Annual dynamics of N_2O emissions from a tea field in southern subtropical China

X.Q. Fu, Y. Li, W.J. Su, J.L. Shen, R.L. Xiao, C.L. Tong, J. Wu

Key Laboratory of Agro-ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Hunan, P.R. China

ABSTRACT

The annual dynamics of N_2O emissions from a tea field in southern subtropical China was observed *in situ* weekly in 2010 using a static closed chamber – gas chromatography (GC) method for three treatments: non-fertilised (CK), conventional (CON) and rice straw mulching (SM). The annual N_2O emissions for CK, CON and SM were 7.1, 17.2 and 16.7 kg N/ha/year, respectively. The N_2O emission factors for the CON and SM treatments were estimated as 2.23% and 1.91% of the total fertiliser N applied, respectively. Rice straw mulching exhibited a potential to reduce the N_2O emissions from the tea field, but not statistically significant ($P = 0.82$). The daily N_2O fluxes were positively correlated with the air temperature. The cumulative precipitation of the previous five days was significantly correlated with the daily N_2O fluxes of CON. The soil water contents were significantly correlated with the daily N_2O fluxes in the three treatments. The N_2O fluxes from CON had a more significant correlation with the soil NH_4^+-N contents than with the soil NO_3^--N contents, while the N_2O fluxes from SM showed an inverse pattern. The N_2O fluxes from CK did not show any significant relationship with the soil mineral N content.

Keywords: fertilised tea field; nitrous oxide; straw mulching; environmental factors

Nitrous oxide (N_2O) is a potent greenhouse gas, and its concentration has increased by 18.5% compared with the pre-industrial era and reached 319 ppb in 2005 (IPCC 2007). Soils are considered to be the most important source of N_2O emissions (Mosier et al. 1998), and the contribution of agricultural soils to the global N_2O source is approximately 35% (FAO 2001) because of the excessive use of chemical nitrogen (N) fertilisers. Large amounts of chemical fertilisers applying to croplands induce strong soil acidification and result in very low pH of soils (Guo et al. 2010). The tea tree is a very special plant, and its plantation causes a decline in soil pH, i.e., soil acidification (Han et al. 2007). Nitrate can accumulate in soils even in a very low pH environment, and nitrifying bacteria can adapt to highly acidic soils (Boer and Kowalchuk 2001). A low pH was demonstrated to be associated with a large source of N_2O from soil nitrification process. Tokuda and Hayatsu (2001) evaluated the potentials of 21 tea soils for N_2O emissions and found that a negative exponential relationship existed between the pH of these soils and their potentials for N_2O emissions and that the N fertiliser application rate of more than 1000 kg N/ha/year significantly enhanced N_2O emissions from these acidic tea fields. The incorporation of plant residues can also enhance soil N_2O emissions. Liu et al. (2011) found that the application of wheat straw to the soil increased N_2O emissions, whereas the incorporation of maize straw did not influence N_2O emissions, compared to a treatment of chemical fertiliser only. The effect of rice straw mulching on N_2O emissions in tea fields has not yet been fully explored to determine whether it is an effective practice for improving the environment. Given the boom of the tea industry in southern subtropical China, we monitored the N_2O emissions from a tea field in the hilly red-soil region maintained under three management practices over the course of an entire year and then analysed the relationships between the N_2O emissions and environmental factors, aiming to estimate the N_2O emission factor for tea plantation in the region.

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MATERIAL AND METHODS

Site description and treatments. The experimental site is located in a tea field at the Changsha Environmental Observation Station of the Chinese Academy of Sciences (CAS) in Hunan, P.R.China (113°20'E, 28°35'N, elevation of 105 m a.s.l.). 70% of the annual precipitation falls during the warm season from April to June. The soil in the tea field is a Haplic Alfisol, developed from highly-weathered granite parent material, and has a sandy loam texture (clay content of ~25%) and a pH of 4.5. The contents of soil organic carbon (SOC), total soil N, total soil phosphorous, and total soil potassium of the topsoil (0–20 cm) are 11.1, 0.86, 0.37 and 19.67 g/kg soil, respectively. A typical row of tea trees (Figure 1) is characterised by a 1.0 m wide and 0.9 m high canopy (two tea plants grown inside) and a 0.5 m wide inter-row space.

