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# The litter layer acts as a moisture-induced bidirectional buffer for atmospheric methane uptake by soil of a subtropical pine plantation

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ABSTRACT

Forest soils are well known sinks for atmospheric methane ($CH_4$), but how the surface litter layer controls gas diffusion into the mineral soil is still unclear. Seasonal rainfall in the humid climate provides a unique opportunity to examine uptake of atmospheric $CH_4$ under a wide range of soil water content (SWC). We studied this question using a litter removal method in a 20-year-old slash pine (*Pinus elliottii*) plantation in subtropical China during 2005–2007. Soil-atmosphere $CH_4$ fluxes of the control ($F_{CK}$) and litter-free ($F_{LF}$) treatments and their differences (litter-affected $CH_4$ flux, $F_{CK-LF} = F_{CK} - F_{LF}$) were all significantly influenced by SWC and not by soil temperature. Litter layer reduced atmospheric $CH_4$ uptake by soil when SWC was below 15.8 vol%, and increased atmospheric $CH_4$ consumption by soil when SWC was above this value. We concluded that the litter layer acts as a moisture-induced bidirectional buffer for atmospheric $CH_4$ uptake by soils in a subtropical humid pine plantation. However, the removal of the litter layer had a minimal effect (+0.7%) on annual atmospheric $CH_4$ uptake by soil, through compensating effects during the wet and dry seasons. Therefore, in the context of climate change, future changes in SWC will alter the strength of atmospheric $CH_4$ uptake by soils of subtropical pine plantations.



## 1. Introduction

Methane ($CH_4$) is the second most important anthropogenic greenhouse gas, contributing approximately 14% to global warming (IPCC, 2007). Moreover, methane plays an important role in changing the chemical composition of the atmosphere (Cicerone and Oremland, 1988). The main route for removing atmospheric $CH_4$ is through reactions with hydroxyl radicals in the troposphere. Atmospheric $CH_4$ uptake by aerobic soils through microbial oxidation is a secondary sink and is large enough (about 30 Tg year$^{-1}$) to influence the global $CH_4$ budget, and this uptake is likely to shift with changes associated with climate change and human activities (Smith et al., 2000; Le Mer and Roger, 2001; IPCC, 2007).

Forested soils are the largest active biotic sinks for atmospheric $CH_4$ on an areal basis (Smith et al., 2000; Le Mer and Roger, 2001). Atmospheric $CH_4$ uptake strength by aerated soils is usually controlled by methanotrophs ($CH_4$ oxidizing microbes) and gas diffusivity. Methanotrophs generally have their highest activity in the uppermost mineral layers (Bender and Conrad, 1994; Price et al., 2003; Wolf et al., 2011) due to lower amounts of ammonium (Schnell and King, 1994) and more favorable soil water content (SWC) (Schnell and King, 1996). Because of the high potential of $CH_4$ oxidation by methanotrophs (Saari et al., 1998), gas diffusivity is generally the primary factor in regulating atmospheric $CH_4$ consumption in forest soils (Striegl, 1993; Brumme and Borken, 1999). Gas diffusivity is greatly affected by SWC, as $CH_4$ diffuses $10^4$ times slower in water than in air (Marrero and Mason, 1972). Litter layers of boreal and temperate well drained forests have generally been reported to have little $CH_4$ oxidation capacities (Saari et al., 1998; Brumme and Borken, 1999; Steinkamp et al., 2001). Thus, litter layers are primarily considered as physical barriers against atmospheric $CH_4$ diffusion to mineral soils. Reductions in atmospheric $CH_4$ uptake by soil (Brumme and Borken, 1999), especially under dry soil conditions, have been shown in litter removal studies (Borken and Brumme, 1997; Dong et al., 1998; Saari et al., 1998; Steinkamp et al., 2001; Price et al., 2003; Yan et al., 2008; Peichl et al., 2010). In support of this concept, Brumme and Borken (1999) found a negative relationship between $CH_4$ uptake rates and thickness of organic horizons. However, Borken and Beese

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(2006) suggested that litter layer removal decreased $CH_4$ uptake by German forest soils because the litter horizon may hold partial rainfall and maintain gas diffusivity of the mineral soil. Furthermore, in contrast to boreal and temperate forests, litter layers of tropical montane forests have high $CH_4$ methane oxidation rate, which can influence $CH_4$ exchange between the soil and atmosphere (Wolf et al., 2011). Thus, under wet soil conditions, litter layers may also mitigate mineral soil water saturation and increase atmospheric $CH_4$ uptake by soils and litter layers.

Subtropical forests of southern China are characterized by a humid climate with high temperatures and precipitation rates. Even though annual rainfall is relatively high, seasonal wet (January–June) and dry (July–December) conditions alternate over an annual cycle. It is not known how this precipitation regime affects atmospheric $CH_4$ consumption by subtropical forest soils. With climate change induced changes in precipitation amount and patterns, we need a better understanding of the potential bidirectional buffering roles of litter layer on $CH_4$ uptake by forest soils. Furthermore, subtropical forests are widely distributed and currently encompass a total area of approximately 53 million hectares. By the late 1970s, however, the majority of natural forests, primarily composed of evergreen broad-leaved species, were heavily destroyed. To prevent environmental degradation, forest restoration campaigns were extensively launched in the 1980s (Wang et al., 2011, 2012b). These forest plantations, which accounted for 41% of the total subtropical forested area, were mainly established by coniferous species. Slash pine (*Pinus elliottii*) is an important member of the conifers due to its fast growth characteristic (Wang et al., 2009, 2012a). Nevertheless, it is not clear how litter layer affects atmospheric $CH_4$ uptake by soils of subtropical humid slash pine plantations in southern China.

