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Impact of forest conversion to oil palm and rubber plantations on microclimate and the role of the 2015 ENSO event

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ABSTRACT

Oil palm and rubber expansion is a main driver of the widespread deforestation of tropical rainforests taking place in South-East Asia, particularly in Indonesia. The replacement of forests with monoculture plantations of rubber and oil palm reduces biodiversity and carbon pools but also modifies canopy structure, which is an important determinant of microclimate. There is, however, a lack of quantitative information characterizing the effect of such land transformation on microclimate. We report the first medium-term observations of below-canopy microclimatic conditions (air temperature, relative humidity, vapour pressure deficit and soil temperature) across forest, jungle rubber agroforest, oil palm and rubber monoculture plantations in Sumatra/Indonesia. The data set covers a period of approximately three years (2013–2016) and includes one of the strongest El Niño-Southern Oscillations (ENSO) of the last decades. Forests were up to 2.3 and 2.2 °C cooler than oil palm and rubber monocultures respectively. The monocultures were also drier (11.9% and 12.8% less in oil palm and rubber respectively) and had higher vapour pressure deficit (632 Pa and 665 Pa higher in oil palm and rubber respectively) than the forest, while differences in soil temperature were less pronounced. Conversion from forest to other land uses, especially to monocultures, also amplified the diurnal range of all microclimatic variables studied. Jungle rubber stands out as the transformed land-use system that maintains more stable microclimatic conditions. Our results indicate that canopy openness is a key driver of below-canopy microclimate, and hence could be used in climate models to better evaluate climatic feedbacks of land-use change to rubber and oil palm. The ENSO event of 2015 led to warmer and drier conditions than in the previous two years in all four land-use systems, especially in the forest (up to 2.3 °C warmer, 8.9% drier and up to 351 Pa more during ENSO). The relative effect of ENSO was lower in the monoculture plantations, where below-canopy microclimate is generally more similar to open areas. Forests exhibited the largest differences with the pre-ENSO years, but still maintained more stable microclimatic conditions (lower temperatures and vapour pressure deficit and higher relative humidity) due to their higher climate regulation capacity. During ENSO, microclimatic conditions in jungle rubber were comparable to those in the monocultures, suggesting that while forests buffered the increase of temperature, jungle rubber might have surpassed its buffering capacity to extreme events. This capacity of buffering extreme climatic events should be considered when assessing the effects of land-use change.

1. Introduction

Global demand for agricultural products such as food, feed and fiber is a mayor driver of land-use change in the tropics, which occurs mainly at the expense of forests (Gibbs et al., 2010). In Southeast Asia, rainforests have been logged since the mid-20th century, usually followed by tree cash crops such as oil palm (Elaeis guineensis) and rubber (Hevea brasiliensis) monocultures (Abood et al., 2015; Wilcove and Koh, 2010; Ziegler et al., 2009). Indonesia has the highest annual loss of rainforest worldwide (Margono et al., 2014), while being the largest palm oil producer and the second largest rubber producer worldwide (FAO, 2017). Oil palm and rubber monocultures are more profitable than forests and agroforests, but are not able to maintain most ecological functions (Clough et al., 2011), as a result of decreases in biomass

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(Kotowska et al., 2015), soil carbon (Guillaume et al., 2015) and biodiversity (Barnes et al., 2014; Rembold et al., 2017).

The climatic impact of carbon emissions associated to deforestation and land-use change have long been studied, including some recent work on carbon dioxide emissions following forest conversion to oil palm (Carlson et al., 2012a, b; Ramdani and Hino, 2013). Biophysical effects of land cover on microclimate remain poorly understood and are therefore not considered in most models and treaties (Alkama and Cescatti, 2016), despite the fact that microclimate differences between different land covers can be of similar scale or even larger than those projected to happen under climate change (Sabajo et al., 2017; Suggitt et al., 2011). Changes in land cover type affect the local climate by modulating the land-atmosphere fluxes of energy and water (Alkama and Cescatti, 2016; Bright et al., 2017; Ellison et al., 2017). Forest conversion to other land uses typically leads to an amplification of the diurnal temperature variation and increases the mean and maximum air temperature (Alkama and Cescatti, 2016). Accordingly, studies in temperate and tropical ecosystems show that forests are usually cooler than clear cut areas or the agroforestry systems that substitute them (Chen et al., 1999, 1993; Porté et al., 2004). The lower temperatures in forests are related to their cooling effect, mainly a result of higher evapotranspiration, which is especially strong in the tropics (Li et al., 2015). Additionally, the top of the canopy reflects or intercepts the sun light, and therefore, denser canopies will result in lower light penetration and thus lower below-canopy temperatures (Foley et al., 2003). For oil palm plantations, the limited studies available suggest that their microclimate is different from that of forests in the same regions (Drescher et al., 2016; Hardwick et al., 2015; Luskin and Potts, 2011; Sabajo et al., 2017), experiencing higher temperatures and lower humidity. Hardwick et al. (2015) observed that maximum temperature in logged forests and oil palm plantations was 2.5 °C and 6.5 °C greater than in primary forests, respectively. Similarly, Luskin and Potts, (2011) measured that during daytime hours, oil palm plantations were 2.8 °C warmer and drier than natural vegetation. These differences seem to be related to decreased leaf area index (LAI) (Hardwick et al., 2015). However, these studies are based on short-term data series or modeled results and fail at providing information on the inter-annual variability.

