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Land-use change affects phosphorus fractions in highly weathered tropical soils

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ABSTRACT

Deforestation and land-use change in tropics have increased over the past decades, driven by the demand for agricultural products. Although phosphorus (P) is one of the main limiting nutrients for agricultural productivity in the tropics, the effect of land-use change on P availability remains unclear. The objective was to assess the impacts of land-use change on soil inorganic and organic P fractions of different availability (Hedley sequential fractionation) and on P stocks in highly weathered tropical soils. We compared the P availability under extensive land-use (rubber agroforest) and intensive land-use with moderate fertilization (rubber monoculture plantations) or high fertilization (oil palm monoculture plantations) in Indonesia. The P stock was dominated by inorganic forms (60 to 85%) in all land-use types. Fertilizer application increased easily-available inorganic P (i.e., H_2O-Pi, $NaHCO_3$-Pi) in intensive rubber and oil palm plantations compared to rubber agroforest. However, the easily-available organic P ($NaHCO_3$-extractable Po) was reduced by half under oil palm and rubber. The decrease of moderately available and non-available P in monoculture plantation means that fertilization maintains only the short-term soil fertility that is not sustainable in the long run due to the depletion of P reserves. The mechanisms of this P reserve depletion are: 1) soil erosion (here assessed by C/P ratio), 2) mineralization of soil organic matter (SOM) and 3) P export with yield products. Easily-available P fractions (i.e., H_2O-Pi, $NaHCO_3$-Pi and Po) and total organic P were strongly positively correlated with carbon content, suggesting that SOM plays a key role in maintaining P availability. Ecologically based management is therefore necessary to mitigate SOM losses and thus increase the sustainability of agricultural production in P-limited, highly weathered tropical soils.

1. Introduction

Land-use change and intensification of cultivation are the predominant global changes of this century. This is mainly because of the global socio-economic demand for food, feed, fiber and biofuel driven by population growth (Geissen et al., 2009; Guillaume et al., 2015). Intensification of agriculture involving high-yielding crop varieties, fertilization, irrigation, and pesticides causes soil degradation. As agriculture land becomes degraded, more forests are cut and converted for the needed agricultural production. This has led to a strong decrease of tropical rainforest area worldwide, especially in Southeast Asian countries (Gatto et al., 2015; Tarigan et al., 2015).

Indonesia is one of the tropical countries with highest deforestation rates, surpassing the rate in Brazil in 2012 (Hansen et al., 2009; Margono et al., 2014). Sumatra (Indonesia) lost more than half of its remaining natural rainforest between 1985 and 2007 due to deforestation and land-use intensification (Laumonier et al., 2010; Wilcove and Koh, 2010). Deforestation and agricultural intensification on the island is ongoing. Natural rainforests are converted to extensively managed agroforest (jungle rubber), then to intensively managed monoculture plantations (i.e., oil palm, rubber). These conversions are among the main drivers of deforestation aside from mining, timber and pulp industries (Guillaume et al., 2015; Villamor et al., 2014; Violita et al., 2015). However, extensive transformation of natural ecosystems to plantation leads to the decreased of soil fertility indicators and to subsequent soil degradation in Sumatra (Guillaume et al., 2016a, 2016b).

Land-use change significantly modifies the physical, chemical and biological soil properties, affects soil fertility, and increases erosion and compaction (Geissen et al., 2009; Matson et al., 1997; Moges et al., 2013). Phosphorus (P) is a key nutrient requiring attention in response to land-use change (Garcia-Montiel et al., 2000): it is the most limiting nutrient for plant productivity, especially in tropical regions (Dieter et al., 2010; Holford, 1997; Sanchez, 1976; Spohn et al., 2013;

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Vitousek, 1984). The highly weathered acidic soils and large quantities of sesquioxides adsorb and chemically fix P, leading to P limitations in tropical ecosystems (Bucher et al., 2001; Holford, 1997). Soil available P is mainly supplied by parent material, is recycled by decomposition of organic matter, and added by fertilizer inputs that enrich different P forms (i.e., available, moderately available, non-available inorganic and organic). When available P is depleted, replenishment from other P forms becomes important (Henriquez, 2002).

Land-use changes affect P availability for plant uptake either by increasing P losses or by transforming it to more recalcitrant pools. This leads to potentially significant effects on the distribution of P within chemically-defined pools, in turn determining availability and stability (Wright, 2009). Some studies on the partitioning of total soil P revealed effects of land-use change (Cassanova et al., 2002; Solomon et al., 2002). The fires – forest burning during plantation establishment – also impact soil P. They release P into the available pool, where it can be taken up by microorganisms, sorbed on the mineral matrix, leached or removed by runoff (Sanchez, 1976). At medium to high fire intensities (>300 °C), however, P mobilization is restricted and fixation increases. This is due to a heat-induced increase in mineral surface area, the production of Fe oxides free of organic matter and high affinity for P sorption (Ketterings et al., 2002). Short-term P fertilization is enhanced by ash of forest fires coupled with root decomposition of the original vegetation (Groppo et al., 2015). Nonetheless, fertility is not sustainable. Nutrient depletion occurs as plantations age (Numata et al., 2007; Townsend et al., 2002), reflecting nutrient removal with yield products. Furthermore, tremendous changes in plant biomass production and nutrient cycling due to vegetation conversions have a great negative or positive influence on soil properties and nutrient availability (Chen et al., 2003). The conversion of P from available to non-available (e.g., Al-P, Fe-P) and organic forms occurs in <50 years after land-use change, much faster than the thousands of years required under natural conditions (Garcia-Montiel et al., 2000). The conversion of forest to cropland decreased the P amount and increased the proportion of non-available P forms (Chacon and Dezzeo, 2004). Accelerated soil erosion due to land-use change reduced organic matter by half or more (Zheng et al., 2005), which is a source of organic substrate for nutrient release such as available P (Groppo et al., 2015; Pimentel et al., 1995).

