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Drivers of difference in CO_2 and CH_4 emissions between rubber plantation and tropical rainforest soils

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ABSTRACT

With large area of primary tropical rainforest converted into rubber (*Hevea brasiliensis*) plantation in Southeast Asia, it is necessary to examine the change in soil CO_2 and CH_4 emissions, and their underlying drivers in tropical rainforest (TRF) and rubber plantation. In TRF and RP in Xishuangbanna Southwest China, we measured the soil CO_2 , CH_4 , temperature, and water content once each week from 2003 to 2008, and twice weeks in 2013 and 2014. Additionally, the concentrations of soil carbon (C) and nitrogen (N) fractions from 2013 to 2014 were observed. Inputs of litter and live, dead, decomposed fine roots dynamics were also included. TRF transplanted to RP did not change significantly the annual soil CO_2 emissions (TRF, 359 ± 91 and RP 352 ± 41 mg CO_2 m^{-2} h^{-1}) but decreased soil CH_4 uptake significantly (TRF, −0.11 ± 0.18 mg CH_4 m^{-2} h^{-1}) RP, −0.020 ± 0.087 mg CH_4 m^{-2} h^{-1}). The most important influence on soil CO_2 and CH_4 emissions in the RP was the leaf area index and soil water content, respectively, whereas the soil water content, soil temperature, and dead fine roots were the most important factors in the TRF. Variations in the soil CO_2 and CH_4 caused by land-use transition were individually explained by soil temperature and fine root growth and decomposition, respectively. The results show that land-use change varied the soil CH_4 and CO_2 emission dynamics and drivers by the variation of soil environmental and plant's factors.

1. Introduction

Hevea brasiliensis is the major source of natural rubber for the annual production of more than one billion car, truck, and aircraft tires worldwide (Li and Fox, 2012). The rapid expansion in this industry is driving land use conversion from tropical rainforests to rubber plantations in Southeast Asia, where 97% of the world's natural rubber is produced (FAO, 2013). Rubber production in Southeast Asia increased from just over 300,000 tons in 1961 to more than 5 million tons in 2011 (FAO, 2013), and this trend is likely to be enhanced as the rubber

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demands keep increasing. While rubber plantations in China, Vietnam, and Thailand are mainly small-holdings, large-scale economic enterprises are dominant in Cambodia, Laos, Indonesia, and Myanmar (Fox and Castella, 2013; Fox et al., 2014). The conversion of rainforests to rubber plantations has many environmental consequences, e.g., decreases in water reserves (Ziegler et al., 2009), exacerbation of seasonal drought (Tan et al., 2011), disrupted local carbon budgets (Song et al., 2014), increases in water-induced soil erosion (Chen et al., 2017), declines in soil productivities and ecosystem biodiversity (Ahrends et al., 2015; Warren-Thomas et al., 2015). The current tendency for rubber plantations to expand may therefore threaten biodiversity and the livelihoods of local inhabitants and may result in ecosystem instability and drought (Song et al., 2017).

The emission of carbon, in the forms of carbon dioxide (CO_2) and methane (CH_4) as greenhouse gases (GHG), from the soil into the atmosphere is one of the major pathways of soil carbon loss. Measuring CO_2 and CH_4 emissions from rubber plantations provides estimates of carbon loss potential due to shifts in soil conditions and plant types as the lands changed from primary tropical forests. Various studies have compared greenhouse gas (GHG) emissions from rubber plantation soils to those from primary forest soils over a short-term (<3 years) (Fang and Sha, 2006; Lang et al., 2017; Yan et al., 2008; Lu et al., 2009; Zhou et al., 2008; Sha et al., 2005; Zhou et al., 2016a). For example, Lang et al. (2017) found in a 2-year study that rubber plantation soils emitted less CO_2 than tropical rainforest soils, and, at the same time, they also consumed less CH_4 which differ to wetland and paddy soil as CH_4 is the prevailing GHGs (Dalal and Allen, 2008; Daniel et al., 2019). Similar results were also reported in the study of Hassler et al (2015). These studies were mostly conducted over a short-term after the land conversion (< 3 years). Over the long-term, plantation characteristics, such as floor diversity, landscape, the understory/soil environment, forest microclimate may vary, and, thus, affect the dynamics of CO_2 and CH_4 emissions. However, studies after >10 years of land conversion are rare. And therefore, there is a need to quantify and assess soil CO_2 and CH_4 emissions and the underlying drivers over the long-term after tropical rainforest is converted to rubber plantation.

Variations in soil CO_2 and CH_4 are influenced by soil temperature, soil moisture (Daniel et al., 2019; Lang et al., 2017; Werner et al., 2006), plant phenology, fine root biomass (Dalal and Allen, 2008), litter inputs (Dou et al., 2016; Gao et al., 2018), pH and microbial dynamics (Lammel et al., 2015; Kooch et al., 2016). In addition, Hassler et al. (2015) found that CH_4 uptake was negatively correlated with net N mineralization rate and soil mineral N content, which may suggest that the soil CH_4 uptake may be enhanced in N-limited rubber plantations as converted from primary forests.

As a tropical rainforest is converted to a rubber plantation, corresponding changes can occur to characteristics of soil, plants, and microbes (Chan et al., 2008; Gao et al., 2018; Zhou et al., 2016a). Consequently, the main factors that drive soil CH_4 and CO_2 emissions may also be altered. At the same time, different management plan and stand age also influences the soil CO_2 emissions of rubber plantations as indicated by studies carried in different age rubber plantations (Cheng et al., 2007; Wu et al., 2014). Specifically, the length of time over which the rubber plantation has been managed may affect the physical and chemical characteristics of the soil and plant growth dynamics, while the age of the plantation may influence CH_4 fluxes. Therefore, we need to understand how one plantation site affects soil CO_2 and CH_4 fluxes by comparing to a local primary forest and track how the fluxes change over time in both the rubber plantation and the primary forest.

Recent meta-analyses on effects of land use change on GHG emissions (Harris et al., 2015; Shrestha et al., 2014) highlighted soil temperature as the most important drivers of GHG emissions caused by land use change. As most environmental factors are collinearly or unlinearly correlated with each other, there are limited reports on multiple factors (characters of soil physical and chemical, LAI, litter and fine roots etc.) influence on soil CO_2 and CH_4 fluxes from different land uses and on mechanisms that cause variations in soil CO_2 and CH_4 fluxes with a change in land use (Gütlein et al. 2017; Wong et al. 2020; Zona et al. 2013). Therefore, it is also necessary to determine how multiple factors contribute to soil CO_2 and CH_4 fluxes from different land use types, particularly those under the conversion to agroforestry rubber plantations in tropical regions. Until now, most studies have focused on how land use affects emission fluxes and mechanisms that control the emissions. However, controls on variations in GHG emissions between tropical rainforest and rubber plantations, and between other changes in land use or land cover, remain unclear. It is therefore important to determine how the fluxes and dynamics of soil CO_2 and CH_4 fluxes differ as well as the main factors that drive the differences in emissions between mature rubber plantations and tropical rainforests.

Given that increasing land areas are being converted to rubber plantations in Southeast Asia, it is important to quantify changes in GHG emissions and the underlying drivers that are associated with the land change. In this study, we have measured CO_2 and CH_4 fluxes from a rubber plantation which has been actively managed for over 10 years. At the same time, CO_2 and CH_4 fluxes were measured from a local primary tropical rain forest. By comparing the fluxes from the two sites, we aimed to answer 1) how soil CO_2 and CH_4 emissions change after the land was converted from tropical rainforests to rubber plantations, and 2) are the factors that control CO_2 and CH_4 fluxes different between the two sites? The results would improve our understanding of the influences of land use change on local soil carbon inventory as well as climate change.

