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Pasture degradation impacts soil phosphorus storage via changes to aggregate-associated soil organic matter in highly weathered tropical soils

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ABSTRACT

Maintaining the productivity of tropical pastures is a major challenge for the sustainable management of tropical landscapes around the globe. To address this issue, we examined linkages between soil organic matter (SOM), aggregation, and phosphorus (P) dynamics by comparing productive vs. degraded pastures in the deforested Amazon Basin of Colombia. Paired plots of productive (dominated by planted *Brachiaria* spp.) vs. degraded pasture were identified on nine farms in the Department of Caquetá and sampled during the rainy season of 2011. Aboveground pasture biomass production and nutrient content were measured. Surface soils (0–10 cm) were also fractionated by wet sieving, and C, ^{13}C, N and P contents were analyzed for the bulk soil and various aggregate size classes. Productive pastures yielded more than double the aboveground biomass compared to degraded pastures (during a 35 day regrowth period following cutting), with over 60% higher N and P contents in this material. Similar trends were observed for the standing litter biomass and nutrient contents. Soil aggregate stability was found to differ between pasture types, with a mean weight diameter of 3590 vs. 3230 μm in productive vs. degraded pastures, respectively. Productive pastures were found to have 20% higher total soil C and N contents than degraded pastures. While there was no difference in total P content between pasture types, organic P was found to be nearly 40% higher in soils of productive vs. degraded pastures. Differences in total SOM between pasture types were largely explained by a higher C content in the large macroaggregate fraction (>2000 μm), and more specifically in the microaggregates (53–250 μm) occluded within this fraction. These findings confirm the role of microaggregates within macroaggregates as a preferential site for the physical stabilization of SOM, and furthermore, suggest that it may serve as a useful diagnostic fraction for evaluating management impacts on SOM in tropical pasture systems. Similar to trends observed for C and N, total P content was 25% higher in the microaggregates within large macroaggregates of productive vs. degraded pasture soils. This correspondence between C and total P contents in large macroaggregate fractions, along with elevated levels of organic P in productive pastures, suggests that this P is likely in an organic form and that there is a close link between soil structure, SOM dynamics and the maintenance of organic P in these soils. Given the potential relevance of organic P for efficient P cycling in these soils, our findings offer critical new insight for the management of SOM and aggregate-associated P pools in tropical pasture systems.

1. Introduction

Conversion of tropical forest to agriculture persists as a critical ecological threat of our time, with severe implications for global biodiversity and climate change. In Colombia alone, more than 8%

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of the remaining forest area has been lost since 2000 (much of this in the Amazon Basin) yielding one of the highest deforestation rates in South America, with the vast majority of this area being converted to pasture systems for livestock production (Asner et al., 2004; Wassenaar et al., 2007). Throughout much of the Amazon Basin, deforested sites are typically slashed and burned, and pastures established after only a few years of cropping (Fujisaka et al., 1996; Martinez and Zinck, 2004). Improved pastures are often established with *Brachiaria* spp. (or other introduced grasses) and moderate inputs of lime and/or fertilizers are typically applied to address soil chemical deficiencies (Miles et al., 2004). Despite this initial investment, the majority of tropical pastures degrade after only a few years if overgrazed or not properly maintained with periodic inputs of fertilizer and lime (Fisher et al., 1997; Jimenez and Lal, 2006). In the process of degradation, pasture productivity and organic matter inputs decrease, non-palatable plant species invade, vegetative cover is reduced (thus increasing susceptibility to erosion), soil becomes compacted and more acidic, and microbial biomass decreases (Fearnside, 1996; de Oliveira et al., 2004; Martinez and Zinck, 2004). This phenomenon has tremendous economic and ecological implications, as it leaves large areas of degraded land and promotes a trend of continuing deforestation (Steinfield et al., 2006).

