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Effects of flooding on phosphorus and iron mobilization in highly weathered soils under different land-use types: Short-term effects and mechanisms

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ABSTRACT

The strong affinity of phosphorus (P) to iron (Fe) oxides and hydroxides in highly weathered tropical soils limits P availability and therefore plant productivity in tropics. In flooded soils, however, P fixed by Fe oxides and hydroxides can be released into more available forms because of Fe^{3+} reduction to Fe^{2+}. These P dynamics in flooded soils are well documented for rice paddies. Such effects are much less studied in other land-use types influenced by seasonal flooding, especially in the tropics during heavy monsoon rains. The aim of this study was to investigate the P mobilization during flooding leading to anaerobic conditions in topsoil and subsoil depending on land-use type. Samples were collected in highly weathered Acrisols from four replicate sites under natural rainforest, jungle rubber, rubber and oil palm plantations in Sumatra, Indonesia. Topsoil and subsoil were taken to ensure a wide range of soil organic matter (SOM) and P contents. Soils were incubated under anaerobic, flooded conditions at 30 ± 1 °C for 60 days. Our results confirmed the hypothesis that soil flooding mobilizes P and increases P availability. Two distinct and opposite periods were observed during the flooding. During the first three weeks of flooding, the dissolved P (DP) concentration peaked, simultaneously with the peak of dissolved Fe^{2+} (DFe^{2+}) and dissolved organic carbon (DOC). After three weeks, P availability in soils decreased, although Fe-P (P_{NaOH}) and available P (P_{NaHCO3}) did not reach the initial, pre-flooding levels. The impacts of flooding on P and Fe forms was strong in the topsoil, where P dissolution and availability were generally higher under forest and, to a lesser extent, under jungle rubber. A positive correlation between DOC and DFe^{2+} ($R^2 = 0.42$) in topsoil indicates that the intensity of microbially-mediated Fe^{3+} reduction is limited by the amount of available carbon (C) as an energy source for microorganisms and as electron donor. Microbial mineralization of organic P from SOM also increases P availability, and this process requires available C. This interpretation was supported by the strong correlation ($R^2 = 0.58$) between available P and DOC, as well as between DP and DOC ($R^2 = 0.56$) in topsoil. The increasing pH in topsoil and subsoil after flooding of all land-use types may also influence the P release over time. In summary, the increase of available P and DP during flooding is due to three main mechanisms: (1) P release via the microbially-mediated reductive dissolution of Fe^{3+} oxides; (2) P release during SOM mineralization and (3) solubility of Fe phosphate due to increasing pH. These mechanisms are relevant not only in riparian areas, where flooding occurs, but also in soils waterlogged after regular heavy rainfalls during the wet season. Therefore, we speculate that the P turnover is faster in compacted soils under plantations because of regular changes of oxic and anoxic conditions. Consequently, more P is pumped by the vegetation and then removed from plantations due to yield export.

1. Introduction

Phosphorus (P) in most soils and especially in the tropics is limited for plant uptake due to its immobilization on iron (Fe) and aluminum (Al) oxides (Dieter et al., 2010; Holford, 1997; Maranguit et al., 2017). These bonds are very stable. Nonetheless, P sorption with Fe oxides

Abbreviations: P, phosphorus; Fe-P, Fe-bound phosphorus; DOC, dissolved organic carbon; DFe^{2+}, dissolved Fe^{2+}; DP, dissolved phosphorus; SOM, soil organic matter; C, carbon

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might be reversible under anaerobic conditions, e.g., after flooding (Parker and Beck, 2003; Ponnamperuma, 1972; Rakotoson et al., 2015, 2016). Large seasonal fluctuations in rainfall, typical of tropical forested ecosystems, can change available P and are highest directly after the onset of the wet season (Wood et al., 2015; Wood and Lawrence, 2008). Flooding increases the available P content by 1.4–60 mg P kg^{-1} compared with aerobic soils (Rakotoson et al., 2014). This is indicated by the increase of extractable P such as $NaHCO_3$-extractable P (Verma and Tripathi, 1982; Zhang et al., 2003).

Once flooded, soils rapidly become anaerobic, resulting in a decline in the redox potential (Eh) (Ponnamperuma, 1972). The microbial community structure shifts to microbes capable of anaerobic respiration (Unger et al., 2009). Microorganisms utilize alternative electron acceptors such as NO_3^{-}, Mn^{4+}, Fe^{3+} and SO_4^{2-} to maintain their metabolism (Loeb et al., 2008; Unger et al., 2009). They use the electron acceptor that yields the highest energy or that is most readily available. In highly weathered acidic soils, Fe^{3+} hydroxides are very abundant. Thus, microorganisms such as *Geobacter sulfurreducens* (Sánchez-Alcalá et al., 2011) will use Fe^{3+} as the terminal electron acceptor (Weber et al., 2006). Hence, Fe^{3+} will be reduced to Fe^{2+}, releasing substantial quantities of associated P (Amarawansha et al., 2015; Loeb et al., 2008; Ponnamperuma, 1972). Therefore, the P concentration in the soil solution will increase together with soluble Fe^{2+} (Kirk, 2004; Quintero et al., 2007). This mechanism, leading to an increase of P and Fe solubility under anaerobic respiration, is known as microbially-mediated reductive dissolution of Fe^{3+} oxides.