2. Materials and methods

2.1. Study site

The studied tropical rainforest (21°56′N, 101°16′E, elevation 720 m a.s.l.) and the managed rubber plantation (21°55′30″N, 101°15′59″E; elevation 580 m a.s.l.) are located in Xishuangbanna, Yunnan Province, Southwest China. In Xishuangbanna, the long-term annual average temperature is 21.7°C and the mean annual precipitation is 1557 mm (Wang & Zhang, 2005). The climate is characterized by a rainy season from May to October with 80% of the precipitation and a dry season from November to March. *Terminalia myriocarpa* and *Pometia tomentosa* are the main species (Cao et al., 1996). The slope angle is between 12° and 18°, and the experimental site soil is mainly composed of oxisol that formed from Cretaceous yellow sandstone. The physical and chemical characteristics of the soil are listed in Table 2.

For the studied rubber plantation, it was converted from a tropical rainforest in 1990 and rubber (*Hevea brasiliensis*) seedlings were planted in May 1993. Trees were planted 2 m apart in rows and either 3 or 19 m apart between rows, resulting in a density of 495 trees per hectare. The rubber plantation is on a 15°slope and is covered with a thick layer of oxisol (see Table 2 for details) (Zhou et al., 2016a). The canopy height of the rubber plantation ranged from 20 to 30 m in 2016. The main rubber-tapping period lasts from May to November each year. The plantation was not irrigated, but fertilizer was applied twice each year in March/April and August/September. In line with local farming practices, 1 kg of mineral fertilizer (Hubei Sanning Chemical, China), containing 15% N as $(NH_2)_2CO$, 15% P as $NH_4H_2PO_4$ and 15% K as KCl in total, was applied to each rubber tree each year, amounting to a rate of 75 kg N ha^{-1} yr^{-1}.

2.2. Experimental design

We established 6 GHG sampling plots (10 m × 10 m) in the tropical rainforest that were randomly selected and located more than 100 m apart to avoid disturbance during sampling. Taking into account fertilizer effect, we also monitored the soil CO_2 and CH_4 fluxes at 14 sites in the rubber plantation, at 4 sites on terraces, 6 sites in the fertilizer trenches (3 during the dry season and 3 during the rainy season), 2 sites on narrow slopes, and 2 sites on wide slopes.

2.3. Litter production

The litter produced in the rubber plantation and the rainforest was collected in 40 circular litter traps made of nylon (1.0 mm mesh, 0.25 m^2) (Gao et al., 2018). The litter in the traps was collected each month on days of CO_2 and CH_4 observations.

2.4. Fine roots

We established three 10 × 10 m plots at each study site, each of which contained ten subplots as replicates. Soil was sampled to a depth of 20 cm every 3 months at each site using a soil corer with a diameter of 8 cm. Samples were sieved (2 mm mesh) to capture fine roots (defined as having a diameter of < 2 mm). The fine roots were classified as live or dead, and were sorted according to colour, elasticity, and shape. They were then dried in an oven (80°C) and weighed to estimate the fine root biomass in a unit area (g m^{-2}) as follows:

$$\text{Fine root biomass} = \text{Fine root biomass of soil core} \times \frac{10^5}{\pi \times \left(\frac{d}{2}\right)^2} \quad (1)$$

where d is the inner diameter (cm) of the soil corer (Fang and Sha, 2005).

2.5. Fine root growth

In each plot, six parallel sampling lines were established in both sites and, along the line, six sample points were defined with a fixed distance between each other. At each sampling point, a 10-cm diameter hole (depth = 5 cm) was made with a soil corer. A nylon bag filled with soil (without roots) was placed into each hole at the beginning of the experiment and then collected afterward every two months. The fine root growth was calculated from the biomass of living roots extracted from the bags (Fang and Sha, 2005).

2.6. Fine root decomposition

Fine roots were first collected from both the study sites and then washed, oven-dried at 80°C, and cut into 5 cm sections. We then placed these fine roots into 15 × 20 cm nylon bags (36 bags in total at per site) with 5.0 g roots each and buried in the soil at a 10 cm depth at the corresponding site. Six of the incubated fine root bags were sampled randomly every two months. The decomposed fine root biomass was calculated as the amount of fine root biomass lost between two sampling occasions.

2.7. Measurement of CO_2 and CH_4 effluxes

Static opaque chamber tops (Zhou et al., 2016a; Gao et al., 2018) were used to measure the GHG effluxes at weekly intervals in the tropical rainforest from 2003 to 2008 and from 2013 to 2014, and in the rubber plantation from 2004 to 2008 and from 2012 to 2014. A chamber base collar made of PVC casing that covered an area of 0.12 m^2 was inserted to a soil depth of 0.10 m at the centre of each plot. The chamber base collars were kept in place throughout the entire measurement period. Open-top-chambers, each with a base area of 0.12 m^2 and a height of 0.2 m, were fixed onto the base collars. The chambers were closed and sealed with a PVC lid during flux measurements which were conducted between 09:00 and 11:00 am. Gas samples were collected with 100-ml gas-tight syringes 0, 15, 30, 45, and 60 min after the chambers were closed. The CH_4 and CO_2 concentrations in the gas samples were determined within 24 h after the sample collection using a gas chromatograph (Agilent 4890D, Agilent Technologies, Palo Alto, California, USA) equipped with an electron capture detector. For details of the CO_2 and CH_4 analysis method, see Zheng et al. (2008). We used the method described by Zhou et al. (2016a) and Gao et al. (2018) to calculate the efflux of soil CO_2 and CH_4:

$$F = \rho \frac{V}{A} \frac{P}{P_0} \frac{T_0}{T} \frac{dC_t}{dt} \quad (2)$$

where F is the observed gas efflux (μg m^{-2} h^{-1}); ρ is the observed gas density at the test temperature (μg m^{-3}); V is the volume of the chamber (m^3); A is the area of ground covered by the chamber (m^2); T and P are the air temperature (°C) and atmospheric pressure (hPa) in the field at the time of sampling, respectively; T_0 and P_0 are the air temperature and atmospheric pressure under standard conditions, respectively (T_0 = 25°C, P_0 = 1013 hPa); and C_t is the observed gas concentration of the mixed volume ratio of gases in the chamber at time t (10^{-6}).

2.8. Measurement of soil physico-chemical properties

During the gas sampling, the corresponding soil volumetric water content (0–12 cm soil depth) was determined with a time-domain reflectometry (TDR100, Campbell Scientific, USA) in the soil at the gas sampling plot. At the same time, soil (0 – 5 cm) and air temperatures were recorded with a needle thermometer.

