emission from the KNO_3 treated soils steadily increased and reached a peak at the day 4 and then either decreased (*P. elliottii and A. mangium*) or stayed relatively unchanged (*S. superba*). The peak values ranged from 4104 μg/(m^2·h) (*A. mangium*) to 4684 μg/(m^2·h) (*S. superba*). Most other treatments dropped to very low values on the day 2 except for the treatment of ammonium sulphate which decreased to a low value on the day 2 (*S. superba*), the day 3 (*P. elliottii*) or the day 4 (*A. mangium*).

NH_4^+-N and NO_3^--N content of the incubated soils corresponding to Fig. 3 are shown in Table 2 and Table 3 respectively. Statistics showed that *A. mangium* soil had higher NH_4^+-N than the other 2 soils. Different fertilizer treatments produced different contents of NH_4^+-N with ammonium sulphate being highest, urea second and the control lowest. All fertilizers yielded similar NO_3^--N

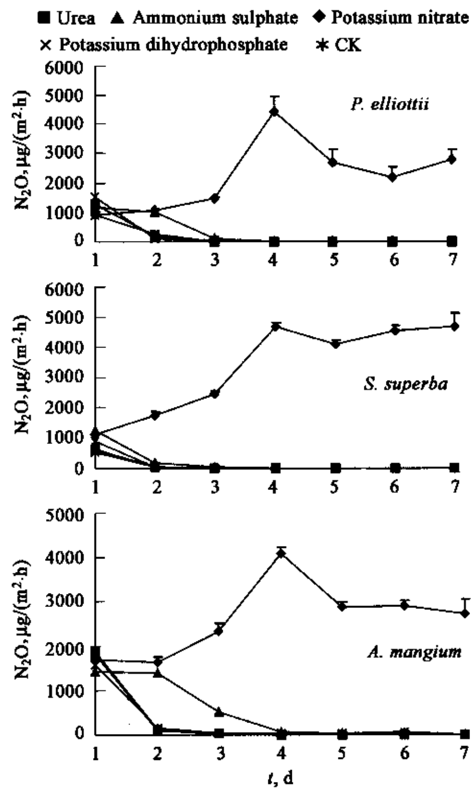

Fig.3 Effect of fertilizers on N_2O emission of 3 plantation soils at 80% saturated water content Fertilizers were applied at a rate of 30 g/m^2

Table 2 NH_4^+-N content of 3 forest soils after incubation with fertilizers (mg/kg) *

Plantation	Days	KNO_3^a	$Urea^b$	$(NH_4)_2SO_4^c$	$KH_2PO_4^d$	CK^{ed}
A. mangium [A]	3^f	34.0 ± 2.5	176.7 ± 13.5	194.1 ± 6.6	32.1 ± 13.8	20.4 ± 1.2
	5^g	62.0 ± 1.9	268.9 ± 2.3	310.4 ± 6.8	31.4 ± 4.4	29.6 ± 1.4
S. superba [B]	3^h	17.6 ± 0.5	179.2 ± 18.2	176.2 ± 4.6	10.5 ± 0.9	6.8 ± 0.9
	5^i	41.1 ± 1.4	219.7 ± 23.2	239.2 ± 9.6	15.1 ± 0.9	15.2 ± 1.4
P. elliottii [B]	3^h	19.9 ± 2.6	171.6 ± 9.0	179.9 ± 0.9	11.5 ± 0.7	9.3 ± 1.5
	5^j	46.8 ± 3.4	218.0 ± 14.5	248.8 ± 23.2	16.6 ± 1.0	17.0 ± 0.6

Notes: * The mean difference is significant at $r = 0.05$ of experiment wise Type I Error with Bonferroni t Statistics

Table 3 NO_3^--N content of 3 forest soils after incubation with fertilizers (mg/kg) *