Various approaches have been developed to study the forms, amount and dynamics of P cycling (Bowman and Cole, 1978; Chang and Jackson, 1957; Hedley et al., 1982; Tiessen and Moir, 1993). The sequential chemical fractionation developed by Hedley et al. (1982) has been widely used in recent decades to study soil P fractions and thus soil P dynamics (Chimdi et al., 2014). The chemical fractionation method evaluates the location and bonding type of P within the soil matrix (Guo et al., 2000; Yang and Post, 2011), and investigates the effects of land-use change on the distribution of P fractions. Hedley fractionation assumes that extractants of varying strength estimate inorganic phosphorus (Pi) and organic phosphorus (Po) fractions of different availability and chemical bindings (Guo et al., 2000; Hedley et al., 1982). The following fractions respond to extractants and are available: (i) H_2O-Pi and $NaHCO_3$-Pi, which are considered the most biologically and readily available Pi form. (ii) $NaHCO_3$-Po, which is easily mineralizable and may contribute to the plant-available Pi. (iii) NaOH-P, which is associated with P and is strongly adsorbed via a covalent bond between phosphate oxygen and the aluminum (Al) and iron (Fe) in clays, which are involved in long-term P transformations. (iv) HCl-Pi, which is relatively insoluble P, often associated with Ca-P. HCl-Po has not been measured in most sequential P fractionation studies. It is reported that this fraction is Ca-bound hydrolysable Po.

Most studies in Sumatra (Indonesia) on the effects of land-use change and deforestation deal with soil carbon contents and stocks. This reflects the importance of low-carbon agriculture, climate change and general soil fertility issues. Nonetheless, only few studies focus on the effect of land-use change on soil P availability; no studies are available on P fractionation of various forms of inorganic and organic P. Our study is designed to assess the effects of land-use change on inorganic and organic P forms of different availability and on the P stocks in highly weathered tropical soils. We hypothesized that inorganic and organic P fractions of different availability will strongly decrease after land-use change. Likewise, P stocks – the total of all P fractions – will also decrease.

2. Materials and methods

2.1. Study area and soil sampling

The study was carried out in Jambi Province in Sumatra, Indonesia. The climate is tropical humid with an average temperature of 27 °C and an average precipitation of 2200 mm $year^{-1}$ and 112–259 mm $month^{-1}$ (Guillaume et al., 2015). Aside from tropical rainforest, the area had three dominating land-use types: (1) jungle rubber, (2) rubber plantation, and (3) oil palm plantation. Jungle rubber is an extensively-managed agroforest (minimum age of 16 years) in which rubber trees are planted in a partially logged forest. Tree species namely: *Alstonia* spp., *Artocarpus* spp., *Fabaceae* sp., *Macaranga* spp., *Porterandia* sp., and *Hevea* sp. are the most common tree species in the agroforest system. On the other hand, rubber (*Hevea brasiliensis*) and oil palm (*Elaeis guineensis*) plantations were intensively managed monocultures of similar average age (14 yrs), ranging from 12 to 17 years (Guillaume et al., 2016a). Rubber and oil palm plantation received high NPK fertilization at a rate of 100–300 kg ha^{-1} $year^{-1}$ and 300–600 kg ha^{-1} $year^{-1}$, respectively. Fertilization happens twice a year once in the rainy season (October to March) and once in dry season (April to September). Herbicides were also applied in both plantations every 6 months (Kotowska et al., 2015).

To assess the effects of land-use change on P fractions, three replicate sites for each land-use type were selected within a distance of 16 km with an elevation varied between 50 and 100 m a.s.l. The soil was Acrisols with sandy loam texture. It is a highly weathered soil with strongly acidic soil pH ranged between 3.9 and 5.1. The base saturation ranged between 16 and 28% and effective CEC ranged between 40 and 46 $mmol_c$ kg^{-1} (Allen et al., 2015). At each site, samples were collected in one pit by horizons down a maximum depth of 1 m. Soils were air-dried and sieved at 2 mm. Plant debris and stones were removed. Soils were brought to the laboratory of the Department of Soil Science in Temperate Ecosystem in Göttingen University, Germany, for further analysis. A detailed description of the study area and soil sampling are available in Guillaume et al. (2015). Further information on land-use history, management and soil characteristics can be found in Allen et al. (2015) and Kotowska et al. (2015).

2.2. Soil incubation and preparation

Five grams of air-dried soil was placed in a glass bottle and incubated at field capacity at 24 ± 2 °C for 14 days prior to the sequential extraction in order to reach equilibrium after sampling, drying and sieving disturbances (Hedley et al., 1982). After the incubation, soils were stored at 4 °C and equilibrated at room temperature overnight prior to P sequential fractionation analysis.

2.3. Phosphorus sequential fractionation

The Hedley et al. (1982) sequential fractionation method as modified by Tiessen and Moir (1993) was used to fractionate soil P. This method uses a sequence of increasingly strong extractants that removed labile inorganic phosphorus (Pi) and organic phosphorus (Po) forms first, then stable P forms (Fig. A.1).

One gram of soil was placed into a 50 ml screw cap centrifuge plastic tube and sequentially extracted with the following extractants in