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Canopy soil of oil palm plantations emits methane and nitrous oxide

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ABSTRACT

Due to an increasing global demand in cheap oils and biofuels, forest conversion to oil palm plantations is rapidly increasing in Indonesia. Oil palm canopy soil, or the soil lodged between the stems and leaf axils of oil palms, is one ecosystem compartment that has yet to be investigated as to its importance on the soil greenhouse gas budget. Our objectives were 1) to quantify nitrous oxide (N_2O) and methane (CH_4) fluxes from oil palm canopy soil, and 2) to determine the factors controlling these fluxes. Our study was conducted in Jambi Province, Indonesia, an area of rapid oil palm expansion. Trace gas fluxes were measured in eight smallholder oil palm plantations (9–16 years old). In each plantation, oil palms were delineated into three 1-m height sections (low, middle, and top) to represent possible gradients of canopy soil conditions that influence N_2O and CH_4 fluxes. Trace gas fluxes were measured by collecting canopy soil from each stem section and immediately incubating in the field in an air-tight glass jar. Canopy soils from all oil palm stem sections emitted N_2O and CH_4. The top stem section had higher N_2O and CH_4 emissions than the lower sections, and this pattern was paralleled by nitrogen availability and water content, which strongly influenced these fluxes. Greenhouse gas emissions per unit dry mass of canopy soil were considerable, but on a hectare basis these emissions were small due to the low amount of canopy soil per hectare ($170\ \mathrm{kg\ ha^{-1}}$). Annual canopy soil N_2O and CH_4 emissions were $10.7 \pm 3.3\ \mathrm{g}\ N_2O\text{-N}\ \mathrm{ha^{-1}\ yr^{-1}}$ and $1.9 \pm 0.5\ \mathrm{g}\ CH_4\text{-C}\ \mathrm{ha^{-1}\ yr^{-1}}$, respectively, which contributed only 1% of the total soil (canopy soil + ground soil) N_2O fluxes and 0.2% of the ground soil net CH_4 consumption. Our estimate of oil palm canopy soil emissions in Jambi Province were $7.7\ \mathrm{Mg}\ N_2O\text{-N}\ \mathrm{yr^{-1}}$ and $1.3\ \mathrm{Mg}\ CH_4\text{-C}\ \mathrm{yr^{-1}}$. Considering the increasing areal coverage of oil palm plantations in Southeast Asia, these fluxes may substantially contribute to soil greenhouse gas budgets.

1. Introduction

Oil palm (*Elaeis guineensis*) is a rapidly expanding land use across Southeast Asia, especially in Indonesia, with a majority of expansion occurring during the last two decades (Carlson et al., 2013). From 2000 to 2010, the area under oil palm in Indonesia increased by four million hectares (FAO, 2016). In Jambi Province, Sumatra, Indonesia, during the period 1990–2011 the land under oil palm increased by 150%, due to the increasing global demand for cheap oils and biofuels, as well as the overall higher economic gains and lower labor costs of cultivating oil palm (Clough et al., 2016).

Though oil palm can be economically profitable, the conversion of forest to monoculture oil palm plantations by smallholders in Jambi Province, Indonesia has shown high ecological costs both above- (Barnes et al., 2014; Drescher et al., 2016; Kotowska et al., 2015) and belowground (Allen et al., 2015, 2016; Hassler et al., 2015, 2017; van Straaten et al., 2015). In particular this conversion decreases soil carbon dioxide emissions and methane (CH_4) uptake from the atmosphere to the soil (Hassler et al., 2015) as well as increases soil nitric oxide (NO) and nitrous oxide (N_2O) emissions from fertilized areas (Hassler et al., 2017). Also, the oil palm canopy could be a substantial source and/or sink of climate-relevant trace gases. Higher fluxes of volatile organic compounds over oil palm canopies compared to rainforest have been reported (Fowler et al., 2011; Hewitt et al., 2009; MacKenzie et al., 2011). Oil palm canopy soil is one compartment of oil palm plantations that has yet to be investigated for its contribution to climate change. Canopy soils in tropical forests play an important role in the cycling of nutrients. For example, in Ecuadorean montane forests, canopy soils have been shown to contribute substantially to total soil (canopy + forest floor) gross rates of mineral nitrogen (N) processes, asymbiotic N_2 fixation and greenhouse gas fluxes (Matson et al., 2014, 2015, 2017). In Costa Rican lowland forest, canopy soils have higher

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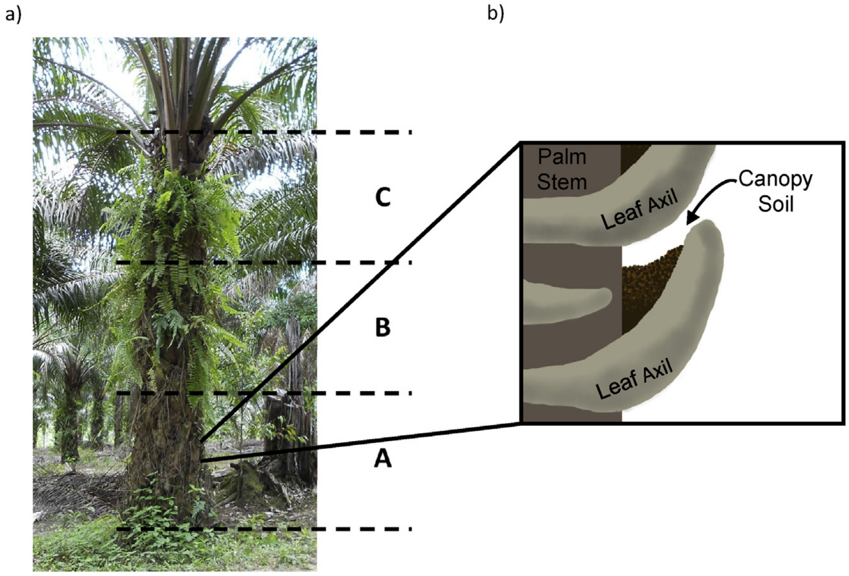