The objectives of this study were to test the following hypotheses: (*i*) the litter layer will reduce atmospheric $CH_4$ uptake by soil under dry conditions, (*ii*) the litter layer may promote atmospheric $CH_4$ consumption by soil under wet conditions, (*iii*) the bidirectional buffering effects will be regulated by soil moisture, and (*iv*) the balance of the bidirectional buffering effects determine the annual role of litter layer on atmospheric $CH_4$ uptake by soil of slash pine plantations in subtropical China.

## 2. Materials and methods

### 2.1. Site description

This research was carried out in an evergreen slash pine (*P. elliottii* Englem.) plantation (26°44′39″ N, 115°03′33″ E, elevation 102 m) at Qianyanzhou Ecological Research Station in subtropical China. This even-aged pine plantation was established in 1985. There were also a few Masson pine (*Pinus massoniana*) in this stand. Mean tree height was 15 m; mean diameter at breast height was 16.1 cm; mean stand basal area was 35 $m^2$ $ha^{-1}$; and mean leaf area index was 4.5 $m^2$ $m^{-2}$. The main understory and midstory species were *Woodwardia japonica* (L. f.) Sm., *Dicranopteris dichotoma* (Thunb.) bernh, *Loropetalum chinense* (R. Br.) Oliver., and *Quercus fabric* Hance. Prior to being a pine plantation, the vegetation was dominated by shrubs and grasses. The soil, weathered from red sandstone and mud stone, is common for this region and classified as a Typic Dystrudepts using the soil taxonomy of United States Department of Agriculture. Soil texture was sandy loam with 68% sand and 15% clay (Wen et al., 2010). Surface (0–20 cm) bulk density was 1.51 g $cm^{-3}$; porosity was 43%; organic carbon was 9.4 g $kg^{-1}$; total N content was 0.66 g $kg^{-1}$; and pH was 4.5. This area was characterized by a humid monsoon climate, with a mean air temperature of 17.9 °C, rainfall amounts of 1469 mm $year^{-1}$ and rainfall frequency of 75–100 days $year^{-1}$ (1985–2008). Annual evapotranspiration was 747 mm $year^{-1}$ (2003–2007; Wen et al., 2010). Even though annual precipitation is high, a seasonal drought (July–December) usually occurs. About 30% of precipitation and 54% of evapotranspiration occurred in the dry season during the period of 2003–2010. Further details can be found in Wang et al. (2011) and Zhang et al. (2011).

### 2.2. Experimental design

The litter layer of the slash pine plantation was approximately 4–5 cm in thickness, with a carbon density of about 900 g C $m^{-2}$. We used a litter layer removal method (Wang et al., 2012b) to investigate the impact of litter layer on soil-atmosphere $CH_4$ flux. The treatments of soil with and without litter layer were defined as control and litter-free, respectively. Each treatment had six sampling points, located about 3–5 m apart. The two treatments were laid out using a pairwise distribution. All chambers were placed at some distance (>1 m) from the tree stems to avoid cutting coarse roots. In the litter-free treatment, nylon nets (2–mm mesh) were placed on the soil surface in order to conveniently remove fresh litter. Litter was removed one or two days before measurement. The ground shrubs and grasses in both treatments were removed during the whole study period.

### 2.3. Measurement of soil-atmosphere $CH_4$ flux

Soil-atmosphere $CH_4$ fluxes of the control ($F_{CK}$) and litter-free ($F_{LF}$) treatments were measured using a closed, static and opaque chamber-gas chromatography system (Wang et al., 2012a, b). Flux measurements were carried out between 9:00–11:00 a.m. approximately twice a week from January 2005 to December 2007. During September–October 2007, flux measurements were intermittent due to an instrument problem. The litter-based $CH_4$ flux ($F_{CK-LF}$) was calculated as the difference between $F_{CK}$ and $F_{LF}$: $F_{CK-LF} = F_{CK} - F_{LF}$. Twelve permanent bases (50 × 50 cm) with troughs made of stainless steel were inserted into the mineral soil to approximately 3 cm deep. Chamber bases were installed more than 3 months prior to the first measurements. The stainless steel chambers (50 × 50 × 50 cm) were covered with cotton pads on the outside to reduce heat exchange between the inside of the chamber and the surrounding environment. The base troughs were filled with water to prevent air exchange between the inside and outside of the chamber. Two small electric fans were fixed at the opposite top corners of each chamber for air mixing. About 100 mL of gas were sampled immediately after the chamber closure using a gas-tight syringe through an F46-tube. Subsequently, four additional samples were collected every 10 min. $CH_4$ concentration of each sample was measured within two days using a gas chromatography instrument (Agilent 4890D; Agilent Technologies, Inc., Wilmington, Delaware, United States) equipped with a flame ionization detector (FID). Chromatographic separations were run using a stainless steel column (2 m long with a diameter of 2 mm) packed with 13XMS (60–80 mesh). The temperatures of the injection/detection and column oven were 200 and 55 °C, respectively. Ultra pure $N_2$ was used as the carrier gas at a rate of 30 mL $min^{-1}$. The limit of methane detection was 0.080 ± 0.008 μL $L^{-1}$. A certified methane standard with a concentration of 4.81 μL $L^{-1}$ (China National Research Center for Certified Reference Materials, Beijing, China) was used for calibration. Soil-atmosphere $CH_4$ fluxes were calculated according to Eq. (1), and further calibrated with changes in temperature and pressure based on Eq. (2).

$$F = \frac{\Delta m}{A \cdot \Delta t} = \frac{V \cdot \Delta c}{A \cdot \Delta t} \quad (1)$$