Plantation	Days	KNO_3^a	$Urea^b$	$(NH_4)_2SO_4^b$	$KH_2PO_4^b$	CK^b
A. mangium [A]	3^f	79.47 ± 5.55	1.13 ± 0.14	0.85 ± 0.08	1.00 ± 0.20	0.74 ± 0.11
	5^f	76.13 ± 6.28	1.61 ± 0.17	0.47 ± 0.00	1.05 ± 0.27	1.23 ± 0.29
S. superba [A]	3^g	69.02 ± 0.34	1.00 ± 0.12	0.82 ± 0.05	0.87 ± 0.10	0.61 ± 0.06
	5^h	89.79 ± 3.87	1.32 ± 0.11	1.17 ± 0.04	0.55 ± 0.03	0.57 ± 0.13
P. elliottii [B]	3^f	81.62 ± 1.43	1.02 ± 0.21	0.83 ± 0.01	0.83 ± 0.06	0.69 ± 0.03
	5^i	34.90 ± 3.07	0.58 ± 0.07	0.25 ± 0.09	0.55 ± 0.16	0.91 ± 0.22

Notes: * The mean difference is significant at $r = 0.05$ of experiment wise Type I Error with Bonferroni t Statistics content except for KNO_3 which had significantly higher NO_3^--N than other fertilizers. As an average, *P. elliottii* soil had slightly lower NO_3^--N content than the other forest soils.

2.3 Effect of water content on N_2O emission from 3 plantation soils

Fig.4 illustrates the effect of different water contents on N_2O emissions from soils. At low water content ($\leqslant 50\%$ SWC), N_2O emissions from *A. mangium* soil did not respond to the variation in water content, but jumped to a very high level at 65% SWC. *S. superba* and *P. elliottii* soils emitted N_2O at relatively low levels at 50% SWC and even less at $< 50\%$ SWC, but at very high levels at $\geqslant 65\%$ SWC.

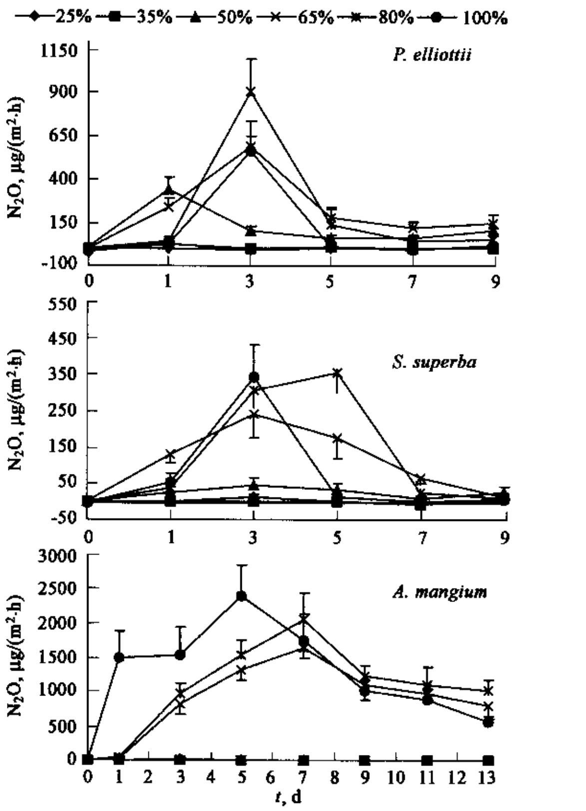

Fig.4 Effect of soil water content on the N_2O emission from 3 plantation soils

N_2O emissions from the soils of *P. elliottii* and *S. superba* mostly peaked on the day 3 for treatments of $\geqslant 65\%$ SWC, then decreased to a very low level until the day 5 for *P. elliottii* or until the day 7 for *S. superba*. *A. mangium* soil emitted N_2O in a different manner. Treatment of 100% SWC increased to 1490 $\mu g/(m^2 \cdot h)$ after 24 h incubation and then steadily increased to a peak value of 2402 $\mu g/(m^2 \cdot h)$ on the day 5. Treatments of 65% SWC and 80% SWC began to increase after 24 h in a nearly linear manner and reached peaks on the day 7. All the 3 treatments fell to a comparatively low level until the day 9 and had very little change until the day 13 when N_2O was released between 564 $\mu g/(m^2 \cdot h)$ (100% SWC) and 1023 $\mu g/(m^2 \cdot h)$ (80% SWC).