Throughout the study period, soil samples (~200 g) were collected at a depth of 0 – 20 cm each month from a location close to the static chambers using a stainless-steel auger (3 cm in diameter). The soils were immediately passed through a 2 - mm sieve to remove roots, gravel, and stones in the lab. The soil samples were mixed with a 2.0 mol L^{-1} KCL solution at a soil: water ratio of 1:10 and shaken for 1 h at 160 rpm. The soil suspension was then filtered and the ammonia–nitrogen (NH_4^+–N) and nitrate–nitrogen (NO_3^-–N) concentrations were determined with a continuous flow auto-analyser (AutoAnalyzer 3; Germany). A portion of each of the treated soil samples was combined to make a composite sample for analyses of microbial biomass nitrogen (MBN), microbial biomass carbon (MBC), dissolved organic carbon (DOC), and total dissolved nitrogen (TDN). Soil MBC and MBN were determined with the chloroform fumigation–extraction method (Wu et al., 1990). Four replicate samples of each treated soil (7.0 g) were fumigated with ethanol-free chloroform for 24 h at 25°C in a sealed incubator in the dark to completely removed chloroform. At the same time, three samples of each treated soil (7.0 g) were left unfumigated. Both the fumigated and unfumigated samples were mixed with 35 ml of freshly prepared 0.05 M K_2SO_4 (soil: water ratio of 1:5), capped, and shaken at 300 rpm for 1 h. The suspensions were then centrifuged for 10 min at 5000 g and the supernatants were filtered through 0.45-μm nitrocellulose membrane filters (Pall Life Science Company, Beijing, China). The dissolved organic carbon (DOC) and dissolved nitrogen (DN) concentrations of the filtered samples were determined using Pt-catalysed high-temperature combustion (680°C) and a total organic carbon/total nitrogen analyser (LiquiTOC II, Elementar Analyzer System, Germany). The concentrations of DOC and TDN on the unfumigated filters were determined, and MBC and MBN were taken as the differences in the DOC and TDN concentrations between the unfumigated and fumigated filters, respectively. Mineral N was the sum of NH_4^+–N and NO_3^-–N, and dissolved organic nitrogen (DON) was the difference between TDN and mineral N. All the soil analyses were completed within 48 hours after the soil sampling.

2.9. Calculations

As the GHG fluxes measured at the rubber plantation covered different treatments and terrains, the mean GHG fluxes was weighed by the areas of terrence, fertilizer trench and slope as follows:

$$F = \frac{\sum_1^i (a_i \times F_i)}{\sum_1^i a_i} \tag{3}$$

where F is the flux of CO_2 (mg m^{-2} h^{-1}) or CH_4 (μg m^{-2} h^{-1}), a_i is the treatment area (ha), F_i is the CO_2 or CH_4 flux under a specific treatment, and i is the treatment.

Compared to the tropical rain forest, the changes at the rubber plantation in all studied variables, including CO_2 and CH_4 effluxes, soil temperature, soil water content, NO_3^-–N, NH_4^+–N, mineral N, DON, MBN, DOC, MBC, litter biomass, leaf area index (LAI), fine root growth, live fine roots, dead fine roots, and decomposed fine roots were calculated as follows:

$$Change\ \% = \frac{F_{Rp} - F_{TRF}}{F_{TRF}} \times 100\% \tag{4}$$

where F_{RP} and F_{TRF} indicate the parameter measured from the rubber plantation and tropical rainforest, respectively.

2.10. Statistical analyses

Mixed effect linear models was used to detect differences between the rubber plantation and the tropical rainforest for variables including monthly soil CO_2 and CH_4 effluxes, soil temperature, soil water content, NO_3^-–N, NH_4^+–N, mineral N, DON, MBN, DOC, MBC, litter biomass, LAI, fine root growth, live fine roots, dead fine roots, and decomposed fine roots. Months were included in the models as a random effect. Pearson correlation analysis was used to determine the relationships between the monthly CO_2 or CH_4 efflux and environmental variables including soil temperature, soil water content, NO_3^-–N, NH_4^+–N, mineral N, DON, MBN, DOC, MBC, litter biomass, LAI, fine root growth, live fine roots, dead fine roots and decomposed fine roots. Stepwise linear regression analysis was used to explore the controls on the monthly CO_2 and CH_4 effluxes. The Kolmogorov–Smirnov test was used for normality of all the data. Data are presented as the mean ± standard deviation (SD). SPSS 16.0 statistical software was used for data analysis.

3. Results

3.1. Effects of land use change on environmental parameters

Both soil water content (0 – 10 cm) and temperatures (0 – 5 cm) were higher in the rainy season than in the dry season in tropical rainforest.

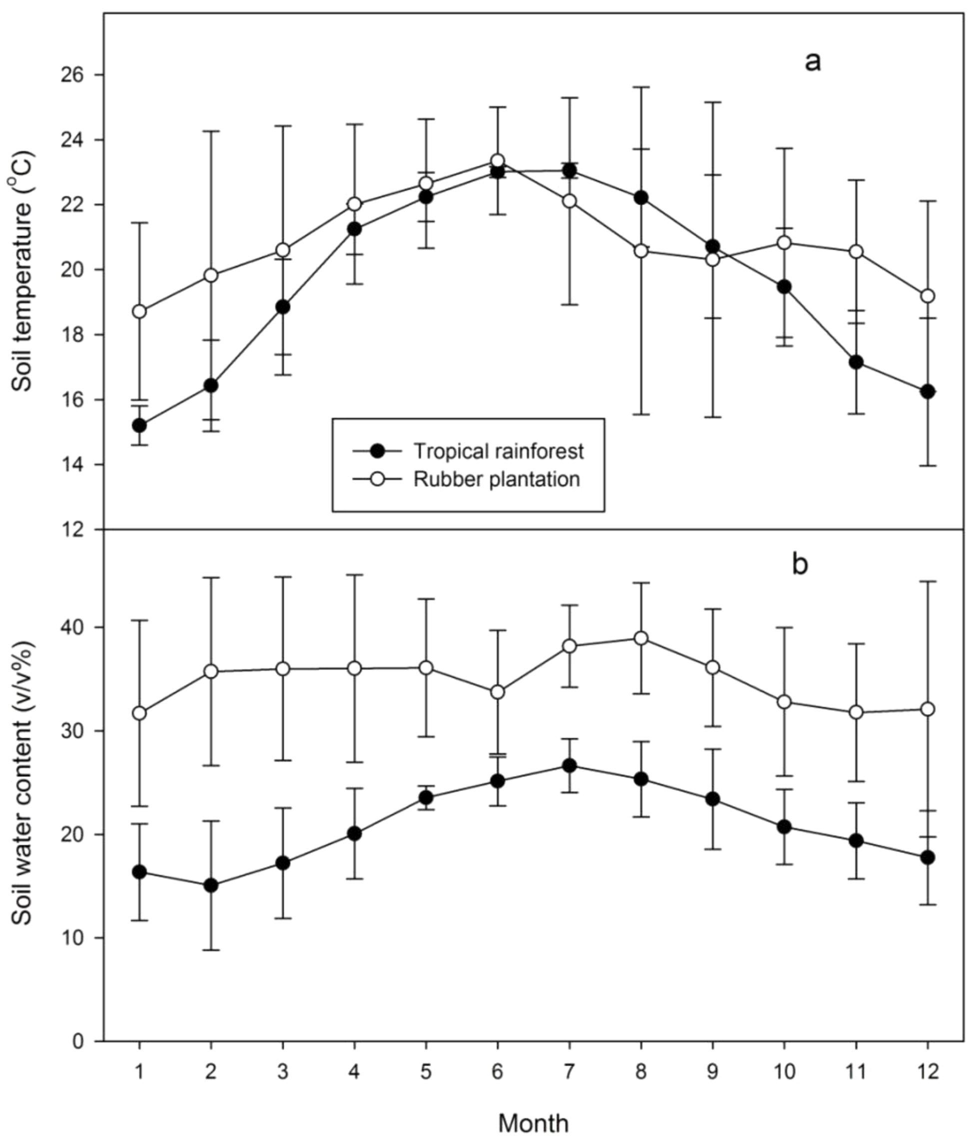

Fig. 1. Soil temperature at 5 cm depth (a) and soil water content (V/V%) at 0–10 cm depth (b) in a tropical rainforest (black circles) and a rubber plantation (open circles) in Xishuangbanna. Monthly mean values (± SD) over 2003-2008 and 2012-2014 are presented.

Table 1
Summary of the analysis of variance (ANOVA) for the mixed effects models for soil C and N fractions and the biomass of litter and fine roots in a tropical rainforest (TRF) and a rubber plantation (RP) in Xishuangbanna.

