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Nitrous oxide fluxes from three forest types of the tropical mountain rainforests on Hainan Island, China

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HIGHLIGHTS

- N_2O fluxes from three forest types were examined in tropical mountain rainforests ecosystems.
- N_2O emissions were twice as high during the wet season than the dry season.
- An exponential relationship was observed between N_2O fluxes and WFPS.
- Primary rainforest conservation may mitigate N_2O emissions.

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ABSTRACT

Tropical rainforest soil is an important source of atmospheric nitrous oxide (N_2O). However, there is still considerable uncertainty about the spatial and temporal variability of N_2O fluxes. To understand these fluxes, we quantified the annual N_2O emissions from three tropical mountain rainforests (primary mountain rainforest, PMR; secondary mountain rainforest, SMR; and *Podocarpus imbricatus* plantation, PIP) in the Jianfengling National Natural Reserve on Hainan Island, China. The average of N_2O emissions in this area was 2.52 ± 0.33 kg N–N_2O ha^{-1} yr^{-1} (3.52 kg N–N_2O ha^{-1} yr^{-1} in the wet season and 1.62 kg N–N_2O ha^{-1} yr^{-1} in the dry season) during our study period, with highly seasonal variations. The mean N_2O emission rates were significantly higher during the wet season (68% of the total average) than the dry season (32% of the total average) ($P < 0.05$). PIP had the highest N_2O emission rate at 3.49 ± 0.61 kg N–N_2O ha^{-1} yr^{-1} (4.74 kg N–N_2O ha^{-1} yr^{-1} in the wet season and 2.32 kg N–N_2O ha^{-1} yr^{-1} in the dry season), followed by SMR at 3.03 ± 0.64 kg N–N_2O ha^{-1} yr^{-1} (4.16 kg N–N_2O ha^{-1} yr^{-1} in the wet season and 1.97 kg N–N_2O ha^{-1} yr^{-1} in the dry season), and then PMR at 1.53 ± 0.49 kg N–N_2O ha^{-1} yr^{-1} (2.21 kg N–N_2O ha^{-1} yr^{-1} in the wet season and 0.94 kg N–N_2O ha^{-1} yr^{-1} in the dry season). We observed a significant Gaussian relationship between the N_2O fluxes and soil temperature for SMR and PIP but no significant relationship in PMR. There was a significant exponential relationship between the N_2O fluxes and water filled pore space (WFPS) in SMR and PIP but not in PMR.

1. Introduction

Atmospheric nitrous oxide (N_2O) is one of the main greenhouse gases, with a warming potential nearly 300 times greater than that of CO_2 over a 100-year period (Forster et al., 2007; Solomon et al., 2007). It also contributes to stratospheric ozone destruction (Ravishankara et al., 2009). Moreover, the concentration of atmospheric N_2O has been increasing rapidly. Ice core measurements indicated that the concentration of atmospheric N_2O had enriched

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approximately 20% since pre-industrial times (Prather et al., 2012). The global atmospheric N_2O concentration increased from a pre-industrial value of approximately 270 ppb to 324.2 ppb in 2011 (IPCC, 2013). The major natural sources of N_2O include oceans, atmospheric chemistry and soil under natural vegetation systems. The soil under natural vegetation emitting 6.6 Tg N–N_2O per year, accounting for 60% of the total N_2O natural sources (IPCC, 2013), and the production of N_2O is mainly from microbial nitrification and denitrification (Davidson et al., 2000; Stevens et al., 1997). Forest soils (~30% of global land cover) have been identified as a significant source of N_2O (Castaldi et al., 2013; Kester et al., 1997; Schmidt et al., 1988; Werner et al., 2007; Yu et al., 2008), but N_2O emissions and processes vary widely among different forest types (Sousa Neto et al., 2010). Among forest types, the tropical forest soils were one of the important N_2O sources, emitting 3.0 Tg N–N_2O per year, accounting for ~18% of the total N_2O sources (Ehhalt et al., 2001).

Although tropical rainforest soil is an important source of atmospheric N_2O, there are only a few studies available regarding N_2O emissions from these forests. Most of the available data come from Brazil (Garcia-Montiel et al., 2003; Keller et al., 1983; Neto et al., 2011; van Haren, 2011; van Haren et al., 2010) and Central America (Bowden et al., 1992; Erickson and Ayala, 2004; García-Méndez et al., 1991; Keller and Reiners, 1994; McSwiney, 1999; McSwiney et al., 2001; Wieder et al., 2011), and there are a few studies from Australia (Breuer and Butterbach-Bahl, 2005; Breuer et al., 2000; Kiese and Butterbach-Bahl, 2002) and Africa (Castaldi et al., 2013; Werner et al., 2007). There are only two studies from the tropical rainforest in Xishuangbanna, southwest China (Werner et al., 2006; Yan et al., 2008), and two from Dinghushan, Southern Subtropical China (Fang et al., 2009; Tang et al., 2006). Hereafter, detailed measurements of N_2O emission rates from other tropical regions around the world, such as Hainan Island, will lead to a better understanding of the global tropical N_2O budget. Hainan Island is the largest island in the tropical region of China, where typical rainforests are distributed.