The total N_2O emission rate followed the order of *A. mangium* (with peak of 2402 $\mu g/(m^2 \cdot h)$ at 100% SWC) > *P. elliottii* (with peak of 909 $\mu g/(m^2 \cdot h)$ at 80% SWC) > *S. superba* (with peak of 357 $\mu g/(m^2 \cdot h)$ at 80% SWC). The accumulated N_2O emission for water content $\geqslant 65\%$ SWC over a period of 13 d had the same order as N_2O emission rates, with 300.89—430.51 mg/m^2 for *A. mangium*, 30.57—70.12 mg/m^2 for *P. elliottii* and 20.21—29.78 mg/m^2 for *S. superba* (Table 4).

Table 4 The accumulated N_2O emission from 3 plantation soils at different water contents over a period of 13 d(mg/m^2)*

Water content, %	*A. mangium*	*P. elliottii*	*S. superba*
25	0.18	0.60	1.99
35	0.88	1.15	1.33
50	2.78	35.88	9.03
65	300.89	70.12	29.78
80	356.19	60.64	35.76
100	430.51	30.57	20.21

Notes: * Water content refers to the percentage of water content relative to saturated water content; N_2O emission in unmeasured time was computed by linear interpolation

3 Discussion

3.1 Effect of fertilizers on N_2O emission at two levels of water content

At low water content (25% SWC), N_2O emissions were generally low whether fertilizers were applied or not. Most N_2O flux rates of *A. mangium* soil with 4 fertilizers were 2.03—29.02 $\mu g/(m^2 \cdot h)$ with only 3 exceptions, KNO_3 treatments (Fig.1). The values were lower than an average of ca. 37.6 $\mu g/(m^2 \cdot h)$ for a coniferous forest in England (Ineson, 1998), or 39.0 $\mu g/(m^2 \cdot h)$ as mean of 3 tropical forest sites (Breuer, 2000), but similar to that for other temperate forests (10.3—24.0 $\mu gN_2O\text{-}N/(m^2 \cdot h)$; Dutch, 1990; 0.34—26.3 $\mu gN_2O\text{-}N/(m^2 \cdot h)$; Matson, 1992).

At low water contents (25% SWC), the fertilizers increased N_2O emissions as compared to the control. However, higher application rates of a fertilizer did not necessarily result in higher N_2O emissions, which agreed with the observation that N_2O emissions were not linearly related to the application rate of N fertilizer (van Groenigen, 2004). KNO_3 fertilized soils emitted slightly more N_2O than other fertilizer treatments. Non-nitrate nitrogen fertilizer did not induce higher N_2O emission than KH_2PO_4, suggesting that the nitrogen in ammonium or urea were not converted into N_2O at low water content. All treatments including both the fertilizers and the control had pulses of N_2O emissions on the day 10, indicating that the fertilization was not the only cause of the peaks observed in Fig.1, rather, soil treatment may also contribute. The result was different from the observation by Pathak and Nedwell (Pathak, 2001), who found higher N_2O emissions from soil treated with urea than with other nitrogen fertilizers when soil moisture was kept at field holding capacity.

By contrast, high water content (80% SWC) caused an immediate increase in N_2O emissions from the fertilized soils (Fig.3). The highest N_2O emissions after 24 h of water addition ranged from 1233 $\mu g/(m^2 \cdot h)$ for *S. superba* soil to 1507 $\mu g/(m^2 \cdot h)$ for *P. elliottii* soil to 1869 $\mu g/(m^2 \cdot h)$ for *A. mangium* soil, which were much higher than the reported data for other fertilized soils (Eichner, 1990). N_2O emissions dropped to low levels shortly, except for KNO_3 treatment which steadily increased N_2O emissions to a very high level. Forest type had very little effect on N_2O emission. Ineson *et al*. (Ineson, 1998) and Peterson (Peterson, 1999) both attributed the high N_2O flux rate to nitrification of NH_4^+ to NO_3^-. Our results showed that high ammonium in both urea and $(NH_4)_2SO_4$ treatments did not result in high N_2O (Fig.3 and Table 2), which might be partially explained by the low rate of nitrification (Table 3).