Parameters	TRF	RP	F	p	Parameters	TRF	RP	F	p
Dissolved organic carbon (mg C kg^{-1})	99.7 ± 27.8	474.9 ± 29.0	87.2	< 0.001	Litter biomass (kg ha^{-1})	801 ± 119	784 ± 119	0.01	0.906
Microbial biomass carbon (mg C kg^{-1})	1963 ± 120	1708 ± 125	2.4	0.147	Leaf area index(m^2 m^{-2})	6.1 ± 0.2	3.1 ± 0.2	254.8	< 0.001
Dissolved nitrogen (mgN kg^{-1})	46.4 ± 3.6	25.8 ± 3.8	16.6	0.002	Growth of fine root (kg ha^{-1})	334 ± 79.4	122 ± 79.4	3.6	0.072
Microbial biomass nitrogen (mg N kg^{-1})	241.2 ± 27.1	66.3 ± 28.3	22.0	0.001	Living fine root (kg ha^{-1})	3697 ± 215	1462 ± 215	54.1	< 0.001
NH_4^+-N (mg N kg^{-1})	4.9 ± 0.6	10.2 ± 0.6	43.8	< 0.001	Dead fine root (kg ha^{-1})	483 ± 44.3	238 ± 44.3	15.2	0.001
NO_3^--N (mg N kg^{-1})	5.4 ± 0.9	5.3 ± 0.9	0.01	0.923	Total fine root (kg ha^{-1})	4180 ± 203	1700 ± 203	74.7	< 0.001
Dissolved organic nitrogen (mg N kg^{-1})	36.1 ± 3.5	11.4 ± 3.6	24.7	< 0.001	Decomposed fine root (kg ha^{-1})	49.5 ± 9.6	17.5 ± 9.6	6.7	0.025

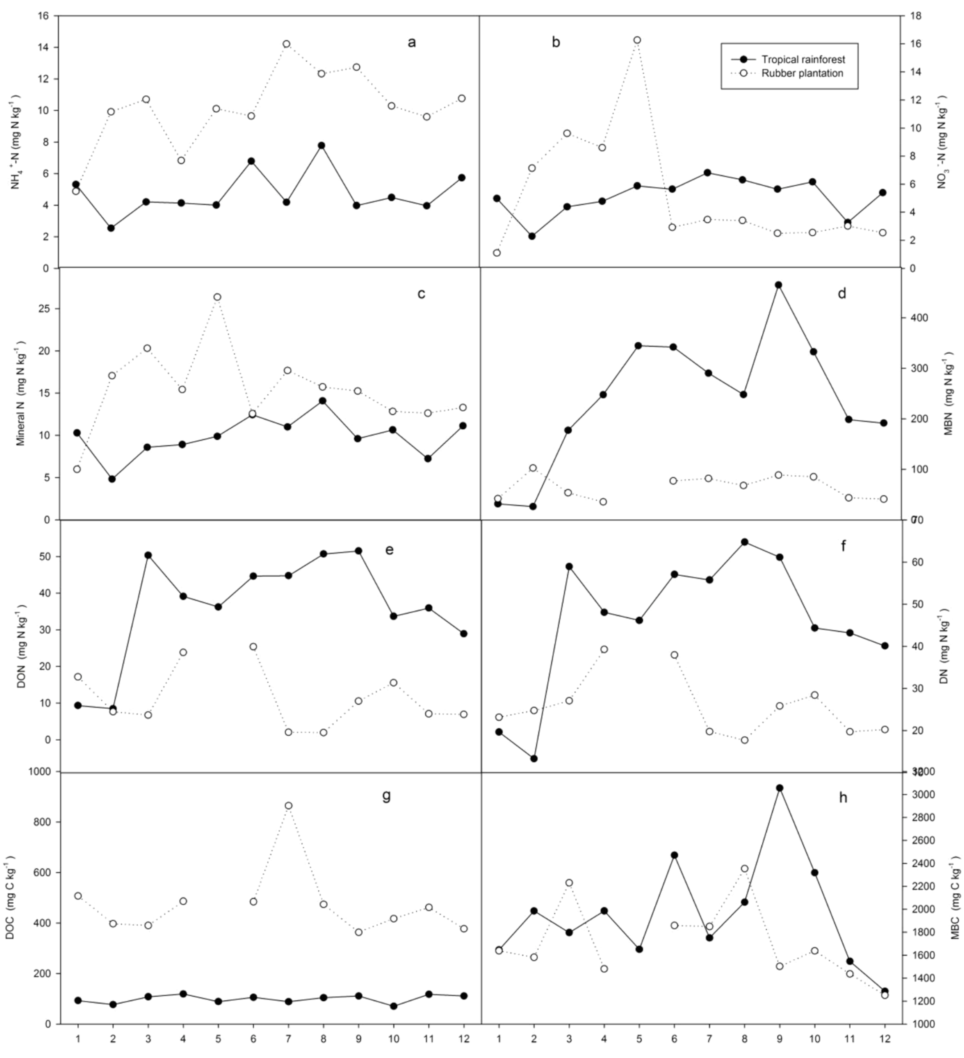

Fig. 2. Soil NH_4^+–N (a), NO_3^-–N (b), mineral N (c), MBN (d), DON (e), DN (f), DOC (g) and MBC (h) in a tropical rainforest (black circles) and a rubber plantation (open circles) in Xishuangbanna. Monthly mean values over 2003-2008 and 2012-2014 are presented.

However soil temperature and soil water content was bimodal dynamic with the highest in June and August respectively in rubber plantation (Fig. 1). The annual average soil water content (RP: 34.9 ± 2.5%, TRF: 20.9 ± 3.9%, $F = 220.6$, $p < 0.001$) and soil temperature (RP: 20.9 ± 1.4°C, TRF: 19.6 ± 2.8°C, $F = 5.8$, $p = 0.035$) were significantly higher in the rubber plantation than in the tropical rainforest, and the differences were greater in the dry season than in the rainy season (Fig. 1 a, b).

The concentrations of DOC, NH_4^+–N, and mineral N were higher, and those of MBC, DN, MBN, and DON were lower, in the rubber plantation than in the rainforest (Table 1). The differences between tropical rainforest and rubber plantation in the soil C and N fractions, except DOC and DON, showed different seasonal patterns, which reached maximum values in July (Fig. 2). Overall, the soil DOC, MBC, DN, MBN, NH_4^+–N, NO_3^-–N, Mineral N, and DON showed strong fluctuations across the seasons in the rubber plantation but were relatively stable in the rainforest (Fig. 2).

The litter input to the soil was higher in the rainy season than in the dry season and in the tropical rainforest than in the rubber plantation,

