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Seasonal differences in soil respiration and methane uptake in rubber plantation and rainforest

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A B S T R A C T

Rubber plantations expanded remarkably in South-East Asia, while the impact of this land use change on soil carbon dynamics and greenhouse gases emissions has not been sufficiently understood. We measured monthly soil CO_2 fluxes during one year as well as CH_4 fluxes during the rainy season in secondary rainforest, 9 and 22 year-old rubber monoculture and 22-year-old rubber-tea intercropping in Xishuangbanna, Southwest China. Our aim was to assess the impact of the land use change on soil carbon fluxes and quantify the factors determining the difference in the carbon fluxes. A linear mixed effect model was used in studying the soil temperature and moisture variation and temperature sensitivity (Q_{10}) of soil respiration.

The temporal pattern of soil respiration distinctly differed between sites during the rainy season: rainforest maintained a high soil respiration rate, while soil respiration became suppressed (by up to 69%) during the most moist period in rubber plantations. Rainforest soils thus emitted the highest amount of CO_2 with an annual cumulative flux of 8.48 ± 0.71 Mg C ha^{-1} yr^{-1}, compared to 6.75 ± 0.79, 5.98 ± 0.42 and 5.09 ± 0.47 Mg C ha^{-1} yr^{-1} for mature rubber, rubber-tea intercropping, and young rubber, respectively. Additionally, the soil CH_4 uptake was stronger in rainforest than in rubber plantations during the wet period. Soil temperature was the main factor explaining the overall seasonal variation of soil respiration. Adding a quadratic soil moisture term into the model accounted for moisture effects, identified moisture tipping points, and improved temperature sensitivity assessment when high soil moisture suppressed soil respiration under rubber. Temperature sensitivity of soil respiration was higher for rainforest soil compared to rubber plantations, Q_{10} values were 3.1 for rainforest and 1.7, 2.2 and 2.4 for mature rubber, rubber-tea intercropping and young rubber respectively.

Converting rainforest to rubber plantations tended to reduce soil CO_2 emissions and weakened CH_4 uptake especially during the very wet period. The altered condition of soil aeration under converted land appears to have a pronounced impact on processes of carbon fluxes from the soil and thus mitigates the positive feedback of climate change given the large area of cultivated rubber.

1. Introduction

Soil respiration, emitting greenhouse gas CO_2 into the atmosphere from roots, microbes, and soil fauna, is the second largest terrestrial carbon flux between the ecosystem and atmosphere (Reichstein et al., 2003). Estimates of the annual global soil respiration in 2008 were 98 ± 12 Pg C (Bond-Lamberty and Thomson, 2010), which was around 10 times that of emissions from fossil fuel combustion and industry with a current CO_2 emission rate of 9.8 ± 0.5 Pg C yr^{-1} (Le Quéré et al., 2015). Methane (CH_4), with 28–32 times the CO_2 global warming potential (GWP) in a 100-year time horizon (Myhre et al., 2013; Neubauer and Megonigal, 2015) is responsible for about 18% of human-induced radiative forcing. The estimated global emissions of anthropogenic CH_4 was 335 (273–409) Tg CH_4 yr^{-1} during 2000–2009, while the soil consumed 32 (26–42) Tg CH_4 yr^{-1} during the same period (Ciais et al., 2013). Small changes in the soil carbon flux pathways

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thus may have a profound impact on the carbon budget and feedback to climate change.

Land use change is the second largest source of human induced greenhouse gas emissions, mainly from deforestation and degradation of forests in the tropics and subtropics (Don et al., 2011). The carbon loss through deforestation and degradation of rainforests was estimated at 0.8 Pg to 1.0 Pg C yr^{-1} in the last decades (Baccini et al., 2012; Harris et al., 2012). Southeast Asia is one of the global deforestation hot spots where rubber (*Hevea brasiliensis*) and oil palm (*Elaeis guineensis*) plantations expanded substantially in the past several decades, at the expense of natural forests and shifting agriculture (Kou et al., 2015; Li and Fox, 2012; Wicke et al., 2011). Though 72% of current rubber plantation areas are already located in environmentally marginal zones with low yield (Ahrends et al., 2015), this land use conversion trend is likely to continue with projected increasing demand of natural rubber and oil palm (Warren-Thomas et al., 2015). Xishuangbanna prefecture, Southwestern China is a typical case for rapid rubber expansion in the upper Mekong. Since the first rubber establishment on state farms in the 1950s, the area of rubber plantations has increased from 4.5% of total land area in 1992 to 8.0% in 2002, 22.2% in 2010, and reached 24.2% in 2014 (Chen et al., 2016; Li et al., 2007; Wu et al., 2001; Xu et al., 2014).

Impacts of converting forests into rubber plantations generally leads to carbon losses from decreased living biomass carbon and soil organic carbon (Blagodatsky et al., 2016; de Blécourt et al., 2013; Guillaume et al., 2015; Li et al., 2008). Measuring soil respiration, especially with determination of respiration components, helps understanding how land use change affects the underlying processes and the carbon budgets (Sheng et al., 2010). The impact of land use change on soil respiration and CH_4 exchange has often been assessed by comparing soil carbon fluxes under different land uses (space substitutes time) (Hassler et al., 2015; Sheng et al., 2010). There are some studies measured soil respiration in either rubber plantations or rainforest in the region, but only a few considered both land uses using the same methodology and measuring devices (Fang and Sha, 2006; Hassler et al., 2015; Ishizuka et al., 2002; Lu et al., 2009; Werner et al., 2006). Due to differences in methodology, considerable spatial heterogeneity, strong seasonality and lacking of long term measurements, previous studies showed large discrepancies in soil greenhouse gas (GHG) fluxes under forest and converted plantations.