The field experiment was block-designed, carried out in 2010 and included three management practices: non-fertilised (CK, no fertiliser or rice straw application); conventional (CON, fertiliser applied at a rate of 450 kg N/ha/year as two additions: one of 300 kg N/ha as urea on April 15, and one of 150 kg N/ha of oilseed residues, banded 10–15 cm under the soil surface at the fertilisation point shown in Figure 1 on November 12); and rice straw mulching (SM, rice straw at a rate of 4200 kg/ha/year was placed on the soil surface, and the fertiliser application was the same as for CON). Each treatment had an area of 600 m^2 (20 m × 30 m). The first straw mulching took place on March 25 and the second on November 12.

Nitrous oxide measurement. The N_2O emissions were measured using a static closed chamber – gas chromatography (GC) method. Each tea row had four specific locations: one inter-row space, one fertilisation point, two under-tree spaces and the in-tree row space. The chamber (0.8 m long × 0.8 m wide × 1.2 m high) was placed on the soil to cover half of the inter-row space, the in-tree row space, the whole fertilisation point, and one under-tree space to obtain measurements representing the tea field landscape (Figure 1), and three replicates were set for each treatment. The observation period started in January 2010, gas samplings were performed almost once a week between 9:00 and 11:00 am, and the daily N_2O fluxes were calculated according to Liu et al. (2011). Gas samples were analysed on a GC fitted with a ^{63}Ni-electron capture detector (Agilent 7890A, Agilent, CA, USA). The annual amount of N_2O emissions (kg N/ha/year) was estimated by the following equation:

$$\left(\frac{f_1+f_n}{2}+\Sigma_{i=1}^{n-1}\frac{(f_{i+1}+f_i)\times(DOY_{i+1}-DOY_i)}{2}\right)\times$$
$$\times\frac{365}{DOY_n-DOY_1+1}\times\frac{10000}{1000000} \quad (1)$$

where: f – the daily N_2O flux (mg N/m^2/day); the subscripts of 1…n represent the number of the discrete daily N_2O flux; and DOY denotes the day of the year (1–365).

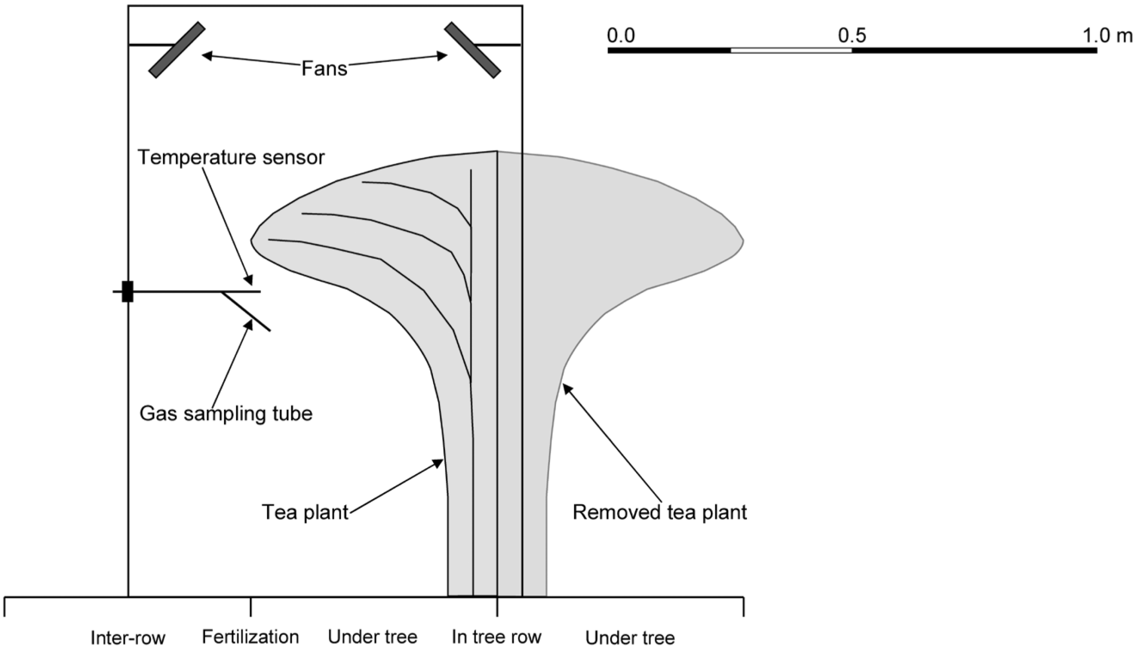

Figure 1. Diagrams of the vertical transect of a tea tree row and the static closed-chamber used for measuring N_2O emissions from the tea field