3.2 Relationship between N_2O emission and NH_4^+/NO_3^- content

It has been generally accepted that N_2O emissions from soil was due to denitrification under anaerobic conditions (Goodroad, 1984). Groffman and Tiedje (Groffman, 1989) considered the lack of available NO_3^- as the primary factor limiting denitrification in summer for temperate forest soils in the U. S. Ammonium oxidizers were also found to be responsible for some N_2O emission under certain conditions (Richie, 1972). However, at low water content, N_2O emissions from soils without fertilizer additions appeared not to have much to do with ammonium and nitrate content (Fig. 2). N_2O emission could have either the opposite trend to the nitrate (*A. mangium* in Fig. 2) or no certain pattern of relationship with nitrate and ammonium (Fig. 2). The results suggested that low levels of N_2O emissions were not regulated by the content of ammonium and nitrate in soils. Petersen (Petersen, 1999) concluded that NO_3^- availability was not correlated with N_2O emission. However, such a conclusion might only be valid when soil moisture content is low, because at high soil moisture content, high levels of N_2O emissions were observed from the KNO_3 treated soil and much lower N_2O fluxes were observed from the soils treated with other fertilizers including non-nitrate nitrogen fertilizers of urea and ammonium sulfate. Velthof *et al*. (Velthof, 1996) also observed that emissions of N_2O and total denitrification losses from NO_3^- containing fertilizers were large after an application to a poorly drained sandy soil during a wet spring, compared to far lower levels of N_2O emissions from NH_4^+ fertilizers and cattle slurry. Pathak and Nedwell (Pathak, 2001) provided similar results that, under submerged conditions, nitrogen fertilizer in form of nitrate (NH_4NO_3 and KNO_3) emitted much more N_2O than those in non-nitrate (urea and $(NH_4)_2SO_4$).

3.3 Effect of water content on N_2O emission

Increasing soil moisture resulted in increasing N_2O emissions, but only when the moisture content exceeded a critical value could N_2O emissions increase sharply. In the 3 plantation soils, 50% SWC was a critical value of water content, above which N_2O emissions increased sharply and below which very low N_2O or nearly no response could be detected. N_2O emissions in paddy field seemed to behave differently, where waterlogged systems released far less N_2O than unsaturated paddy fields (Xu, 2004). The response of N_2O emission to high soil moisture could be very rapid. The first measurement 24 h after water addition yielded 100 fold higher N_2O emissions as compared to that before soil moisture was adjusted (Fig.3 and 4). Breuer *et al*. (Breuer, 2000) also observed that N_2O emissions strongly increased approximately 6—8 h after precipitation. In one incubation study, production of N_2O even began within a few minutes after water was added to field-dry soil (Davidson, 1992). In a field study at the end of the dry season in a savanna, N_2O emissions increased markedly within 30 min after soil wetting and peaked after 2 to 5 h (Scholes, 1997).

High levels of water content induced high levels of N_2O emissions, but, for *P. elliottii* and *S. superba*, it did not necessarily mean the water content was closely correlated with N_2O (Fig.4). Instead, high levels of N_2O could be found at any level of water content after it exceeded a critical value. For *A. mangium* soil with high nitrogen content, N_2O emissions followed a sequence of 100% > 80% > 65% water content before the day 5, which suggested N_2O emissions were more closely correlated with the water content than other forest soils. The results agreed with the observation by Ineson *et al*. (Ineson, 1998) and Kusa *et al*. (Kusa, 2002) that rainfall incidents were associated with pulses of increased N_2O emissions. An investigation conducted in 3 tropical forests sites in Northeast Queensland, Australia also showed that mean N_2O emissions during the wet season (80.8—242.0 $\mu g/(m^2 \cdot h)$ was significantly higher than that during the dry season (< 20 $\mu g/(m^2 \cdot h)$; Kiese, 2002). However, Petersen (Petersen, 1999) found that increasing soil moisture content had no significant effect on accumulated N_2O losses from a field of spring barley. Our results indicated that the observation by Petersen (Petersen, 1999) might be due to soil moisture content lower than a critical value. A 5 to 10 mm rainfall dripped at a rate of 20—30 mm/h is unlikely to increase soil moisture higher than 50% SWC.

