



Pasture degradation decreases organic P content of tropical soils due to soil structural decline



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ABSTRACT

Degradation of tropical pastures on highly weathered soils is linked to soil structural decline and associated losses of organic matter, which could both also affect soil phosphorus (P) dynamics and availability. Our aim was to elucidate these linkages by examining the effect of pasture degradation on the contents and forms of P contained within aggregate size classes and macroaggregate fractions (collectively referred to as soil structural components). We conducted a study on nine farms in a deforested part of the Colombian Amazonia, each farm with degraded and productive *Brachiaria* spp. pastures. Topsoil (0–10 cm) samples were separated by wet-sieving into aggregate size classes, and macroaggregates were further separated into occluded fractions. Soils and structural components were analyzed for concentrations of total P, available P (extracted using anion exchange resins), NaOH–EDTA extractable organic and inorganic P, and enzyme-hydrolyzable organic P (simple monoester-like, DNA-like, *myo*-inositol hexakisphosphate-like) in the NaOH–EDTA extracts. Degraded pasture soils had significantly fewer large macroaggregates and more microaggregates, both with significantly lower organic P concentrations (in mg P kg⁻¹ of structural component) than those in productive pasture soils. At the same time, total and extractable inorganic P concentrations in bulk soil and structural components did not differ between pasture types, suggesting a shift from organic to non-extractable P upon degradation. Soils under productive pastures contained 37% more organic P than degraded pasture soils (in mg P kg⁻¹ soil), mainly in large macroaggregates. The organic P concentrations were strongly correlated with C concentrations across all soil structural components, suggesting similar stabilization mechanisms for organic P and C. In bulk soil and most structural components, around 60% of organic P was enzyme-hydrolyzable. The lower contents of all enzyme-hydrolyzable as well as enzyme-stable organic P in degraded vs. productive pasture soils indicate a reduction of all organic P classes during pasture degradation. The large macroaggregates and, in particular, microaggregates occluded within this fraction were identified as an important site for organic P storage. Our results highlight a linkage between soil structure and organic P, both of which can play an important role in maintaining the productivity of pastures established on highly weathered soils.

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1. Introduction

Highly weathered soils of the humid tropics typically have low total and available phosphorus (P) contents and P is often the primary limiting nutrient to plant growth (Nziguheba and Bünemann, 2005; Vitousek et al., 2010). On deforested areas in South America, pastures sown with introduced grasses (*Brachiaria* spp.) represent a dominant land use, and the majority of pastures exist in some stage of degradation (Jimenez and Lal, 2006). Pasture degradation is understood as a marked reduction

in livestock production due to a significant decrease in plant biomass production and invasion of non-palatable plant species, and it leads to appearance of bare soil patches, soil compaction and reduced soil microbial biomass (Boddey et al., 2004; de Oliveira et al., 2004). Pasture degradation has enormous economic implications. For example, in Brazil every year about 8 million ha of degraded pastures require considerable investment for renewal and/or recovery (Jank et al., 2014), with estimated costs of 100 to 200 US\$ ha⁻¹, i.e., around 1 billion US\$ in total (FAO, 2006). Soils of degraded pastures have been shown to store less carbon (C) than soils of productive pastures (Asner et al., 2004; Fonte et al., 2014). Pasture over-grazing and reduced pools of available nitrogen (N) and P are seen as the principal causes of degradation (Dias-Filho et al., 2001; Fisher et al., 2007). While the importance of

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N cycling and availability has been demonstrated previously (Boddey et al., 2004), a mechanistic understanding of the role of P in maintaining pasture productivity is missing.

Because most inorganic P is strongly sorbed, organic P has been suggested to play a critical role in sustaining P availability in highly weathered soils (Tiessen et al., 1984; Turner et al., 2006). Biological P cycling through plant uptake, residue decomposition and microbial turnover, which includes synthesis of organic P, appears to be crucial to protect P from sorption and to maintain P availability in highly weathered tropical soils (Oberson et al., 2006). Organic P constitutes 16% to 65% of total P in highly weathered soils (Nziguheba and Bünemann, 2005).

A single-step procedure involving sodium hydroxide and EDTA (ethylenediaminetetraacetate) is often used for the extraction of soil organic P from strongly weathered tropical soil (Turner, 2008). Additions of enzymes to various soil extracts have been used to characterize hydrolyzable forms of organic P, as reviewed by Bünemann (2008), e.g., addition of acid phosphatase or phytase to soil water extracts (Fox and Comerford, 1992; Shand and Smith, 1997). As different enzymes hydrolyze different organic P bonds, this approach delivers information on the chemical form of organic P in soils (He and Honeycutt, 2001; Turner et al., 2002a). Based on P release by acid phosphatase, phytase and nuclease from defined organic P compounds, Annaheim et al. (2013) classified the hydrolyzed P into simple monoesters, *myo*-inositol hexakisphosphate and nucleic acids. Keller et al. (2012) used the same approach to classify organic P in NaOH-EDTH extracts. Enzyme-hydrolyzable organic P identified by phytase addition to EDTA extracts was shown to be greater in Oxisols under no till than with conventional tillage (Pavinato et al., 2010), suggesting that enzyme-hydrolyzable organic P is a sensitive indicator for the impacts of soil management on soil P status.