The amount of P released into the soil solution depends on: soil characteristics involved in reduction processes: 1) abundance of Fe oxides and their crystallinity; 2) soil organic matter (SOM) content and its microbial availability as electron donors (Quintero et al., 2007; Scalenghe et al., 2002); 3) total P content and its forms (Amarawansha et al., 2015) and 4) soil pH neutralization as a result of soil flooding, which increases the P availability by increasing the solubility of Fe- and Al-P compounds in acid soils (Chacon et al., 2005; Zhang et al., 2003). Additionally, SOM is used as a source of carbon (C) and energy by microorganisms to fuel and stimulate the microbially-mediated reductive dissolution of Fe^{3+} minerals (Rakotoson et al., 2015; Scalenghe et al., 2002; Zhang et al., 1994). Hence, we hypothesize that P released by Fe^{3+} reduction is stimulated in soil with high labile C availability. Furthermore, we hypothesize that P release is influenced by land-use changes because of their impacts on SOM and P contents.

Land-use conversion is the predominant global change in this century, driven by the high demand for food, fiber and other products (Geissen et al., 2009; Guillaume et al., 2015). In the tropics, for example in Indonesia, agricultural intensification is ongoing mainly for rubber and oil palm at the expense of primary and secondary forest (Gibbs et al., 2010; Guillaume et al., 2016). Forest conversion in general, strongly changes soil physical, chemical and biological properties (Geissen et al., 2009; Moges et al., 2013) as well as ecosystem functioning (Barnes et al., 2014) especially after conversion to rubber and oil palm monoculture plantation. Indeed, almost 70% SOC in the topsoil of oil palm and rubber plantations has been lost compared to rainforest in Indonesia (Guillaume et al., 2015). P forms changes from easily available to non-available forms due to P fixation by Fe and Al oxides. Organic P which is considered as reserve pool buffering available inorganic P becomes depleted and total P decreases after conversion of forest to oil palm and rubber plantations (Maranguit et al., 2017). Moreover, rubber and especially oil palm plantations suffer from soil compaction, resulting in higher bulk density and less water infiltration (Guillaume et al., 2016; Merten et al., 2016). Plantation soils are therefore quickly waterlogged by regular heavy rainfalls. This results in a series of biogeochemical changes that profoundly influence P status and availability. No studies are available on transformed systems in Sumatra, Indonesia, in particular studies focusing on the mobilization of P forms (Fe-bound P) that are normally retained by well-drained soils when these become partly waterlogged or flooded by regular heavy rainfalls during the wet season. Moreover, most of the literature on Fe dynamics and P availability after soil flooding pertains to rice paddies (e.g., Ponnamperuma, 1972; Rakotoson et al., 2015; Zhang et al., 2003).

In this study, we investigated the effects of flooding on the P and Fe dynamics in topsoil (0–10 cm) and subsoil (20–30 cm) horizons of Acrisol under forest, agro-forest (jungle rubber) and monoculture plantations of rubber and oil palm on Sumatra, Indonesia. The study was designed to assess changes in Fe and P solubility and mobility under flooded anaerobic incubation. We hypothesized that under flooding: (1) Fe^{3+} will be reduced to Fe^{2+}, thereby liberating P adsorbed on Fe^{3+}, as indicated by P in the solution and $NaHCO_3$-Extractable P in the soil; (2) the content of P bound to Fe oxides, which is measured by NaOH-Extractable P, will decrease; and (3) Fe^{2+} and P in the soil solution will increase and will be higher in the topsoil under forest and jungle rubber, which have a higher SOM content than soils under monoculture plantations.

2. Materials and methods

2.1. Study site and soil sampling

The soil samples were collected in the lowland of 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). Experiments were carried out in (1) tropical rainforest and three land-use types dominating in the study region: (2) jungle rubber, (3) rubber plantations and (4) oil palm plantations. Jungle rubber is an extensively-managed agroforest in which rubber trees are planted in a partially logged forest. Rubber and oil palm plantations were intensively managed monocultures. Rubber and oil plantations were mature plantations of 15 and 14 years old in average, respectively, while jungle rubber were older than 20 years old. The region is covered by tertiary sediments (Barber et al., 2005). Sites ranged between 50 and 100 m a.s.l. Soils were well-drained Acrisols according to the World reference Base classification with sandy loam texture. Further description of the study site is available in Guillaume et al. (2015).

To assess the effects of soil flooding on P mobilization, four replicate sites for each land-use type were selected. At each site, samples were collected in the topsoil (Ah horizon; 0–10 cm) and in the subsoil (20–30 cm) by digging a pit. These topsoil and subsoil samples were taken to ensure a wide range of soil properties with regard to SOM and P content (Table 1). Soil samples were air-dried and sieved at 2 mm. Plant debris and stones, if present, were removed.

2.2. Soil flooding and incubation

2.5 g of soil sample were filled into a 12 ml glass tube (Labco Exetainer). Six milliliters of purified distilled water were added in each tube and air was driven out by purging N_2 gas. The suspension was then covered with a rubber stopper to prevent O_2 diffusion, evaporation losses and to ensure anaerobic conditions. Four field replicates of each land-use type and depth for each determination were incubated in the dark at 30 ± 1 °C. Directly after water addition (1 h) and after 7, 14, 21, 28, 45, and 60 days of continuous soil flooding, samples were shaken and pH was determined. Then, samples were filtered using a syringe filter with 0.45 µm pore size (Labsolute, Germany). The extracts for dissolved P (DP) and dissolved Fe^{2+} (DFe^{2+}) determination were acidified immediately with 1 ml of 0.1 M HCl per 2 ml of solution to prevent oxidation. The remaining extracts were analyzed for dissolved organic C (DOC) (*see* Section 2.3). The samples were further analyzed for available-P and Fe-P (*see* Section 2.4).