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Forest conversion impacts on the fine and coarse root system, and soil organic matter in tropical lowlands of Sumatera (Indonesia)

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ABSTRACT

Deforestation and land-use change are occurring on an increasing scale throughout Indonesia with profound effects on ecosystem structure and functions marked by consequences in biogeochemical cycles. This study investigates the influence of forest conversion on soil organic matter as well as the fine and coarse root system. Furthermore, the relationships between carbon (C) and nitrogen (N) stocks in the root biomass were related to the total aboveground tree biomass. Root biomass and fine root morphology were investigated in 150 cm-deep soil pits along a gradient of increasing land-use intensity, i.e. in natural forest, rubber under a natural forest cover ('jungle rubber'), rubber and oil palm monocultures. Total root biomass generally decreased with increasing land-use intensity together with aboveground tree biomass. Subsequently, carbon and nutrient stocks in the root system were over 50% lower in the monoculture plantations compared to the natural forest. Vertical root distribution showed distinct different patterns across the land-use types with a pronounced logarithmic decrease in vertical total root abundance in the natural forest and the jungle rubber plots that was less distinctive in the plantation systems. However, fine root morphology in the jungle rubber system revealed a large specific root area and specific root tip abundance, therefore partly compensating for the reduction in the fine root system after forest conversion. Soil organic matter was particularly low in rubber plantations. In conclusion, the results of our study suggests that conversion of natural forest to agroforestry and monoculture systems has a profound belowground impact reflected in the decrease of root biomass, nutrient stocks in coarse roots, and total soil organic matter.

1. Introduction

Sumatera's forests have yet again gained international attention as Southeast Asia was engulfed in the haze from fires affecting over 2.6 million hectares of forest and cropland in the autumn of 2015 (Tacconi, 2016). Over the past 30 years approximately 550,000 ha of Sumatras forests annually have been lost, of which 85% was due to conversion and forest fires in the lowland forests of Jambi and Riau provinces (Laumonier et al., 2010; Margono et al., 2012). Historically, forests in the Jambi province were converted into agroforestry rubber systems, where rubber trees (*Hevea brasiliensis*) were planted within the natural forest landscape (Gouyon et al., 1993). However, this form of agriculture quickly morphed into complete conversion of entire forests into monoculture plantations, such as rubber and more recently oil palm (*Elaeis guineensis*) (Fitzherbert et al., 2008). Conversion of lowland forests on highly weathered soils to rubber and oil palm plantations has already decreased soil nutrient and carbon levels in this region (e.g. Corre et al., 2006; Davidson et al., 2007; van Straaten et al., 2015). Recent studies on aboveground C changes reveal that conversion of lowland forests to oil palm and rubber plantations can reduce aboveground biomass up to 151 Mg C ha^{-1} with severe impacts on regional carbon budget (Kotowska et al., 2015a).

Focusing on land-use change effects on aboveground systems is of key importance, however, belowground alterations have a long-lasting influence on the ecosystems sustainability and resilience (Jandl et al., 2007). The root systems of trees play a critical role in the ecosystem functions, as the nutrient and organic matter input to soil through roots maintains soil fertility and carbon sequestration. Fine and coarse roots contribute to about 30–50% of the total annual net primary production, and therefore have a significant role in the global C cycle (Xiao et al., 2003). Fine roots

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less than 2 mm in diameter are recognized as the most important component contributing to nutrient absorption (Röderstein et al., 2005). They enrich the soil with nutrients and organic matter by rapid turnover (Persson, 1979) and may become proportionally more important than the leaf litter input (Arunachalam, 1996). The coarse roots (>2 mm) comprised of larger, structural roots which provide support to the network of fine roots, deliver nutrients and water to the shoots, support the tree structure (Fogel, 1983) and are assumed to be of great importance in the long-term nutrient budget of forests (Hellsten et al., 2013). Furthermore, the decomposition of coarse roots has been regarded as an important component providing a slow delivery of C and nutrients to the soil and soil biota influencing the long-term ecosystem productivity and CO_2 emissions from forests (Giardina et al., 2004; Sierra et al., 2007). It has been shown that with increasing land-use intensity the importance of root litter carbon input to the soil organic matter pool strongly increases and greatly surpasses that of leaf litter carbon input to this pool (Hertel et al., 2009). Based on density, soil organic matter can be classified into the light fraction, the intermediate fraction, and the heavy fraction (Hassink, 1995; Meijboom et al., 1995). The light fraction, known as the active fraction is the most sensitive to change through management and is often used as an indicator of soil quality (Rovira and Vallejo, 2003). The rapid decomposition of the light fraction of soil organic matter is a key for nutrient availability in soil (Lu et al., 2014) and therefore, eventually has a strong impact on stimulating the root system to exploit these nutrient resources.