4 Conclusions

At low water contents (25% SWC), neither nitrogen nor phosphorus (or potassium) fertilizers led to high levels of N_2O emission, which generally ranged from 2.03 to 29.02 $\mu g/(m^2 \cdot h)$. However, at high water contents (80% SWC), the fertilizers could result in much greater N_2O emissions in spite of the different forest soils. The highest N_2O emissions after 24 h of water addition were 1233 $\mu g/(m^2 \cdot h)$ for *S. superba* soil, 1507 $\mu g/(m^2 \cdot h)$ for *P. elliottii* soil and 1869 $\mu g/(m^2 \cdot h)$ for *A. mangium* soil respectively. N_2O emissions from soils treated with urea, $(NH_4)_2SO_4$ and KH_2PO_4 shortly dropped to low levels but KNO_3 treated soils steadily increased N_2O emissions to a very high level. High NO_3^- content is the basis of high levels of N_2O emissions. N_2O emissions from soils peaked shortly after flooding. Such high levels of N_2O fluxes shortly dropped to a very low level in the soil from non-legume plantations, but lasted for a relatively long period in the soil from legume plantations. When soil water content increased to equal to or higher than 65%, the accumulated N_2O emissions over a period of 13 d ranged from 20.21—29.78 mg/m^2 for *S. superba*, 30.57—70.12 mg/m^2 for *P. elliottii* to 300.89—430.51 mg/m^2 for *A. mangium*. The critical water content was 50% SWC, above which high levels of N_2O emissions could be expected, and below which very little N_2O could be detected. The results suggest that, at low water content (< 50% SWC), fertilization practices are safe with regard to N_2O emissions.

At high water contents(> 50% SWC), nitrogen fertilizer in the form of nitrate could yield a hundred-fold increase in N_2O emissions over baseline. Legume plantations like *A. mangium* should be avoided in low lands which could easily suffer from flooding or poor drainage.

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References:

Bolle J J, Seiler W, Bolin B, 1986. Other greenhouse gases and aerosols, assessing their role for atmospheric radiative transfer [M]. In: The greenhouse effect, climate change and ecosystems(Bolin B. *et al*., ed.). SCOPE 29, New York: John Wiley & Sons. 157—197.

Breuer L, Papen H, Butterbach-Bahl K, 2000. N_2O emission from tropical forest soils of Australia [J]. Journal of Geophysical Research, 105 (D21): 26353—26367.

Cai Z C, Xing G X, Yan X Y *et al*., 1997. Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilizers and water management[J]. Plant and Soil, 196: 7—14.

Davidson E A, 1992. Source of nitric oxide and nitrous oxide following wetting of dry soil[J]. Soil Sci Soc Am J, 56: 95—102.

Dutch J, Ineson P, 1990. Denitrification of an upland forest site[J]. Forestry: 63: 363—377.

Eichner M J, 1990. Nitrous oxide emission from fertilized soils: Summary of available data[J]. J Environ Qual, 19: 272—280.

Firestone M K, Davidson E A, 1989. Microbiological basis of NO and N_2O production and consumption: I. soil[M]. In: Exchange of trace gases between terrestrial ecosystems and the atmosphere(Andreae M.O., Schimel D.S. ed.). New York: John Wiley. 7—21.

Goodroad L L, Keeney D R, 1984. Nitrous oxide production in aerobic soils under varying pH, temperature and water content[J]. Soil Biol Biochem, 16(1): 39—43.

Groffman P M, Tiedje J M, 1989. Denitrification in north temperate forest soils: Spatial and temporal patterns at the landscape and seasonal scales[J]. Soil Biology and Biochemistry, 21(5): 613—620.

