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Seasonal changes in the spatial structures of N_2O, CO_2, and CH_4 fluxes from *Acacia mangium* plantation soils in Indonesia

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ABSTRACT

We evaluated the spatial structures of nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) fluxes in an *Acacia mangium* plantation stand in Sumatra, Indonesia, in drier (August) and wetter (March) seasons. A 60 × 100-m plot was established in an *A. mangium* plantation that included different topographical elements of the upper plateau, lower plateau, upper slope and foot slope. The plot was divided into 10 × 10-m grids and gas fluxes and soil properties were measured at 77 grid points at 10-m intervals within the plot. Spatial structures of the gas fluxes and soil properties were identified using geostatistical analyses. Averaged N_2O and CO_2 fluxes in the wetter season (1.85 mg N m^{-2} d^{-1} and 4.29 g C m^{-2} d^{-1}, respectively) were significantly higher than those in the drier season (0.55 mg N m^{-2} d^{-1} and 2.73 g C m^{-2} d^{-1}, respectively) and averaged CH_4 uptake rates in the drier season (−0.62 mg C m^{-2} d^{-1}) were higher than those in the wetter season (−0.24 mg C m^{-2} d^{-1}). These values of N_2O fluxes in *A. mangium* soils were higher than those reported for natural forest soils in Sumatra, while CO_2 and CH_4 fluxes were in the range of fluxes reported for natural forest soils. Seasonal differences in these gas fluxes appears to be controlled by soil water content and substrate availability due to differing precipitation and mineralization of litter between seasons. N_2O fluxes had strong spatial dependence with a range of about 18 m in both the drier and wetter seasons. Topography was associated with the N_2O fluxes in the wetter season with higher and lower fluxes on the foot slope and on the upper plateau, respectively, via controlling the anaerobic-aerobic conditions in the soils. In the drier season, however, we could not find obvious topographic influences on the spatial patterns of N_2O fluxes and they may have depended on litter amount distribution. CO_2 fluxes had no spatial dependence in both seasons, but the topographic influence was significant in the drier season with lowest fluxes on the foot slope, while there was no significant difference between topographic positions in the wetter season. The distributions of litter amount and soil organic matter were possibly associated with CO_2 fluxes through their effects on microbial activities and fine root distribution in this *A. mangium* plantation.

1. Introduction

Tropical forest soils are an important source of nitrous oxide (N_2O) and carbon dioxide (CO_2), and act as sinks for methane (CH_4) (Keller et al., 1986; Potter et al., 1996; Mosier et al., 1998; Raich et al., 2002). The recent rapid increases in the atmospheric concentrations of these major greenhouse gases significantly contribute to global warming (IPCC, 2007). N_2O is emitted from soils via microbial processes of nitrification under aerobic conditions and via denitrification under anaerobic conditions (Davidson et al., 2000). CO_2 is produced mainly through the microbial decomposition of organic matter and through respiration by living plant roots (Boone et al., 1998; Hanson et al., 2000). Soil surface CH_4 fluxes depend on the balance between production by methanogenic microbes at anaerobic microsites and consumption by methanotrophic microbes at aerobic microsites (Le Mer and Roger, 2001). The magnitudes of N_2O, CO_2, and CH_4 fluxes are highly variable and are strongly influenced by changes in environmental conditions, such as temperature, soil moisture, and substrate availability (Firestone and Davidson, 1989; Raich and Tufekcioglu, 2000; Le Mer and Roger, 2001).

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In tropical areas, industrial plantations of fast-growing tree species have recently been expanded, both to supply wood and to fix atmospheric CO_2. *Acacia* is one of the most important leguminous trees in industrial plantations because of its fast growth and tolerance to acidic and nutrient-poor environments. Worldwide, acacia had been planted on over 8,317,000 ha by 2000 and 96% of the total global acacia plantation area is located in Asia (FAO, 2001). However, the presence of leguminous and other nitrogen (N)-fixing trees in forests may enhance N_2O emission from soils by producing N-rich litter through symbiotic N fixation, leading to high soil N availability and fast soil N cycling (Binkley et al., 1992; Garcia-Montiel and Binkley, 1998; Erickson et al., 2001; Dick et al., 2006; Arai et al., 2008). In the fast-growing leguminous tree plantations of tropical Asia, soils also have been demonstrated to be a significant source of N_2O (Arai et al., 2008; Konda et al., 2008), and the importance of emissions from plantations will increase over the coming decades because of the increase in area of leguminous tree plantations in Asia. Therefore, one must elucidate the temporal and spatial dynamics and underlying mechanisms involved in N_2O emissions in fast-growing leguminous tree plantations to accurately estimate the magnitude of global warming mitigation provided by the plantations and to develop management options.

N-fixing trees not only enhance N_2O emission from soils but may also reduce the ability of soils to function as CH_4 sinks. Many studies have reported that N fertilization of forest soils reduced CH_4 oxidation (Steudler et al., 1989; King and Schnell, 1994), although the findings of some studies have been inconsistent (Castro et al., 1993; Bodelier and Laanbroek, 2004). High N input through the decomposition of N-rich litter may inhibit CH_4 oxidation in *Acacia mangium* Willd. plantations.