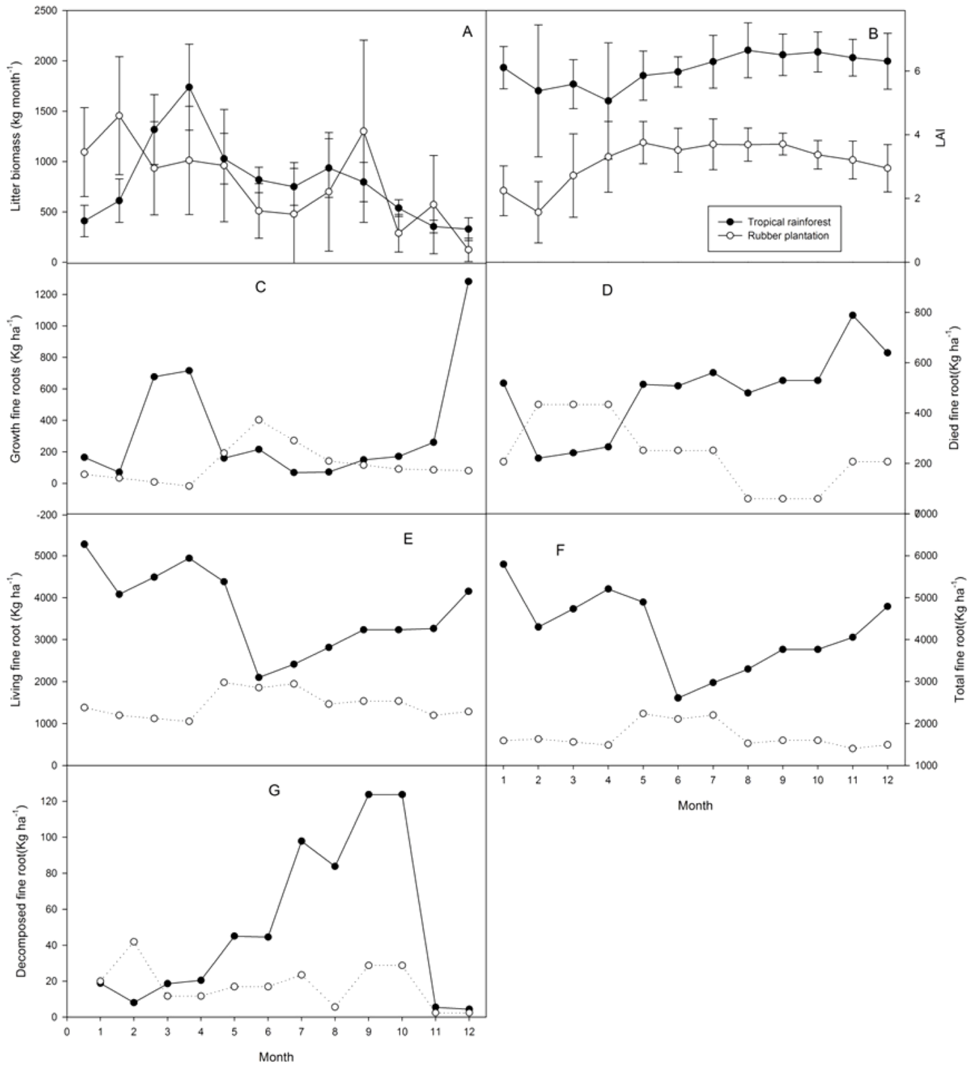

Fig. 3. Litter biomass (a), LAI (b), fine root growth (c), dead fine roots (d), live fine roots (e), total fine roots (f) and decomposed fine roots (g) in a tropical rainforest (black circles) and a rubber plantation (open circles) in Xishuangbanna. Monthly mean values (± SD) over 2003-2008 and 2012-2014 are presented.

but the annual sums were similar between the two sites (Fig. 3a; Table 1). All other biotic variables, including LAI, fine root growth, live fine roots, dead fine roots, total fine roots, and decomposed fine roots, were generally lower in the rubber plantation than in the tropical rainforest, and the difference were more pronounced during the dry season than in the rainy season (Fig. 3).

3.2. Effect of land use change on soil CO_2 and CH_4 emissions

The soil CO_2 efflux followed a unimodal pattern in both ecosystems with peaks exhibited in the rainy season (Fig. 4a; Fig. 5). However, the peak occurred much later in the tropical rainforest than in the rubber plantation (Fig. 4a). The annual mean CO_2 fluxes were similar between the two sites (359.95 ± 92.11 and 351.99 ± 41.29 mg CO_2 m^{-2} h^{-1} in the rainforest and rubber plantation, respectively). The annual soil CO_2 emission was 11.53 ± 2.92 t C ha^{-1} yr^{-1} and 11.30 ± 1.32 t ha^{-1} yr^{-1} in tropical rainforest and rubber plantation respectively (Table 2).

Soil CH_4 sink was significantly higher in tropical rainforest (-12.83 ± -12.8kg C ha^{-1} yr^{-1}) than rubber plantation (-2.34 ± 2.34n kg C ha^{-1} yr^{-1}) ($F = 56.6$, $p < 0.001$). Across the studied period, soil was sinks for CH_4 except August in the rubber plantation (Fig. 4b; Fig. 5b). The CH_4 consumptions in the rubber plantation (−0.020 ± 0.087 mg CH_4 m^{-2} h^{-1}) were overall significantly lower than in the tropical rainforest (−0.11 ± 0.18 mg CH_4 m^{-2} h^{-1}). It is noteworthy that rubber plantation exhibited a strong seasonal variation in the CH_4 fluxes with a peak during the rainy season, while the tropical rainforest site showed no clear seasonality.

There was not significant difference in global warming potential (GWP) of soil CO_2 and CH_4 between tropical rainforest and rubber plantation (Table 2).

3.3. Drivers of the soil CO_2 and CH_4 difference between rubber plantation and tropical rainforest

There were more environment factors significantly correlated with CO_2 and CH_4 fluxes in the tropical rainforest than in the rubber plantation (Table 3). The differences in CO_2 emissions between the two sites were positively correlated with litter biomass, soil water content, soil temperature, decomposed fine roots, DN, and MBN, and was negatively correlated with LAI, live fine roots, fine root growth, and total fine roots. The differences between TRF and RP in the CH_4 flux were negatively correlated with fine root growth and live fine roots, and positively correlated with soil temperature (Table 3).

The linear stepwise regressions showed that soil CO_2 and CH_4 fluxes were driven by different factors in the two sites. For the soil CO2 flux, LAI ($R^2 = 0.31$) and SWC ($R^2 = 0.84$) was the main control in rubber plantation and tropical rainforest separately. For the soil CH_4 flux, SWC was the main control of the CH_4 flux ($R^2 = 0.56$), followed by the dead