Soil aggregation is considered important for regulating the storage and turnover of soil organic C (Six et al., 2000a) and nitrogen (N) (Bosshard et al., 2008). Relatively few studies have examined the effect of aggregation on P and these have suggested that P availability, P concentrations and forms can be influenced by aggregation (McDowell et al., 2007; Wang et al., 2001). For example, P uptake was greater in plants grown in large aggregates (2–6 mm) than in plants grown in small aggregates (<0.5 mm) of highly weathered Oxisols because P bound to large aggregates was more readily desorbed (Wang et al., 2001). The water extractable P concentration decreased with smaller aggregate sizes in cropped soils in Canada (Messiga et al., 2011). The concentrations of orthophosphate, monoesters, diesters and pyrophosphates determined by ^{31}P -nuclear magnetic resonance (^{31}P -NMR) spectroscopy increased with decreasing aggregate size in a soil from New Zealand, while phosphonates and polyphosphates were unaffected (McDowell et al., 2007). We also note that the effect of management (or landuse) on P concentrations in different structural components is amplified when the proportion of these components on a whole soil mass basis is also affected.

In a recent study, the distribution of soil mass among aggregate size classes was found to differ between degraded and productive pasture soils (Fonte et al., 2014). Although soils of both pasture types had a high aggregate stability, the proportion of large macroaggregates (>2000 μm) was significantly higher in productive (65 g 100 g $^{-1}$) than in degraded pasture soils (56 g 100 g $^{-1}$). Soil of productive pastures had 20% higher total C and N contents (in g kg $^{-1}$ soil) than degraded pastures. These differences in total soil organic matter (SOM) between pasture types were largely explained by a greater C content in the large macroaggregate fraction, and more specifically in the microaggregates (53–250 μm) occluded within this macroaggregate fraction (Mmicros). Interestingly, there was no difference in total P content between pasture types, but organic P content was found to be nearly 40% greater in soils of productive vs. degraded pastures. The findings of Fonte et al. (2014) suggest that different organic P contents in the bulk soils of productive and degraded pastures could be related to differences in soil structure and the distribution of C across aggregate

fractions. Specifically, these results lead us to hypothesize that greater organic P content is associated with the greater protection of SOM in the Mmicros fraction of productive pastures.

To further elucidate the role of aggregation in the P status of highly weathered tropical soils we examined the distribution of organic, inorganic and available P across aggregates and occluded macroaggregate fractions of the same degraded and productive pasture soils studied by Fonte et al. (2014). To obtain information on organic P forms, we determined enzyme-hydrolyzable organic P classes by enzyme additions. Finally, we studied the relationship between C and organic P across the different soil structural components.

2. Material and methods

2.1. Site description, experimental design and soil sampling

The study was conducted on nine farms located in the deforested Amazon region of Colombia. All farms are situated within a 30 km radius of the city of Florencia, in the Department of Caquetá (1°36'50"N 75°36'46"W) with an average elevation of 280 m.a.s.l. The region has a humid tropical climate with a mean annual precipitation of 3400 mm and a mean annual temperature of 25 °C. The mildly undulating topography is characterized by acid soils, mainly Oxisols and Ultisols (Mosquera et al., 2012) with textures in the 0–10 cm soil layer ranging from silty clay to sandy clay loam (Fonte et al., 2014).

The design of the study has been described in Fonte et al. (2014). Briefly, on each of the nine farms, areas of productive and degraded pasture were identified together with farmers. Degraded pastures had clear signs of degradation (e.g., patches of bare soil, invasion of herbaceous weeds and grasses other than the sown species, significant or total loss of previously sown *Brachiaria* spp.), while productive pastures were those dominated by *Brachiaria* spp. (mainly *Brachiaria humidicola* CIAT 679 and *Brachiaria decumbens* CIAT 606). Productive pastures had significantly greater live and litter biomass than degraded pastures (Table 1). Degraded and productive pastures had similar topography and age since pasture establishment. All farms experienced similar management histories, with forest cleared at least 40 years earlier. Basic soil properties are shown in Table 1.

For aggregate separation and P analyses, four soil sub-samples were taken from regularly spaced sampling points, at 3 m from a central point in each pasture type on all nine farms in July 2011 (Fonte et al., 2014). Samples were carefully collected to a depth of 10 cm using a soil knife so as to incur minimum disruption of aggregates. The four sub-samples were combined, resulting in one sample per each pasture type per farm, or 18 samples in total. Field moist soil clods were gently broken along natural planes of weakness, so that they also passed the 8 mm sieve. Earthworms, termites, plant debris and stones were removed. The soil was dried at 50 °C and shipped to the Soil Physics Laboratory of the International Center for Tropical Agriculture (CIAT) in Cali, Colombia for aggregate separation.

2.2. Soil and macroaggregate fractionation

We analyzed sub-samples of the various aggregate size classes and occluded macroaggregate fractions isolated by Fonte et al. (2014). We here summarize the fractionation method. Soil samples were first wet-sieved based on Elliott (1986) into large macroaggregates (>2000 μm), small macroaggregates (250–2000 μm), microaggregates (53–250 μm) and the silt&clay (<53 μm) fraction (Fig. 1). To this end, 80 g of soil was submerged in deionized water on a 2000 μm sieve and slaked for 5 min. The soil was then sieved by oscillating the sieve in and out of the water 50 times over a period of 2 min. Macroaggregates remaining on the sieve were then washed into a pre-weighed aluminum pan for drying. Soil which passed through the sieve was transferred to a smaller sieve and the sieving process repeated with a 250 μm and with a 53 μm sieve. All free aggregate size classes were

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