Table 1. Descriptive statistics of the N_2O fluxes (N_2O, mg N/m^2/day), soil water content (SWC, cm^3/cm^3), soil ammonium-nitrogen content (NH_4^+-N, mg N/kg soil) and soil nitrate-nitrogen content (NO_3^--N, mg N/kg soil)

Treatment	Variable	Mean	Minimum	Maximum	*CV* (%)	Data distribution
Non-fertilised (CK)	N_2O	2.10	0.11	8.03	78.6	normal
	SWC	0.255	0.176	0.317	10.7	normal
	NH_4^+-N	13.8	0.2	39.2	72.1	normal
	NO_3^--N	7.15	1.94	19.7	55.7	normal
Conventional (CON)	N_2O	5.03	0.14	18.82	88.4	log-normal
	SWC	0.283	0.228	0.411	11.5	normal
	NH_4^+-N	46.2	0.6	227.2	117.1	normal
	NO_3^--N	18.9	5.5	42.2	47.8	normal
Rice straw mulching (SM)	N_2O	5.04	–1.56	25.80	110.9	log-normal
	SWC	0.294	0.206	0.392	11.6	normal
	NH_4^+-N	45.2	2.5	162.4	96.8	normal
	NO_3^--N	17.5	5.4	35.7	41.8	normal

Soil sampling and analyses. The soil samples at the depth of 0–20 cm were collected from a 2–3 m diameter circle around chambers during the flux measurements. The soil bulk density was also determined. Each fresh soil sample was homogenised manually and divided into two portions. One portion was used for determining soil volumetric water content (SWC), while the other was analysed for soil ammonium-N (NH_4^+-N) and nitrate-N (NO_3^--N) using an automated flow injection analyzer (Fiastar 5000, FOSS, Hillerød, Denmark). All of the results of the soil analyses are presented on the oven-dried soil basis (105°C, 24 h). Since July 1, 2010, the SWC was measured by an automatic soil moisture monitoring system (ECH$_2$O, Decagon, WA, USA).

Statistical analysis. The statistical analyses were performed using the R software (http://www.r-project.org). All of the variables were tested for normality and homogeneity of variance. The Pearson's correlation analysis was carried out to evaluate the relationships between the daily N_2O fluxes and environmental factors. Differences between management treatments were evaluated by performing *t*-tests and considered statistically significant at $P < 0.05$.

RESULTS

Soil volumetric water content. For all the three treatments, the SWC data of the 0–20 cm topsoil were normally distributed (Table 1). As shown in Figure 2, during the one-year observation period, CK had a relatively lower SWCs, including lower mean, minimum and maximum values, than those of other fertilised treatments. SM had lower maximum and minimum values than CON, but a higher mean value (0.294 cm^3/cm^3) than CON (0.283 cm^3/cm^3).

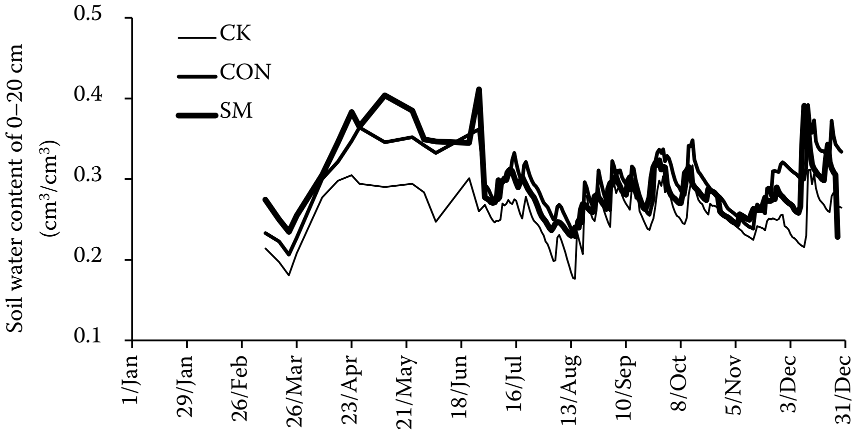

Figure 2. Dynamics of soil water contents (cm^3/cm^3) of the 0–20 cm topsoil for the three treatments of non-fertilised (CK), conventional (CON) and rice straw mulching (SM) in the tea field

There is a slight discrepancy between the SWCs for CON and SM from March to June, when the SWCs were measured manually, indicating a higher SWC in CON than in SM.

