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How do the heterotrophic and the total soil respiration of an oil palm plantation on peat respond to nitrogen fertilizer application?

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ABSTRACT

Increasing oil palm (OP) plantation establishment on tropical peatlands over the last few decades has major implications for the global carbon (C) budget. This study quantified total and heterotrophic soil carbon dioxide (CO_2) emissions in an industrial OP plantation (7 year old, 149 trees ha^{-1}) on peat located in the eastern coast of the Sumatra Island (Jambi district), Indonesia, after two doses of nitrogen (N) fertilizer application at rates typical of local practice. The first dose applied in March 2012 (first Fertilization event FE) consisted of 0.5 kg urea per palm (equivalent to 371 kg N ha^{-1} at the base of the palm which when extrapolated across the plantation was 35 kg N ha^{-1}) and the second dose applied in February 2013 (second FE) amounted to 1 kg urea per palm. Soil CO_2 fluxes were measured using an infrared gas analyzer (IRGA) in dark closed chambers. The measurements were made daily from 1 day before to 7 days after fertilizer application. Soil heterotrophic respiration (Rh) and total soil respiration (Rs) were measured in trenched plots (where root respiration was excluded) and non-trenched plots, respectively. Concomitant with CO_2 flux measurements, air and soil temperatures, rainfall and the water table level were measured. To estimate the fertilizer effect during the different times of the day, CO_2 fluxes were monitored every 3 h during a 24 h period on days 2 and 3 after fertilizer application during the second FE. Shortly after fertilizer application, substantial pulses of CO_2 were detected in the IRGA chambers where the fertilizer was applied. Even though the fertilized area represents 9.4% of the plantation area only, the impact of fertilizer application at the plantation scale on CO_2 fluxes was noteworthy when compared to non-fertilized control treatments. The Rs was 36.9 kg CO_2–C ha^{-1} (7 days)$^{-1}$ greater in the fertilized than in the non-fertilized plots after the first FE but no enhancement was observed after the second FE (−72.2 kg CO_2–C ha^{-1} 7 $days^{-1}$). The Rh was 340.5 and 98.9 kg CO_2–C ha^{-1} (7 days)$^{-1}$ greater in the fertilized than in the non-fertilized plots after the first and second FE, respectively. The larger CO_2 flux enhancement in Rh as compared to Rs may be the result of fertilizer uptake by the palm roots in the un-trenched plots, while in the trenched ones where roots were absent, microorganisms used the fertilizer to accelerate soil organic matter mineralization. Although the response of Rh to N addition and the priming effect were high as compared to results in the literature, the impacts were short-term only and may not have implications on the annual C budget of the plantation.

1. Introduction

Worldwide the area under oil palm is currently estimated as 10.7 million hectares. Demand for edible or biofuel palm oil along with other derivatives (e.g. soap and makeup) has increased the planted area at an average annual rate of 6% since 2003 (FAO, 2011). This expansion is often made to the detriment of tropical rain forest and peat swamp forest in particular (Carlson et al., 2012, 2013) as oil palm (*Elaeis guineensis*, OP) is one of the few crops that can produce high yields on tropical peatlands (Boehm et al., 2013; Miettinen et al., 2012; Ramdani and Hino, 2013). If land-use change, chiefly driven by industrial enterprises, is maintained at the current rate, all the undisturbed peat swamp forest may vanish by 2030 (Koh et al., 2011; Lee et al., 2014; Miettinen et al., 2011; Rudel et al., 2009). Peatlands of Southeast Asia store a significant amount of carbon (C) (>50 Gt) in their soil. However, these peatlands are concentrated in a few areas of mainly Borneo, Sumatra and Papua (total 247.700 km^2) (Page et al., 2011; Yu et al., 2010). Contrasting with peatlands of the temperate

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and boreal zone, peat in Southeast Asia accumulates under tall rainforest and can reach depth up to 20 m (Posa et al., 2011).

The conversion of tropical peat swamp forest into OP plantation requires drainage which typically accelerates the rate of peat mineralization (Hergoualc'h and Verchot, 2011, 2014) and enhances soil CO_2 emissions to the atmosphere. The large carbon dioxide (CO_2) fluxes from tropical peatlands play an important role in global climate change (Frolking et al., 2011); therefore promoting policies and strategies to manage peatlands more sustainably is of global concern (Murdiyarso et al., 2010). For climate change mitigation mechanisms such as REDD+ (reducing emissions from deforestation and forest degradation) or for national greenhouse gas accounting, accurate emission factors of C dynamics are essential. A number of recent studies have evaluated the effect of nitrogen (N) fertilizer on CO_2 emissions in tropical peatlands. Of those, Sakata et al. (2015) and Watanabe et al. (2009) did not find any significant effect of fertilizer on emissions, whereas Jauhiainen et al. (2014) observed an increase in CO_2 flux from agricultural land and a decrease from degraded land after N fertilizer application. No study has assessed the short-term changes in peat-derived CO_2 fluxes following N fertilizer application (priming effect) in oil palm plantations.

Recommended fertilizer application rates in oil palm plantations vary according to climatic conditions, soil type, age of palms, and palm yield potential (Comte et al., 2012). Malaysian recommendations for peat soil range from 50 to 100 kg N ha^{-1} y^{-1} for immature (less than 3 years old) palms and from 120 to 160 kg N ha^{-1} y^{-1} for mature ones (Mutert et al., 1999). Present application in major growing areas on peat for 4–10 year old palms amounts to 0.45 kg N per palm (68 kg N ha^{-1} y^{-1} for a density of 150 palms ha^{-1}; ZZ von Uexkull, 2014). Fertilizer is typically spread in a circle which radius is defined by the longest fronds or in a circular area with a radius of ~2.5 m from the palm trunk (FAO, 2012; Lim et al., 2012). Timing of fertilizer application is site-specific, based on plant demand and is made at any moment during the year except during high rainfall periods (Lim, 2005).