Many previous studies in tropical forests have found pronounced seasonal fluctuations in N_2O, CO_2, and CH_4 gas fluxes, with higher N_2O and CO_2 emissions and lower CH_4 uptake during the wet season than in the dry season (Verchot et al., 2000; Ishizuka et al., 2002; Kiese et al., 2003; Werner et al., 2007). Arai et al. (2008) found the same pronounced seasonal fluctuation in N_2O fluxes in accordance with seasonal changes in the water-filled pore space (WFPS) in *A. mangium* plantation soils. These gas fluxes are known to show large spatial variability in agricultural (Folorunso and Rolston, 1984; Robertson et al., 1997; Stoyan et al., 2000), grassland (Ambus and Christensen, 1994; van den Pol-van Dasselaar et al., 1998), and forest soils (Prieme et al., 1996; Ishizuka et al., 2005b; Konda et al., 2008; Nishina et al., 2009). The seasonal and spatial variability of these gas emissions contributes significantly to the uncertainty of estimates of the source and sink capacities of tropical rain forest ecosystems. Konda et al. (2008), who investigated the spatial structures of N_2O, CO_2, and CH_4 fluxes in *A. mangium* soils in the drier season, suggested that the spatial distributions of N_2O and CO_2 fluxes were mainly associated with soil resources such as readily mineralizable carbon (C) and N. However, most of our knowledge about seasonal changes in the spatial structures of these gas fluxes is still based on a small number of measurements taken from tropical forest soils (Kosugi et al., 2007; Adachi et al., 2009) and none from *A. mangium* plantation soils. Understanding seasonal changes in the spatial structures of these gas fluxes is essential to conduct accurate, quantitative temporal and spatial evaluations of these gas emissions in leguminous tree plantation soils.

Our objectives were to evaluate seasonal and spatial variations in N_2O, CO_2, and CH_4 fluxes in a fast-growing leguminous tree plantation; and to clarify the major factors controlling the variation in these fluxes by elucidating the relationship between gas fluxes and soil properties, particularly addressing topographic influences on the WFPS and substrate (C and N) availability.

2. Materials and methods

2.1. Site description

Field measurements were taken from an *A. mangium* plantation area (3°52′40″S, 103°58′40″E) in South Sumatra, Indonesia, in August 2005 and March 2006 (Fig. 1). The experimental site was located within a large area (about 1930 km^2) of *A. mangium* plantation. In the study stand, trees were planted at 2 × 4-m intervals in 1997, and 85 g of phosphate fertilizer (SP-36) and 35 g of urea per tree were applied once on planting. The mean tree height, diameter at breast height (DBH), and basal area in 2004 were 23.6 m, 22.5 cm, and 24.2 $m^2\ ha^{-1}$, respectively (Kaneko et al., unpublished observations). The mean annual temperature and rainfall from 1991 to 2002 were 27.3 °C and 2750 mm, respectively (Hardjono et al., 2005). The drier season normally lasts from June through September (average monthly precipitation < 150 mm), while the period from November through April is wetter as the monthly precipitation is beyond 250 mm (Table 1; Hardjono et al., 2005). The measurements were carried out once during the drier and once during the wetter season. The topography is undulating and the soils are Acrisols (ISSS Working Group RB, 1998) derived from Tertiary sedimentary rock.

2.2. Plot setting

A 60 × 100-m plot was established in an 8-year-old *A. mangium* plantation that included different topographical elements, upper plateau, lower plateau, upper slope and foot slope (Fig. 1). The slope was relatively steep and convex with average and maximum inclinations of 21.8° and 31.4°, respectively. The 60 × 100-m plot was divided into 10 × 10-m grids, and gas and soil samples were collected once at each grid point ($n = 77$) on 8 August 2005 and 3 March 2006.

2.3. Gas and soil sampling and analyses

We measured N_2O, CO_2, and CH_4 fluxes using the static chamber method (Ishizuka et al., 2002; Konda et al., 2008). Polypropylene chambers (22.2 cm upper diameter, 18.7 cm lower diameter, 12.0 cm high) were inserted into the soil to a depth of 2 cm 1 day before sampling in each season. We took three time series (0, 15, 30 min) of gas samples per chamber after covering each chamber with a lid. We measured the concentrations of N_2O, CO_2, and CH_4 using gas chromatographs (GC-14B; Shimadzu Co. Ltd., Kyoto, Japan) equipped with an electron capture detector for N_2O, a thermal conductivity detector for CO_2, and a flame ionization detector for CH_4. We calculated the gas flux using a linear regression because the increase in gas concentration in the chamber during the sampling period appeared to be linear. The gas sampling and analysis methods are detailed in Konda et al. (2008). After gas sampling, we collected the litter sample from inside of the gas sampling chamber (0.027 m^2) and from an additional chamber set (0.027 m^2) close to the gas sampling point for every sampling site ($n = 77$), and we separated the litter into fresh (L layer) and decayed (FH layer) litter. The dry weights of the L and FH layers were determined with oven-drying (105 °C, 24 h). After litter sampling, we collected the top 10 cm of mineral soil from the inside of each gas sampling chamber ($n = 77$) using two 200-ml (5.1 cm diameter, 10 cm height) sampling cylinders in the drier season and one 200-ml soil cylinder in the wetter season. One cylinder soil sample (200 ml) from the drier season ($n = 77$) was used for bulk density analysis through oven-drying (105 °C, 24 h). We used the bulk density from the drier season for the wetter season bulk density calculations. The 200-ml soil samples