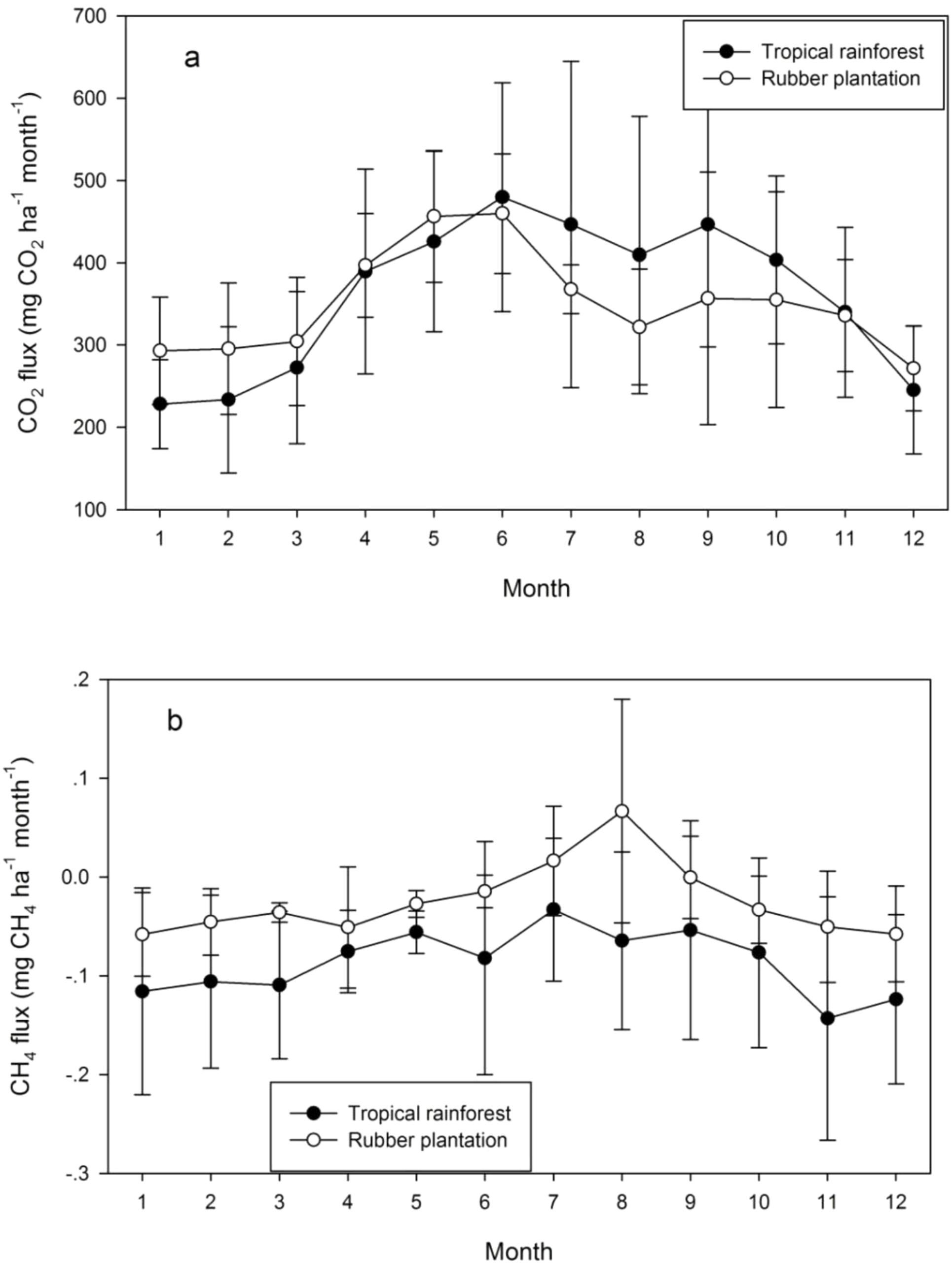

Fig. 4. Soil CO_2 (a) and CH_4 fluxes (b) in a tropical rainforest (black circles) and a rubber plantation (open circles) at Xishuangbanna. Monthly mean values (± SD) over 2003-2008 and 2012-2014 are presented.

fine roots; together, SWC and dead fine roots explained 87% of the CH_4 flux variance in rubber forest. In the rainforest, soil temperature and dead fine roots together explained 79% of the variantion in the CH_4 flux.

Linear regression models for the flux differences between the two sites showed that the soil temperature explained 76% of the variance in the CO_2 flux differences. By adding soil water content, dead fine roots and litter biomass to the regression, up to 97% of the variance in the CO_2 flux differences was explained. For the CH_4 flux differences between the tropical rainforest and rubber plantation, fine root growth was the most important factor which explained 47% of the variance (Table 4).

4. Discussion

4.1. Soil CO_2 fluxes

The annual soil CO_2 emissions in the tropical rainforest were not significantly higher than those in the rubber plantation (Table 2). Soil CO_2 emissions in the rubber plantation showed a significant seasonality, which is in line with the previous studies in south Asia (Lang et al., 2017; Zhang et al., 2015; Fang and Sha, 2006; Lu et al., 2009; Zhou et al., 2008; Sha et al., 2005; Fang et al., 2010) (Table S1). The observed CO_2 flux differences between the tropical rainforest and the rubber plantation soils was much smaller than those reported by Lu et al. (2009), Lang et al. (2017) and Fang and Sha (2006), which found higher CO_2 emissions from the rubber plantation than from the tropical rainforest in Xishuangbanna, possibly due to the physical and chemical characteristics of the study sites and also the observation methods. Our measurements spanned over the period 2003-2014, representing 8 years of intensive monitoring (Fig. 4, Fig. 5). Our results present the average seasonal patterns in soil CO_2 and CH_4 fluxes that minimized the effect of inter-annual variations.

As the main carbon substrates, SOC concentrations were higher in

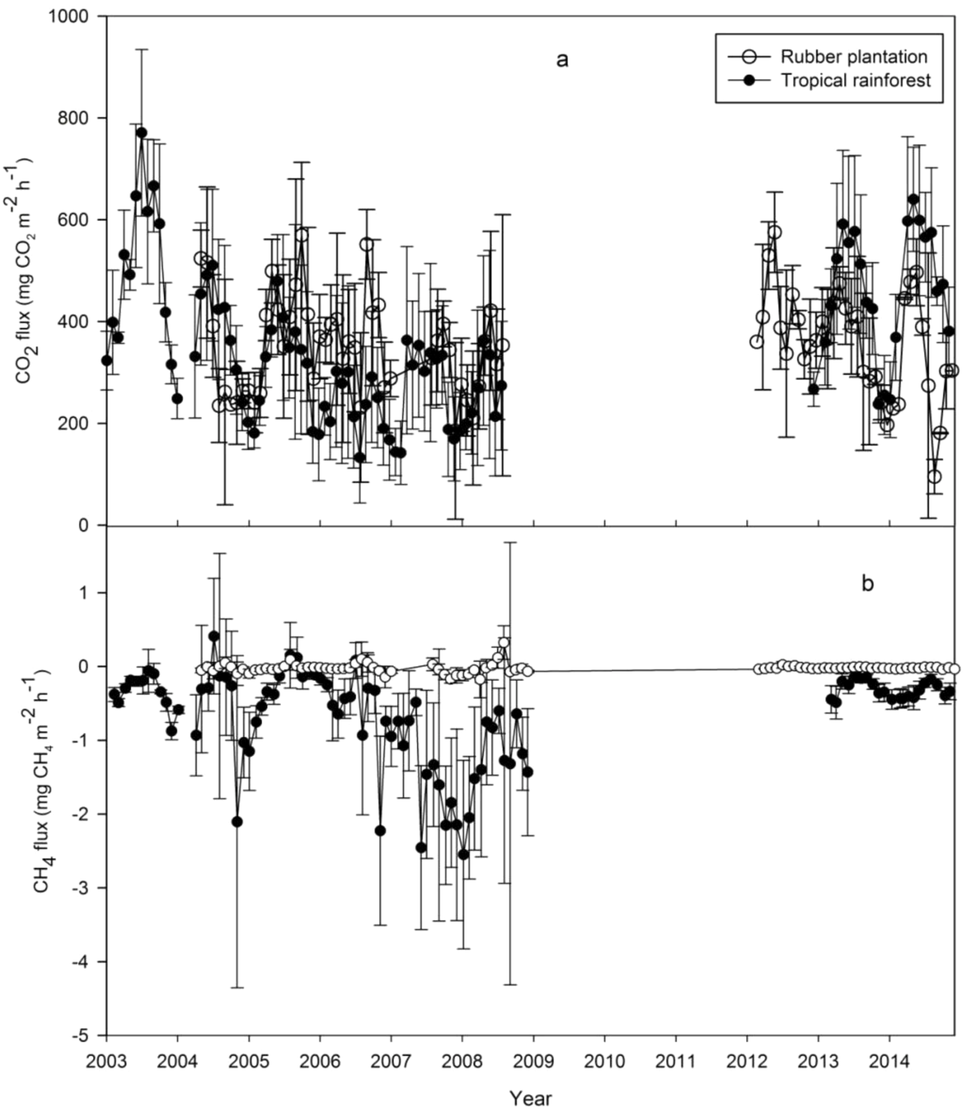

Fig. 5. Temporal variations in monthly soil CO_2 (a) and CH_4 (b) fluxes in a tropical rainforest and a rubber plantation in Xishuangbanna during 2003-2008 and 2012-2014.

Table 2
Global warming potential of soil CO_2 and CH_4 in tropical rainforest and rubber plantation in Xishuangbanna.