Despite of the relevance of oil palm expansion, in the Indonesian island of Sumatra, where oil palm production is concentrated (OECD-FAO, 2012) and the highest forest cover loss in Indonesia is found (Laumonier et al., 2010; Margono et al., 2014; Miettinen et al., 2011), rubber plantations cover more than 25% of the territory (Clough et al., 2016). Rubber is grown mainly as a monoculture, but also as an agroforestry system (i.e. jungle rubber) where secondary forests are enriched with rubber (Gouyon et al., 1993). Therefore, in order to assess microclimatic effects due to land-use change in the region, rubber ecosystems should also be studied. Studies so far (Böhnert et al., 2016; Clough et al., 2016; Drescher et al., 2016, Sabajo et al., 2017) have been based on measurements over short time periods. Jiang and Wang, (2003) assessed the climatic effects due to the conversion of natural forest to rubber plantations and found that replacement of natural forest with rubber had no effect on the local rainfall. However, to our knowledge there are no detailed studies addressing microclimatic effects (i.e. temperature or relative humidity) of rubber, neither as monoculture nor as agroforestry system. Thus, there is a need to understand how microclimate varies with the change in land-use systems in a tropical landscape, where forests are being replaced by oil palm and rubber plantations. Additionally, climatic impacts due to land-use change are expected to be stronger under maritime conditions, as found in Indonesia, than under continental conditions, as 40% of the global tropical latent heating of the upper troposphere takes place over the Maritime Continent (van der Molen et al., 2006). Therefore, the climatic effects of extensive land-use change due to oil palm and rubber expansion in Indonesia could have global climatic implications, which need to be properly evaluated.

The El Niño Southern Oscillation (ENSO) is a major mode of variability of global precipitation and temperature, comprising alternating warming (El Niño) and cooling (La Niña) phases. The El Niño event in 2015 could be the second strongest ENSO event reported so far after 1997 (Varotsos et al., 2016). In Indonesia, ENSO is expected to create hotter and drier conditions (Allan, 2000; Harger, 1995; Susilo et al., 2013). To our knowledge, no studies are available showing the effect of the ENSO event on microclimatic conditions in these land-use systems, but results from a modeling study suggest that land clearing can amplify the effect of ENSO in Southeast Asia (Tölle et al., 2017). Natural ecosystems have greater climate regulation capacities than agroecosystems (Anderson-Teixeira et al., 2012), and thus, responses to climate warming are attenuated in forests with denser canopies (De Frenne et al., 2013). Therefore, we hypothesized that ENSO will have a stronger effect on the less natural land-use systems. Buffering from extreme conditions is beneficial for biodiversity and ecosystem functioning (Chen et al., 1999; Clough et al., 2016), and on this basis, the stability in microclimatic conditions is assessed.

We performed the first systematic study evaluating the microclimatic conditions below the canopy in different land-use systems in the lowlands of Sumatra, namely forests, jungle rubber, rubber and oil palm monocultures. We measured air temperature (Ta, °C), relative humidity (RH, vol%), vapor pressure deficit (Vpd, Pa) and soil temperature (Ts, °C), and assessed the microclimate in these land-use systems during three consecutive years including the ENSO event in 2015. The aims of this study were i) to quantify microclimatic conditions in forests, rubber agroforests, oil palm and rubber monocultures and evaluate their differences; ii) to investigate the drivers of these climatic differences and iii) to assess the effect of the ENSO event in 2015 on the microclimatic conditions in the different land-uses evaluated.

2. Materials and methods

2.1. Measurements sites

Our study was carried out within the frame of the EFForTs project (Drescher et al., 2016) in the Jambi province in Sumatra, Indonesia. Average annual temperature and rainfall in the area of study (mean ± sd between 1991 and 2011, data from the Airport Sultan Thaha in Jambi) were 26.7 ± 0.2 °C and 2235 ± 381 mm. We evaluated microclimatic conditions below the canopy in four land-use systems: primary degraded forest (see Drescher et al., (2016) for definition), from now on called forest (F), jungle rubber (JR), rubber monoculture (R) and oil palm monoculture (O). We established eight 50 × 50 m core plots from each land use system in two different landscapes (4 each) in the lowlands of the Jambi province (Fig. 1). The two landscapes, i.e., the 'Bukit Duabelas landscape' and the 'Harapan landscape' had a clay loam and sandy loam texture respectively (Allen et al., 2015; Drescher et al., 2016). There was a total of 32 plots in our study, 16 in each landscape.

We additionally installed four "reference meteorological stations" in open areas, two in each landscape, one closer to the forests plots and the other one closer to the transformed land uses (rubber and oil palm plots; Fig. 1). Additional details on the experimental design can be found in Drescher et al., (2016).

2.2. Micrometeorological measurements

A meteorological station was installed in the center of each core plot. Each station was equipped with a thermohygrometer (Galltec Mela, Bondorf, Germany) placed at 2 m height to record Ta (°C) and RH (%) below the canopy, and a Trime-Pico 32 (IMKO, Ettlingen, Germany) at 0.3 m depth in the soil to monitor Ts (°C). Both sensors measured once every hour, and data were recorded in a UIT LogTrans 16-GPRS data logger (UIT, Dresden, Germany). Data were collected from April 2013 to March 2016 in the 32 core plots.