Fig. 1. Sampling scheme of oil palm stem for measurements of CH_4 and N_2O fluxes from canopy soil **(a)** (i.e., soil that is lodged between the leaf bases and stem **(b)**) and for determination of the amount of canopy soil per stem. A - covers from the stem base to 1-m height; B - is a 1-m section between A and C; C - covers from the lowest palm fronds at the stem apex down to 1 m.

net N mineralization, microbial biomass, extractable ammonium (NH_4^+), and water contents compared to the forest floor (Cardelús et al., 2009; Wanek et al., 2002). The morphology of the oil palm stem may harbor hidden stocks of canopy soil, which could potentially act as sources and/or sinks of greenhouse gases, such as CH_4 and N_2O.

In oil palms, canopy soil is the organic material lodged between the leaf bases and stem (Fig. 1a and b) and is comprised mainly of decomposed organic matter and decomposing leaf bases and epiphytic material. In addition, the leaves at the stem apex of the palm are arranged in sets of spirals, allowing for higher moisture content at the top of the stem and decreasing toward the bottom of the stem. Thus, canopy soils at the top of the stem are often wetter than those below. Organic-rich canopy soils are able to hold large amounts of water and contain high nitrogen availability, two major controlling factors in the production of greenhouse gases from these systems (Matson et al., 2014, 2017). During its lifetime an oil palm can have up to 400 exposed leaf axils (Henson et al., 2012), potentially creating an abundance of moisture and nutrient rich canopy soil environments for greenhouse gas emissions. To our knowledge, only one study thus far has quantified greenhouse gas fluxes from canopy soils, and this was conducted in tropical montane forests of Ecuador (Matson et al., 2017). Although N_2O and CH_4 fluxes from canopy soils of N-poor montane forests in Ecuador appeared to be very low, canopy soil fluxes from fertilized, warmer lowland ecosystems could be more substantial. Thus, it is important to quantify these previously unknown fluxes of N_2O and CH_4 from canopy soils of oil palm plantations, especially as these systems are rapidly expanding in tropical regions and are contributors to international biofuel networks.

Our objectives were to 1) quantify N_2O and CH_4 fluxes from oil palm canopy soil, and 2) determine their controlling factors. We hypothesized that canopy soil from the uppermost stem section (which will be wetter than the lowermost stem section) will have larger N_2O and CH_4 fluxes than the lowermost stem section, and that mineral N and moisture content will strongly influence these greenhouse gas fluxes from oil palm canopy soil. Our results provide the first knowledge of greenhouse gas fluxes from oil palm canopy soil, and aid in determining the full extent of greenhouse gas fluxes from this growing agricultural cash crop system.

2. Materials and methods

2.1. Study area and experimental design

The study took place in smallholder oil palm plantations located in the lowlands of Jambi Province, Sumatra, Indonesia (2° 0′ 57″ S, 103° 15′ 33″ E, 35–95 m above sea level). The mean annual temperature in Jambi is 26.7 ± 1.0 °C and the mean annual precipitation is 2235 ± 385 mm (1991–2011; data from a climate station at the Jambi Sultan Thaha airport). In 2013, total rainfall was 3447 ± 29 mm (data from climate stations at the villages of Sarolangun and Lubuk Kepayang and from the Harapan Forest Reserve which were approximately 10–20 km from our study sites) and total dissolved N deposition through rainfall ranged from 12.9 ± 0.1 to 16.4 ± 2.6 kg N ha^{-1} yr^{-1} (Kurniawan, 2016).

The study region, Jambi Province, was selected as a hotspot of new or first generation oil palm expansion by the large collaborative research consortium in which this study was conducted (*Ecological and Socio-economic Functions of Tropical Lowland Rainforest Transformation Systems (EFForTs);* Drescher et al., 2016). Approximately 62% of oil palm landholdings in the Jambi Province are owned by smallhold farmers (BPS, 2014). Eight smallholder oil palm plantations were selected as replicate sites (n = 8) by the *EFForTs* project, four of which were on clay Acrisol soil and the other four on loam Acrisol soil with about 60 km distance between each soil type. In each site, 50 m × 50 m plots were established, and the minimum distance between plots within each soil type was 330 m. All plots were on a flat, well-drained area of the landscape. Plantation age ranged from 9 to 16 years and palms were typically established in 9 m × 9 m grids. Based on interviews from a number of farmers in our study region, the management practices (fertilization, weeding, harvest, etc.) are typical of the common practices of smallholder oil palm plantations (Euler, 2015). Details of soil management practices in these smallholder plantations are described by Allen et al. (2015) and Hassler et al. (2015). In summary, fertilization rates varied between 48 and 88 kg N ha^{-1} yr^{-1} (except two smallholders who applied 138 kg N ha^{-1} yr^{-1}), 21–38 kg P ha^{-1} yr^{-1} and 40–157 kg K ha^{-1} yr^{-1} with the lower range in the clay Acrisol soil and the upper range in the loam Acrisol soil. Occasional liming (one smallholder applied 200 kg $CaMg(CO_3)_2$ ha^{-1} yr^{-1}) and weeding (manually and using herbicides) were conducted, and all applied management techniques depended on the smallholders' availability of funds.

2.2. Canopy soil sampling

Measurements of greenhouse gas fluxes and their controlling factors from canopy soils were conducted from February 2013 to May 2014. Measurements were rotated among the eight plots with bi-weekly to monthly intervals, such that each plot was measured twice during the