Ineson P, Coward P A, Benham D G *et al*., 1998. Coniferous forests as "secondary agricultural" sources of nitrous oxide [J]. Atmospheric Environment, 32(19): 3321—3330.

Kiese R, Butterbach-bahl K, 2002. N_2O and CO_2 emissions from three different tropical forest sites in the wet tropical of Queensland, Australia[J]. Soil Biology and Biochemistry, 34: 975—987.

Kuehl R O, 2000. Design of experiment: Statistical rinciples of research design and analysis[M]. U.S.: Duxbury Press. 123—147.

Kusa K, Sawamoto T, Hatano R, 2002. Nitrous oxide emission for 6 years from a gray lowland soil cultivated with onions in Hokkaido, Japan[J]. Nutr Cycl Agroecosyst, 63: 239—247.

Li Z A, Fang W, Lu D M, 1995. Physical and chemical properties of soils in Heshan hilly land[J]. Acta Ecologica Sinica, 15(supp. A): 93—102.

Liu G S, 1996. Soil physical and chemical analysis and description of soil profiles [M]. Beijing: Standards Press of China. 24—43.

Matson P A, Gower S T, Volkmann C *et al*., 1992. Soil-nitrogen cycling and nitrous-oxide flux in a Rocky-Mountain Douglas Fir forest — effects of fertilization, irrigation and carbon addition [J]. Biogeochemistry, 18: 101—117.

McElroy M B, Woofsy S C, 1985. Nitrous oxide sources and sinks[M]. In: World meteorological organization, atmospheric ozone 1985. Washington DC: NASA. 81.

Nanjing Institute of Soil, 1978. Soil physical and chemical analysis [M]. Shanghai: Shanghai Science and Technology Press. 522—525.

Pathak H, Nedwell D B, 2001. Nitrous oxide emission from soil with different fertilizers, water levels and nitrification inhibitors[J]. Water Air and Soil Pollution, 129: 217—228.

Petersen S O, 1999. Nitrous oxide emissions from manure and inorganic fertilizers applied to spring barley[J]. Journal of Environmental Quality, 28: 1610—1618.

Ren H, Huang P, Zhang Q M *et al*., 2002. Forest resources and ecosystem service in Guangdong Province[M]. Beijing: Environmental Science Press of China. 62—68.

Richie G A F, Nicholas D J D, 1972. Identification of the sources of nitrous oxide produced by oxidative and reductive processes from *Nitrosomonas europaea* [J]. Biochemistry Journal, 126: 1181—1191.

Scholes M C, Martin R, Scholes R J *et al*., 1997. NO and N_2O emission from savanna soils following the first simulated rains of the season[J]. Nutr Cycl Agroecosyst, 48: 115—122.

Solomon S, 1999. Stratospheric ozone depletion: A review of concepts and history [J]. Review of Geophysics, 37: 275—316.

van Groenigen J W, Kasper G J, Velthof G L *et al*., 2004. Nitrous oxide emission from silage maize fields under different mineral nitrogen fertilizer and slurry applications[J]. Plant and Soil, 263: 101—111.

Velthof G L, Oenema O, Postma R *et al*., 1996. Effects of type and amount of applied nitrogen fertilizer on nitrous oxide fluxes from intensively managed grassland[J]. Nutrient Cycling in Agroecosystems, 46(3): 257—267.

Wang Y S, Liu G R, Wang Y H *et al*., 2003. Use one improved gas chromatography measuring CO_2, CH_4 and N_2O emissions from terrestrial ecosystem [J]. Techniques and Equipment for Environmental Pollution Control, 4(10): 84—90.

Xu H, Xing G X, Cai Z C *et al*., 1999. Effect of soil water regime and chemical N fertilizers application on N_2O emission from paddy field[J]. Chin J Appl Ecol, 10(2): 186—188.

Xu Y C, Shen Q R, Li M L *et al*., 2004. Effect of soil water status and mulching on N_2O and CH_4 emission from lowland rice field in China[J]. Biol Fertil Soils, 39: 215—217.

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