Soil mineral nitrogen content. The application of urea on April 15 resulted in a rapid increase on the mineral N content in the CON and SM soils (Figure 3). NH_4^+-N contents in CON varied greatly, ranging between 0.6 and 227.2 mg N/kg soil, compared with SM (2.5–162.4 mg N/kg soil). As a result of applying the same amount of N fertilisers in CON and SM, two treatments had almost identical NH_4^+-N mean values (46.2 and 45.2 mg N/kg soil, respectively), which were much higher than that for CK (13.9 mg N/kg soil). The NO_3^--N contents in the three treatments were significantly lower than the NH_4^+-N contents ($P < 0.001$) and followed the same pattern as the NH_4^+-N contents. The soil NH_4^+-N and NO_3^--N contents in CK remained nearly constant during the whole observation year, except for a small increase in NO_3^--N during September.

Nitrous oxide emissions. The seasonal variations of the N_2O fluxes are presented in Figure 4. Low fluxes corresponded well to cold seasons, and high fluxes corresponded to rainy seasons. The N_2O fluxes in CK ranged from 0.11 to 8.03 mg N/m^2/day, with an average daily flux of 2.10 mg N/m^2/day. CON and SM had almost the same average daily fluxes (5.03 and 5.04 mg N/m^2/day, respectively), but very different ranges of fluxes. The N fertiliser application on April 15 resulted in high N_2O emissions in CON and SM: the first large emission peak (18.82 ± 4.15 and 25.80 ± 0.28 mg N/m^2/day, respectively) occurred on May 30 and a second peak (10.85 ± 1.61 and 18.17 ± 0.31 mg N/m^2/day, respectively) was presented on June 27. The N_2O fluxes in CK displayed similar N_2O emission dynamics to those in CON and SM, but they had much lower values during the same period. Using Eq. 1, the annual N_2O emissions for the CK, CON and SM treatments were estimated as 7.1, 17.2 and 16.7 kg N/ha/year, respectively. In general, the N_2O emissions from CK were significantly lower than those from CON and SM ($P <$ 0.01), whereas there was no significant difference between the fluxes from CON and SM ($P = 0.82$).

Correlation of N_2O fluxes with environmental factors. The N_2O fluxes had stronger significant correlations with the daily maximum and minimum air temperatures in SM than in CON (Table 2). The cumulative precipitation of the previous five days