Several long-term studies, carried out on mineral soils, have shown that an adequate fertilizer application rate leads to increased crop yields and that crop residues can enhance soil organic matter (SOM) levels without affecting the turnover of native SOM (Snyder et al., 2009). It has also been reported that application of N fertilizer can chemically stabilize soil C, which limits the rate of soil C decline or can even increase the levels of C in the soil (Lemke et al., 2010; Minasny et al., 2012; Paustian et al., 1997; Wilts et al., 2004). However, drained tropical peat soils cropped to OP, display high mineralization rates that greatly exceed C increases through residue inputs (Hergoualc'h and Verchot, 2014). This can be attributed to the fact that SOM with a C:N ratio greater than 20 typically requires additional N for decomposition to occur (Elser et al., 2007; Snyder et al., 2009). Because tropical peats commonly have a C:N ratio greater than 30, N fertilizer application is expected to enhance organic matter mineralization in these soils and increase CO_2 emissions.

Little is known about the impact of applying N fertilizer to tropical peat soils. Simulation models of peat C dynamics such as ECOSSE require information about the effect of fertilizer application on SOM mineralization and CO_2 fluxes (Smith et al., 2010). In turn, the Roundtable on Sustainable Palm Oil (RSPO) seeks reliable scientific data to issue N fertilizer recommendations for tropical peats to achieve optimal production with reduced environmental impacts (Lim et al., 2012). The aim of this research was to quantify total and heterotrophic soil CO_2 emissions from an OP plantation on a tropical peat soil after two customary doses of N fertilizer.

2. Materials and methods

2.1. Study site

The research site was a 7 year old OP plantation located on a deep peat coastal plain in the province of Jambi, Sumatra, Indonesia (Fig. 1). The climate in the region is tropical humid. The average annual rainfall is 2466 mm with a season drier than the rest of the year from June to August. The minimum and maximum values of the mean monthly temperatures are 22 °C and 33 °C, respectively (NOAA, 2011; Siderius, 2004). The OP site was situated in the Bakrie Sumatera Plantation of SNP (Sumber-Tama Nusa Pertiwi) (1°39'S, 103°52'E), which is an 8000 ha typical industrial plantation. The landscape was flat in the study area. The palms were planted in 2005 at a density of 149 palms ha^{-1} in a triangular design (8.8 m distance between palms) and usually received, after reaching maturity in 3 years, 149 kg urea ha^{-1} yr^{-1} (70 kg N ha^{-1} yr^{-1}) in either one or two applications. Agrochemicals were used to control pests and weeds within the harvesting rows where the soil was maintained free of vegetation. In the non-harvesting rows, fronds were left to decompose and the soil was covered by ferns. The average peat depth in the plots was 5.75 ± 1.5 m. The drainage system was dug when the land was deforested in 2004 and the water table had been maintained between −50 and −100 cm since 2005. Drainage in the plot consisted of a 1.5 m deep secondary drainage canal perpendicular to the palm rows, and 75 cm deep tertiary canals parallel to the palm rows with one canal every 8 rows. The soil was classified as a Hemic Histosol (Dystric, Drainic) (IUSS-Working-Group-WRB, 2006).

2.2. Experimental design

A longer-term experiment monitoring Rs and Rh was established in September 2011. The emissions after fertilizer applications were measured in March 2012 and February 2013, six and seventeen months after the start of longer-term monitoring.

The experimental design consisted of two sections of about 500 m^2, one fertilized and the other one non-fertilized (Fig. 2). The two sections, located in an area assigned by the plantation administration, were about 30 m apart along the same harvesting row to ensure no fertilizer contamination from the fertilized section to the non-fertilized one. Within each section ten 2.5 × 2.5 m plots were delineated; half of them were trenched (root exclusion technique) while the other half were not. The non-trenched plots were used for measuring total soil respiration (Rs) while the trenched plots where root respiration was excluded, were used to measure heterotrophic soil respiration (Rh). In the following text Rs and Rh correspond to the CO_2 flux measured in the non-trenched and trenched treatments, respectively. Each plot was associated with one oil palm. The trenched and non-trenched plots were paired along the non-harvesting row and located about 8 m apart (Fig. 2). In each trenched and non-trenched plot two soil respiration collars were installed, one close to the palm tree (close-to-tree) at a 1 m distance from the trunk and the other one further from the trunk (far-from-tree) at a distance of 2.5 m (Fig. 2). The far from tree collars were outside canopy and rooting zone. Previous root and CO_2 measurement studies made on the same plots showed that 1 and 2.5 m distances from the palm trunk were representative of the dense and low root areas at the plantation scale (Farmer, 2013). In the fertilized section, urea was applied to all collars located close to the palms in both trenched and non-trenched plots. In the non-fertilized section, no fertilizer was applied. The effect of N fertilizer application on Rs and Rh was evaluated by comparing the fertilized—non-trenched to the non-fertilized—non-trenched treatments and the fertilized—trenched to the non-fertilized—trenched treatments, respectively.

To exclude the roots in the trenched plots, trenches of 2.5 m × 2.5 m × 1 m deep were dug using a chainsaw. The trenches were located at about 25 cm from their corresponding palm trunk. The 0.5 m wide inner side of the trenches was lined with five layers of construction plastic and the trenches were backfilled. Therefore the area inside the trenches where the collars were positioned was 4 m^2. A potential dead root decomposition effect was minimal since the first fertilizer application event took place six months after trenching. Several trenching studies made on none-tropical