Forest	Annual flux		GWP (1×10^3)	
	CO_2t C ha^{-1} yr^{-1}	CH_4kg C ha^{-1} yr^{-1}	20 years	100 years
Tropical rainforest	11.53 ± 2.92	−12.83 ± 21.02	11.42 ± 3.10	11.49 ± 2.99
Rubber plantation	11.30 ± 1.32	−2.34 ± 10.16	11.29 ± 1.35	11.30 ± 1.35

The global warming potential (GWP) inclusion of climate–carbon feedbacks of CH_4 is 86 and 34 times that of CO_2 over a period of 20 and 100 years respectively (Myhre et al., 2013).
Where GWP_{20} and GWP_{100} indicates the GWP during 20 and 100 years for summary of the CO_2 and CH_4.

the rubber plantation than in the tropical rainforest (Tang et al., 2007), but this difference did not result in a higher CO_2 emissions from the rubber plantation than from the tropical rainforest (Fig. 4a). This is likely because the amount of chemical fertilizer that was added to the rubber plantation did not change the soil C mineralization significantly. By contrast, previous studies found that land use change has an effect on soil CO_2 emissions due to fertilizer application (de Urzedo et al., 2013; Gütlein et al., 2017; Shrestha et al., 2014; Wong et al., 2020; Zona et al., 2013).

The annual soil CO_2 fluxes of the tropical rainforest and the rubber plantation in this study differ from those reported from other studies in Xishuangbanna (Fang and Sha, 2006; Fang et al., 2010; Lang et al., 2017; Lu et al., 2009; Zhou et al., 2008; Sha et al., 2005) (Table S1). This difference may due to the fact that the studies were carried out in different sites in Xishuangbanna with great differences in soil characteristics, especially in soil temperature without considering land use types. And furthermore, the soil CO_2 emissions from the tropical rainforest in this study are lower than those reported by Lang et al. (2017) in Xishuangbanna, and by other researchers in South Asia (de Urzedo et al., 2013; Hassler et al., 2015; Mohd Kusin et al., 2015; Shrestha et al., 2014). Our results are in line with Lang et al. (2017), which reported an increase in annual soil CO_2 flux along with the increasing annual mean temperature and precipitation.

Previous studies have reported that soil temperature is the main driver of soil CO_2 dynamics, followed by soil water content (Oertel et al., 2016). We found that had the greatest influence on soil CO_2 dynamics in both the tropical rainforest and rubber plantation. As LAI is positively

Table 3
Statistically significant correlations between soil CO_2/CH_4 fluxes and environmental parameters in a tropical rainforest (TRF) and a rubber plantation (RP) in Xishuangbanna.

	TRF		RP		Difference between TRF and RP in percentage [a]	
	CO_2	CH_4	CO_2	CH_4	CO_2	CH_4
Litter biomass					0.509*	
LAI			0.618**	0.561*	-0.847***	
Growth fine root					-0.710***	-0.721***
Living fine roots	-0.682**				-0.755***	-0.533*
Died fine roots			-0.599**			
Total fine roots	-0.682**				-0.743***	
Decomposed fine roots	0.686**	0.760***			0.522*	
SWC	0.926***	0.789***		0.765***	0.816***	
T5	0.915***	0.838***			0.884***	0.657**
DOC						
MBC	0.574*			0.698**		
DN	0.711***	0.511*			0.575*	
MBN	0.878***	0.662**			0.538*	
NH_4^+-N				0.677**		
NO_3^- -N	0.643**	0.633**				
DON	0.704**					

*** statistically significant at the 0.01 level,
** statistically significant at the 0.05 level,
* statistically significant at the 0.1 level.
[a] (RP – TRF)/TRF × 100.

Table 4
Results of stepwise linear regression for CO_2 and CH_4 fluxes with soil C, N fractions, soil water content, soil temperature, litter fall, LAI, died and growth roots as independent variables in a tropical rainforest and a rubber plantation in Xishuangbanna.

	CO_2			CH_4		
	Equation	R^2	p	Equation	R^2	p
TRF	$-100.2 + 22.0$ SWC	0.84	$<$ 0.001	$-0.3 + 0.01\ T_5$	0.67	$<$ 0.001
	$-15.2 + 14.6$ SWC + 0.3 MBN	0.90	$<$ 0.001	$-0.2 + 0.007\ T_5$ - 0.2DFR	0.79	$<$ 0.001
RP	$229.9 + 37.2$ LAI	0.31	0.034	$-0.04 + 0.01$ SWC	0.56	0.009
				$-0.04 + 0.01$ SWC -0.0001 DFR	0.87	$<$ 0.001
Difference between TRF and RP (%)	$-11.4 + 1.8\ T_5$	0.76	$<$ 0.001	-81.8 - 0.3GFR	0.47	0.03
	$-28.1 + 7.7\ T_5 + 0.\ 3$ SWC	0.84	$<$ 0.001			
	$-60.5 + 0.7\ T_5 + 0.7$ SWC - 0.2 DFR	0.94	$<$ 0.001			
	$-70.0 + 0.8\ T_5 + 0.8$ SWC - 0.2 DFR - 0.06 LB	0.97	$<$ 0.001			

Note: acronym for terms
SWC, soil water content; MBN, Microbial biomass nitrogen; LAI, Leaf area index; T_5, Soil temperature at 5 cm depth; DFRB, Dead fine root biomass; LB, litter biomass; GFR, Growth fine root biomass; TRF, Tropical rainforest; RP, Rubber plantation

link to photosynthesis and then its effect on autotrophic respiration (Zhou et al., 2008). Furthermore, photosynthesis also regulate root excreta which will supply subtracts for heterotrophic respiration (Lu et al., 2009). Thus, LAI has the direct correlation with soil respiration and soil water content, but not with soil temperature. As soil temperature has greater influence on soil CO_2 with LAI due to annual variation, of soil water content which is greater than soil temperature (Fig. 1).

However, other studies in similar settings concluded that soil temperature is the most important control on soil CO_2 emissions (Fang and Sha, 2006; Lang et al., 2017; Lu et al., 2009; Zhou et al., 2008; Sha et al., 2005). This indicates that causes of the flux differences may be due to other different environmental conditions between the sites.

Due to a stronger seasonality in the precipitation than in the temperature in Xishuangbanna, soil water content at both sites exhibited a stronger seasonal variation than soil temperature (Fig. 1). This seasonal soil water content variation also showed a greater influence on the CO_2 flux than soil temperature in this tropical rainforest. Heterotrophic respiration has been reported as the main contributor to soil CO_2 production in tropical rainforests (Zhou et al., 2016b), accounting for 74% of the CO_2 fluxes. Soil heterotrophic respiration is mainly controlled by soil microbes, phenology of fine root growth and litter decomposition and these processes tended to have similar seasonal dynamics with soil temperature and soil water content (Zhou et al., 2016b). Thus, soil water content is the most important factors for soil respiration in this tropical rainforest.

In the rubber plantation, the area-weighted mean value of soil CO_2 flux used in the present study differ from the values documented in other studies (Fang and Sha, 2006; Lang et al., 2017; Lu et al., 2009). These previous studies did not consider differences in topography throughout the rubber plantation. Management activities (e.g., weeding, pesticide application, tapping, and fertilization) disturb surface soil and influence soil microbial activity in a rubber plantation. We found a lower sensitivity of soil CO_2 fluxes to changes in temperature and soil water content in the rubber plantation than in the tropical rainforest (Tables 2 and 3). Because of the intensive management and trampling by farmers during the rubber tapping period, the soil is more tightly packed in the rubber plantation than in the tropical rainforest. In addition, there is more seasonal variation in soil erosion in the rubber plantation than in the tropical rainforest (Chen et al., 2017). Consequently, more seasonal variation in the soil carbon substrate is present in the rubber plantation than in the tropical rainforest (Zhang et al., 2010). The ratio of autotrophic respiration to total soil respiration for rubber trees was 42% (Lu et al., 2009), which is higher than the value of 27% reported by Zhou et al. (2016b) in a tropical rainforest in the same region of Xishuanbanna. Soil respiration was also controlled in part by photosynthesis, as indicated by the significant effect of LAI on the CO_2 flux (Tables 3, 4). More factors (e.g., soil temperature, soil moisture, fine roots, and different soil C and N fractions) contributed to soil CO_2 emissions in the tropical rainforest than in the rubber plantation (Table 3), which again confirms that soil CO_2 emission mechanisms differ when the tropical rainforest was replaced by the rubber plantation in Xishuangbanna.