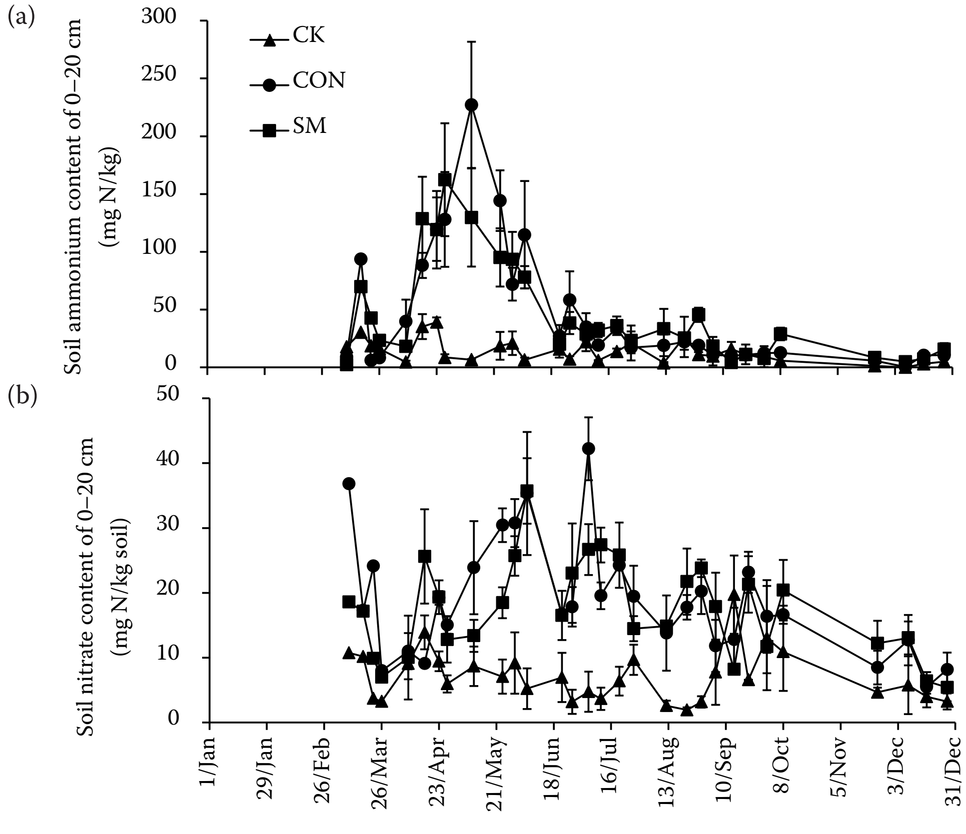

Figure 3. Dynamics of (a) soil ammonium-nitrogen contents (mg N/kg soil) and (b) soil nitrate-nitrogen contents (mg N/kg soil) of the 0–20 cm topsoil for the non-fertilised (CK), conventional (CON) and rice straw mulching (SM) treatments in the tea field. Bars represent standard error

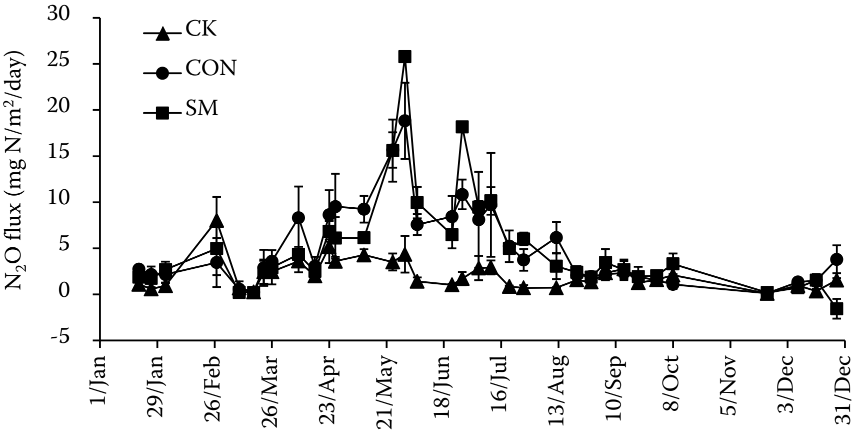

Figure 4. The N_2O fluxes (mg N/m^2/day) from the non-fertilised (CK), conventional (CON) and rice straw mulching (SM) treatments in the tea field. Bars represent standard error

was significantly correlated with the N_2O fluxes from CON, but not those from SM and CK (r = 0.04–0.27, $P > 0.12$), as shown in Table 2. In all three treatments, the N_2O fluxes were significantly correlated with the SWCs (r = 0.45–0.66, $P < 0.05$). Both the soil NH_4^+-N and NO_3^--N contents were significantly correlated with the N_2O fluxes from CON and SM. However, the NH_4^+-N contents had a stronger correlation with the N_2O fluxes than that with the NO_3^--N contents in CON ($r = 0.55$, $P < 0.01$ *versus* $r = 0.40$, $P < 0.05$), while the NO_3^--N contents had a stronger correlation with the N_2O fluxes than that with the NH_4^+-N contents in SM ($r = 0.49$, $P < 0.01$ versus $r = 0.39$, $P < 0.05$).