By severely changing structure and composition of the vegetation during forest conversion, nutrient cycling above and belowground will be altered as a consequence of modified litter input to the soil and changed decomposability of organic matter due to soil moisture and temperature regimes (Post and Kwon, 2000; Lal, 2005; Isaac et al., 2005). Even though a substantial proportion of carbon is stored belowground (Lehmann and Zech, 1998; Jobbágy and Jackson, 2000), the effects of forest conversion to tree plantations on root and soil carbon are underrepresented in the literature (Upadhaya et al., 2005; Powers et al., 2011) and strongly controversial particularly regarding soil organic carbon (Frazao et al., 2013; Chiti et al., 2014; Grace et al., 2014) despite rapidly increasing monoculture plantation cover in the tropics. Considering the effects of land-use change on root systems and soil organic matter is crucial for the sustainable management of these ecosystems, and will help to understand the tropical carbon budget while giving support for carbon modeling approaches and policy making. Therefore, the aims of our study are (1) to quantify the fine and coarse root bio- and necromass, coarse root C and N stocks and their relation to aboveground biomass, (2) to analyse changes in vertical root distribution with increasing land-use intensity, (3) to study changes in fine root morphological properties with forest conversion, and (4) to determine the active fraction of soil organic matter along the gradient of increasing land-use intensity in the lowlands of Jambi province (Sumatera, Indonesia).

2. Methods

2.1. Study area

The study was conducted from June 2014 until January 2015. The study areas was located in the Harapan Forest Jambi, Indonesia (S 01°30′2.98″–S 01°7′1.07″ and E 103°40′1.67″–E 103°40′0.23″) at an altitude of 60 m a.s.l. Based on data from BMKG Jambi Province, the average annual rainfall is 2296.1 mm, with humidity ranging between 82 and 87% and the average annual temperature ranging from 22.1 to 23.3 °C.

The Harapan Forest is one of the last remaining lowland rainforest remnants in Sumatera. Nowadays, the forest area is threatened as a result of development in the plantation sector. Oil palm plantations area in Jambi increased fourfold from 150,000 ha in 1996 to 550,000 ha in 2011 (BPS, 2012). For this study, four major land-use types in the region were selected which together cover over 80% of the Jambi province (Clough, 2016). The four land-use types were defined as follows; natural forest (HF) in this study is degraded primary forests with minor logging activities in the past, but still in close to natural state; jungle rubber (HJ) is an agroforestry system, which involves the planting of rubber trees in between remaining natural forest trees, while rubber (HR) and oil palm (HO) plantation represented monocultures systems established on smallholder owned estates (up to 50-ha landholding) in their first rotation cycle after clearing and burning the previous forest or jungle rubber forest (Euler et al., 2012; Drescher et al., 2016). The management of the plantations continued with intensities typical for the respective land-use system and included manual and chemical weeding throughout the year at the rubber and oil palm plantations and fertilizer application one or two times a year (Table 1). Fertilizer additions to the oil palm plantations ranged from 300 kg to 550 kg NPK-fertilizer ha^{-1} $year^{-1}$ (ie, Phonska, Crown), potassium chloride and urea, while rubber plantations are fertilized irregularly (Allen et al., 2015). Oil palm plantations in this study were around 9–10 years old and the stand age of rubber plantations ranges between 8 and 10 years. The soil in the region is acrisols with a sandy loam texture and the basic soil physical and chemical properties varied independently from the land-use system and were in general comparable across the study sites (Allen et al., 2015; Kurniawan et al., unpubl.).

2.2. Experimental design

For each land-use type, four replicate plots with comparable soil, management and vegetation characteristics were selected. In the destructive area of each of these long-term research plots, which is located 5 m beside the main 50 m × 50 m plot (Fig. 1), two soil pits down to 150 cm depth were excavated at a distance of 80 cm to a randomly selected tree with a diameter of $\geqslant$10 cm.

Aboveground biomass was calculated for the area of the 16 main plots (50 m × 50 m) with a total of 1929 trees. To estimate the aboveground biomass several genera-specific allometric equations were used. For tree biomass in natural forest, we used the formula developed by Chave et al. (2005) for tropical moist stands. In order to estimate rubber biomass, we used the allometric equations by the IPCC (2003). In the oil palm plantations, we applied the allometric equation by Asari et al. (2013).

2.3. Belowground biomass, root C and N content, and fine root morphology

The root sampling took place in the destructive sampling area. In each of the 16 selected plots representing four land-use types two soil pits down to 150 cm depth were excavated (total n = 32). Root samples were taken at a minimum distance of 80 cm from a tree with a diameter of >10 cm in soil monoliths of 30 cm × 30 cm. In the oil palm plantation, the samples were taken at two different distances (at a distance of 80 cm from the palm and at a distance of 4.5 m). The root material was separated into five mineral soil depths (0–10, 10–30, 30–50, 50–100, and 100–150 cm). All visible roots were manually removed from the soil material, put into plastic bags and transported to the laboratory and kept under cold conditions until processing.

In the laboratory, samples were washed with tap water and differentiated into live and dead roots under the microscope based on colour, root elasticity, and the degree cohesion of cortex, periderm and stele. Several indicators were used to identify of the dead root among others are a dark cortex and stele, a