As regional differences are mainly attributable to differences in soil temperature (Table S1; Lang et al., 2017), the difference in soil temperature explained 76% of the seasonal variations in the soil CO_2 emissions percentage change between the tropical rainforest and the rubber plantation. Adding soil water content, dead fine roots and litter biomass, the CO_2 emission differences were explained by up to 97% (Table 3), indicating that fresh labile C inputs through litters influence the soil CO_2 fluxes (Zhou et al., 2015). This also indicates that dead fine roots substantially contribute to the soil CO_2 production (Zhou et al., 2008; Zhou et al., 2016a). In summary, with the limitation of linked knowledge in variations of characteristics of the environment and substrates, to disclose the drive mechanisms of spatial heterogeneity in soil CO_2 fraction emission after land use change should be concerned in future studies.

4.2. Soil CH_4 flux

The annual means of CH_4 sinks in the tropical rainforest (-12.83 ± 21.02 kg C ha^{-1} yr^{-1}) is stronger than rubber plantation (-2.34 ± 10.16 kg C ha^{-1} yr^{-1}) (Table 2, Fig. 4). These results agree with most previous studies that studied CH_4 flux in rubber plantations (Lang et al., 2017; Fang et al., 2010; Hassler et al., 2015) in Xishuangbanna. By contrast, Ishizuka et al. (2005) found higher CH_4 sink in a rubber plantation than in a tropical rainforest with loam Acrisol. This may indicate that the sink strength of a rubber plantation for CH_4 depends on the physical and chemical characteristics of the soil. Overall, considering soil CO_2 and CH_4 contribute to the 20-year and 100 year GWP, soil CH_4 sink is far more less than soil CO_2 emission in tropical rainforest and rubber plantation, soil CO_2 and CH_4 contributions to the GWP are similar without considering tropical rainforest and rubber plantation carbon cycle (Table 2).

After tropical rainforest is converted to a rubber plantation, the rate of soil to uptake CH_4 decreases (Fig. 4B), possibly because of changes in the soil water content, soil temperature, dead fine roots and fine roots growth (Tables 2, 3). These changes in the environmental factors are generally reflections of the more intensive management activities (e.g., fertilizer application) after the forest conversion, as discussed earlier. Due to the human interferences, less environmental factors were found to be correlated with CH_4 fluxes in the rubber plantation than in the tropical rainforest (Table 3).

In the tropical rainforest, the soil CH_4 flux is affected by a combination of soil temperature, soil DN, MBN, NO_3^- -N, DON, and decomposed fine roots. Among the factors, soil temperature was the most important control (Table 3). By contrast, soil water content was the most important control in the rubber plantation, reflecting the different soil physico-chemical characteristics caused by distinctive vegetation composition and management practices of the two ecosystems. Since soil water content was less than 30% in the tropical rainforest and the soil contained more gravel particles in the surface layer than that in the rubber plantation soil (Tang et al., 2007), the soil oxygen content was likely higher in the tropical rainforest than in the rubber plantation. With a better soil aerobic condition, soil water content was less a limiting factor for CH_4 consumption/production in the tropical rainforest and soil temperature played a dominant role in controlling methanotrophic/methanogenic activities (Table 4). Soil methanotrophic communities were more abundant and active when soil temperature was higher, leading to more CH_4 uptake (Dunfield et al., 1993). In the rubber plantation, soil water content was generally higher than that in the rainforest (Fig. 1), making water content the primary control on the CH_4 flux. This result is in line with Fang et al. (2010) and Werner et al. (2006) and this may relate to lower soil porosity (Chen et al., 2017) and a heavy soil structure. Net CH_4 fluxes (emission or uptake) are the result of both CH_4 consumption and production. When soil water content is high, CH_4 consumption is inhibited and production is promoted, which results in smaller net CH_4 uptake rates and weakens CH_4 sink.Under a high moist condition in the rainy season, the rubber plantation can even turn into a CH_4 source in August (Fig. 1, 4b) as CH_4 productions exceeded consumptions.

Production of CH_4 in the soil is also influenced by soil mineral N. The NO_3^-–N concentrations in the tropical rainforest, which were slightly higher than those of NH_4^+–N, may have influenced the seasonal dynamics of CH_4 according to Fang et al. (2010) and Lang et al. (2017). In addition, soil MBN and DN, but not NH_4^+–N, were strongly correlated with soil CH_4 flux in the tropical rainforest, suggesting that methanogens do not compete for electrons with nitrate, ferric iron, or sulphate reducers (Chidthai-song and Conrad, 2000). This may also explain that CH_4 uptake decreased with the increase in soil NO_3^-–N in the tropical rainforest (Table 3). In agreement with King and Schnell (1994), only the soil NH_4^+–N was significantly and positively correlated with soil CH_4 fluxes. As suggested by King and Schnell (1994), the inhibition of NH_4^+–N on CH_4 consumption may intensify as the CH_4 concentration increases, because of competitive inhibition of NH_4^+–N oxidation to NO_2^-, resulting in a negative relationship between CH_4 consumption and NH_4^+–N (Kiese et al., 2003).

Plant growth, above- and below-ground litter decomposition have significant influences on soil carbon emissions as they reduce the activity carbon supply for soil microbes, which then influence the soil CH_4 flux. In our study, we found that dead fine roots provided organic matter for microbes and that most of the decomposition occurred under aerobic conditions, such that the oxides competed for CH_4, resulting in a negative correlation between CH_4 flux and dead fine roots (Tables 2, 3). The growing fine roots consume more nutrients and compete for nutrient ions, and, at the same time, root exudates in the rhizosphere promotes CH_4 production. However, these processes did not seem to alter soil CH_4 fluxes as associated with the land use change (Table 4). There was a significant difference in the living fine roots between the rubber plantation and the tropical rainforest (Table 2).The greater below-ground productivity in the rainforest was likely driven by a greater nutrient availability and higher soil temperature. This high root productivity may also have stimulated CH_4 production in the rhizosphere through a greater supply of labile substrates to methanogen communities (King and Schnell, 1994; Lammel et al., 2015; Oertel et al., 2016). Accordingly, the differences in fine root growth explained 47% of the difference in CH_4 fluxes between the tropical rainforest and the rubber plantation (Table 4).

5. Conclusions

This study indicates that CO_2 emissions did not vary with land use change, but the sink strength for CH_4 decreased significantly, and the GWP contribution of soil CO_2 and CH_4 did not change significantly. The associated seasonal dynamics in CO_2 and CH_4 were also changed due to different environmental drivers that controlled the underlying processes. Specifically, soil temperature and soil water content were the main controls on CO_2 fluxes differs, while fine root growth was the main control on CH_4 fluxes variation. Our results suggest that the soil biogeochemical processes associated with fine roots and C and N mineralization should be considered as effects of land use change on soil C dynamics and emissions. Future evaluations of effects of land use change on the local environment should also consider the carbon balance at the ecosystem level.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2021.108391.

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