DISCUSSION

N_2O emissions from fields under different management practices. The N_2O emissions from soils are mainly attributed to two soil microbial processes, nitrification and denitrification, the most important pathways of N cycling in agroecosystems (Granli and Bøckman 1994). Because NH_4^+-N and NO_3^--N are the direct substrates for these processes, the more N fertiliser that is applied, the more N_2O that is emitted from agricultural soils. Our tea field results demonstrate that N fertilisation significantly enhanced N_2O emissions. As a result of the application of urea, the CON and SM fields emitted more N_2O than the CK field, and presented several peaks in N_2O emissions. The high N_2O fluxes after fertilisation in CON and SM lasted for three months, from mid-April to the end of July, much longer than the effect observed in other field studies (e.g., Liu et al. 2011). The annual N_2O emissions from CK, CON and SM ranged from 7.1 to 17.2 kg N/ha/year, which are not as high as those from a Japanese tea field (24.3 ± 16.3 kg N/ha for 209 days) reported by Akiyama et al. (2006); however, these tea field N_2O emissions were markedly higher than those from other land-use types, such as grasslands, forests and paddy fields (Corre et al. 1999). By considering the CK N_2O emissions as the background emissions and also taking into account the extra 50 kg N/ha/year input from the rice straw mulching, the N_2O emission factors for the CON and SM treatments were estimated as 2.23% and 1.91% of the total N applied, respectively, for the tea field soils, about twice the IPCC recommended default value (1% of the total N fertiliser input).

Effects of environmental factors on N_2O emissions. Temperature plays an important role in regulat-

Table 2. Pearson's correlation coefficients between the N_2O fluxes of the three treatments and environmental factors, including daily maximum (T_{max}, °C) and minimum (T_{min}, °C) air temperatures, cumulative precipitation of the previous five days (Rain5, mm), soil water content (SWC, cm^3/cm^3), soil ammonium-nitrogen content (NH_4^+-N, mg N/kg soil) and nitrate-nitrogen content (NO_3^--N, mg N/kg soil)

Treatment	T_{max}	T_{min}	Rain5	SWC	NH_4^+-N	NO_3^--N
Non-fertilised (CK)	0.04	0.09	0.05	0.45*	0.26	0.20
Conventional (CON)	0.35*	0.34*	0.36*	0.66***	0.55**	0.40*
Rice straw mulching (SM)	0.43*	0.41*	0.27	0.45*	0.39*	0.49**

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

ing soil N_2O emissions. The results of the Pearson's correlation analysis demonstrate that the daily maximum and minimum air temperatures had a positive correlation with the N_2O fluxes from CON and SM.

Numerous studies reported that soil moisture, N fertilisation and the SOC content are the major driving forces behind N_2O emissions from agricultural soils (Bouwman 1996). In the CON and SM treatments of this study, the N_2O emissions were significantly correlated with the SWCs. Keller and Reiner (1994) found the same phenomenon in an old growth forest with relatively high soil nitrate content. However, when there was no N fertiliser applied to CK, only the SWCs were significantly correlated with the N_2O fluxes ($r = 0.45$, $P < 0.05$).

Hayatsu and Kosuge (1993) reported that acid-tolerant or acidophilic autotrophic nitrification can occur in acid tea soils in Japan and that the rate of nitrification increased with an increase in NH_4^+-N contents from 50 to 300 mg N/kg soil. Our data showed that both the NH_4^+-N and NO_3^--N contents were significantly correlated with the N_2O fluxes in the fertilised tea soils (Table 2). The NH_4^+-N content exhibited a slightly stronger association with the N_2O fluxes than NO_3^--N in CON did, while the inverse was observed in SM. This discrepancy implies that nitrification might play a more important role than denitrification in contributing to the N_2O emissions from CON, and the opposite for SM. Compared with CON, a large amount of fresh organic carbon was applied in the form of rice straw in SM. This rice straw application in SM can change the topsoil micro-environment in tea plantation by decreasing the topsoil temperature, preventing the evaporation and consequently increasing the SWC, and increasing the soil microbial biomass, resulting in more favourable conditions for denitrification. Rice straw mulching may have also improved the N fertiliser use efficiency of tea plantation, similar to the findings of Patra et al. (1993), and thus there were lower annual N_2O emissions observed from SM than from CON.

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Corresponding author:

Prof. Yong Li, Ph.D, Chinese Academy of Sciences, Institute of Subtropical Agriculture, 410125 Hunan, P.R. China
tel: + 86 731 8461 5291, fax: + 86 731 8461 2685, e-mail: yli@isa.ac.cn