The main objectives of this paper were 1) to quantify variations of N_2O fluxes in the primary mountain rainforest (PMR), secondary mountain rainforest (SMR), and the *Podocarpus imbricatus* plantation (PIP); and 2) to better understand key factors controlling the variation of N_2O fluxes in tropical mountain rainforests in China.

2. Materials and methods

2.1. The study site

The rainforests that were studied are located in Jianfengling National Natural Reserve (18°23′–18°52′N, 108°36′–109°05′E), southwest Hainan Province, South China. The total area of the Jianfengling National Natural Reserve is approximately 470 km^2; the mountain rainforests cover approximately 150 km^2 (Chen et al., 2010). This region has a tropical monsoon climate with markedly wet and dry seasons. Based on observations over a 26-year period from 1980 to 2006, the annual mean temperature is 19.8 °C, annual mean precipitation is 2449 mm and annual mean relative humidity is 88%. The wet season is from May to October, and the dry season is from November to April; more than 80% of the annual precipitation falls during the wet season (Chen et al., 2010). The annual mean precipitation during our study period, from June 2012 to May 2013, was about 1990 mm.

We selected three forest types, primary mountain rainforest (PMR), secondary mountain rainforest (SMR), and *P. imbricatus* plantation (PIP), each representing a typical forest of the Jianfengling region (Fig. 1), and all of which are located 800–900 m above sea level. SMR and PIP were clear-cut in the 1960s-1970s, and PIP was reforested with native trees, such as *P. imbricatus* and *Dacrydium pierrei*. No fertilization was recorded in any plot. In PMR, the dominant trees were *Gironniera subaequalis*, *Cryptocarya chinensis*, *Livistona saribus*, and *Mallotus hookerianus*. The dominant herbs were *Psychotria rubra* and *Prismatomeris connata* sp. *hainanensis*. In SMR, the dominant trees were *Castanopsis tonkinensis*, *Castanopsis jianfenglingsis* and *Syzygium tephrodes*. The dominant understory herbs were *Smilax hypoglauca* and *Adiantum flabellulatum*. In PIP, the dominant trees were *P. imbricatus*, *Schima superba* and *D. pierrei*. The dominant understory herbs were *Smilax lanceifolia var. opaca* and *Psychotria serpens*.

2.2. Sampling plot set up and gas flux measurement

We measured the soil N_2O flux twice a month from June 2012 to May 2013, excepting one time in July 2012 due to the extreme weather (typhoon). Nine static chambers were placed randomly at PMR, and six at SMR and PIP, respectively. We kept a distance of at least 10 m between replicates in the same forest. The chambers were made of 20 cm (internal diameter) polyvinylchloride (PVC) pipe and consisted of two parts, a permanent collar and the chamber. The collars were permanently installed in the field at a depth of approximately 7 cm. The height of the chamber was 40 cm. We collected gas samples from 8:30 a.m. to 12:30 p.m., with 10 mL disposable vacuum blood tubes (without additives) at 10-min intervals over a 30 min period after closing the chamber. We recorded the air temperature inside the chamber at 0 and 30 min. The concentration of N_2O in the samples was determined by a gas chromatograph (Agilent 7890A, Agilent Co., USA) equipped with an electron capture detector (ECD), which operated at 350 °C. The column temperature was maintained at 60 °C, and the carrier gas was pure nitrogen at a flow rate of 20 mL min^{-1}. The flux J of N_2O was calculated as:

$$J = \frac{d_c}{d_t} \cdot \frac{P}{P_0} \cdot \frac{M}{V_0} \cdot \frac{T_0}{T} \cdot H \quad (1)$$

where d_c/d_t is the rate of concentration change; P is the atmospheric pressure of the sampling site; M is the molar mass of N_2O; T is the absolute temperature at sampling time; V_0, P_0, and T_0 are the molar volume, atmospheric pressure, and absolute temperature, respectively, under standard conditions; and H is the chamber height over the soil surface.

For each sampling, we calculated the N_2O flux of each chamber according to the flux equation (1), so every time we got a total of 21 data of N_2O flux from the three forests. Based on all data obtained during the sampling period, we calculated the mean for a year. At last we made unit conversions (mg N–N_2O m^{-2} h^{-1} to kg N–N_2O ha^{-1} yr^{-1}).

2.3. Soil characteristics

We randomly collected soil samples (0–10 cm deep) quarterly from June 2012 to May 2013 within 30 cm distance around each chamber. After clearing the leaf litter off of the ground, we collected five randomly selected soil samples for each chamber and then mixed them into a composite sample. The samples were transported in a portable ice box to the lab where we divided each composite sample into two parts and immediately sieved one part through a 2 mm mesh to remove visible fragments, stones, coarse roots, and animals and stored it at 4 °C. This portion of fresh soil was used to determine the NH_4^+-N and NO_3^--N concentrations. We air-dried the other part at room temperature and then passed it through a 0.25 mm sieve to determine other chemical properties. We extracted the soil NH_4^+-N and NO_3^--N contents with 2 M KCL on