Regardless of the considerable amount of literature describing the controlling factors of soil respiration, the impact of land use change on soil CO_2 flux has not been well understood particularly in tropical ecosystems (Adachi et al., 2006; Sheng et al., 2010; Veldkamp et al., 2008). Soil CO_2 flux is regulated by factors such as photosynthetic activity or vegetation productivity (Tang et al., 2005), soil properties including substrate quantity and quality (Wan and Luo, 2003), soil temperature and water status (Bolstad and Vose, 2005; Geng et al., 2012; Suseela et al., 2012; Werner et al., 2006), while only soil temperature was extensively used as controlling factor to explain the seasonal variation of soil respiration (Jia et al., 2013; Lloyd and Taylor, 1994; Raich and Schlesinger, 1992; Wood et al., 2013; Zhou et al., 2013). Their relationship is often assessed with temperature sensitivity, expressed as Q_{10}, a parameter reflecting the respiration rate response to a temperature increase of 10 °C. The Lloyd and Taylor equation (Lloyd and Taylor, 1994) was frequently used in soil respiration studies because of the unbiased estimation across a wide range of ecosystems. Considering the joint effect of soil moisture and temperature on respiration rate, more recent studies are trying to separate these two effects, either by building mathematical functions based on field measurements (Ali et al., 2015; Demyan et al., 2016; Qi and Xu, 2001; Tan et al., 2013 Qi and Xu, 2001; Tan et al., 2013), or manipulating temperature and moisture in controlled experiments (Jiang et al., 2013; Zimmermann et al., 2015). To our knowledge, no studies on soil respiration under rubber investigated its temperature sensitivity with separating the moisture effect. Therefore, for the SE Asia region, like in Xishuangbanna, China where both temperature and moisture are either high or low during wet versus dry period, analyzing the temperature sensitivity under two land uses helps understanding the response of soil CO_2 flux to land use and climate change.

Upland soils are normally a net sink for atmospheric CH_4, but current understanding of CH_4 fluxes in upland systems especially in tropical forests is incomplete (Megonigal and Guenther, 2008). Studies on the combined effect of land use change and rubber cultivation on soil CH_4 flux are scarce, compared to soil respiration studies. It is known that the production or consumption of CH_4 depends on the soil water content, soil gas diffusivity and oxygen availability in the soil profile. Whether a soil acts as CH_4 source or sink depends on the balance between methane production and oxidation (Megonigal and Guenther, 2008; Smith et al., 2003; Wood and Silver, 2012). Ammonium fertilizers in cultivated soils can serve as competitive inhibitors for CH_4 oxidation decreasing the methane uptake (Nesbit and Breitenbeck, 1992). Compared to tropical forests, converted plantations showed a reduced CH_4 uptake by soil to a different extent (Hassler et al., 2015; Verchot et al., 2000), being sometimes comparable with uptake in forest (Ishizuka et al., 2005).

Therefore, this study focused on (1) the temporal dynamics of soil CO_2 fluxes under rainforest and rubber plantations, and CH_4 fluxes estimated during the wet period of the rainy season when the largest differences in CO_2 flux between rainforest and rubber plantations was observed; (2) separating the soil temperature and moisture impact on soil respiration using a linear mixed model; and (3) reviewing of available soil CO_2 and CH_4 fluxes data obtained in rubber plantations and rainforests in Southeast Asia. By comparing both soil CO_2 and CH_4 fluxes under different land uses and corresponding relationships with controlling factors, we aimed to assess the impact of land use change from rainforest to rubber plantation on soil gaseous carbon fluxes.

2. Methods

2.1. Study sites

The study was carried out in Xishuangbanna prefecture, Yunnan province, SW China. Xishuangbanna is a Dai Ethnic nationality autonomous prefecture, located between 99.94°E – 101.84°E and 21.14°N – 22.59°N, known as the Upper Mekong region (Fig. 1). The prevailing monsoon climate is characterized by strong seasonality, i.e. the tropical southwest monsoon from the Indian Ocean delivers about 80% of annual rainfall from May to October (rainy season), whereas dry, cold air from subtropical regions in the east dominates from November till April (dry season) (Cao et al., 2006). The average annual temperature was 22.26 ± 0.55 °C, and average annual precipitation was 1166 ± 165 mm, of which 987 mm (85%) occurred during May to October (data are from the Jinghong meteorological station, located in 50 km from study sites at altitude 582 m, averaged from 1957 to 2012). Laterite soil, lateritic red soil, and limestone derived soil are the three main soil types in Xishuangbanna, and natural vegetation is dominated by five main types of tropical rainforest according to the formation, community structure and habitat (Zhu, 2006).

We chose four nearby sites along the Luosuo river, a tributary of the Mekong river to conduct soil carbon flux measurements, including tropical rainforest (RF), 22-year-old rubber monoculture (MR) and 22-year-old rubber-tea intercropping (RT) within Xishuangbanna Tropical Botanical Garden, and 9-year-old rubber monoculture (YR) near Menglun town. The rainforest site was