The maintenance of productive pasture systems in much of the Amazon Basin, and many other regions where tropical pastures are common, is complicated by poor soil quality. Many tropical soils are highly weathered and acidic, with severe problems of Al toxicity and nutrient deficiency, particularly P (Rao et al., 1999; Oberson et al., 2006). To address issues of P limitation, considerable research has sought to better understand and ameliorate P deficiencies in these soils. This work has considered extensively the management of organic resources for moderating P availability (Nziguheba et al., 1998), and more specifically the mechanisms by which soil microbial activity regulates P cycling in these systems (Oberson et al., 2001, 2006). Given the high P-sorption capacity of these soils, this strategy seeks to maintain P in a biologically active form in order to avoid fixation of P to mineral surfaces.

In conjunction with this focus on P cycling, much could be also gained through increased recognition of the role of soil organic matter (SOM) as a primary substrate for and determinant of soil microbial activity in these soils. The accumulation or loss of SOM is driven by a number of management associated factors including C inputs, soil disturbance and fertilization (Paustian et al., 1997; Fonte et al., 2009). Of great importance to SOM dynamics is the formation and turnover of soil aggregates. The incorporation of fresh organic residues into aggregates has been long considered a key factor in the physical stabilization of SOM (Tisdall and Oades, 1982). Microaggregates (53–250 μm) in particular, are thought to be of particular relevance for SOM storage due to their relative stability (Angers et al., 1997). However, macroaggregates (>250 μm) have also been suggested to play a fundamental role in the early stages of organic matter protection, as they represent a preferential site for the formation of, and the stabilization of C within microaggregates (Six et al., 2000, 2002), and these can persist well beyond the life of a typical macroaggregate (Oades, 1984; Angers et al., 1997). Disruption of soil structure by overgrazing, compaction, or management factors can therefore have important consequences for SOM storage and needs to be examined in the context of tropical pasture degradation and associated SOM and P dynamics.

This research sought to address these issues by examining the C, N and P contents of aggregate size fractions within degraded and productive pastures of the Colombian Amazon Basin. Preliminary research at the study site demonstrated soils of degraded pastures to be more compacted and have lower pH than productive soils (Hegglin, 2011). Based on these findings, we hypothesized that reduced soil structure within degraded pastures (associated with compaction) would correspond with declines in SOM, via alterations to organic matter storage in key aggregate size fractions. We used the fact that pastures based on C4 grasses were originally converted from forest dominated by C3 species in order to better examine the dynamics of new C from C4 grass entering into pasture soils. Additionally, we hypothesized that a decrease in SOM would lead to reductions in total and organic P, thus indicating important consequences for biologically-associated P pools in these systems.

2. Materials and methods

2.1. Study site and experimental design

Research was conducted on farms located near the city of Florencia, in the Caquetá Department of Colombia (1°36′50″N, 75°36′46″W). Situated in the northern Amazon Basin, this region sits along the eastern slope of the Andean Cordillera Oriental and is largely composed of pasture areas that were deforested more than 50 years ago. With an average elevation of 280 m, the region experiences a mean annual temperature of 25 °C and an annual precipitation of 3400 mm, with a mild dry season typically occurring between November and March. The mildly undulating topography is characterized by acid soils, mainly Ferralsols and Acrisols (Mosquera et al., 2012) with textures ranging from silty clay to sandy clay loam.

Nine replicate farms were selected for this research, each possessing areas of productive and degraded pasture. Participating farmers helped to identify degraded vs. productive pastures (minimum 1 ha) that were implemented at approximately the same time and using similar interventions (i.e., introduction of *Brachiaria* spp, fertilizer and lime). Informal interviews on the management history of each pasture indicated that grazing intensity (i.e., the ratio of grazed to ungrazed days) was generally higher for the pastures identified as degraded, at least in the last several years leading up to this study. Further investigation confirmed farmer observations, noting that degraded pastures demonstrated clear signs of productivity loss (e.g., patches of bare soil, invasion of other grasses and herbaceous weeds, 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) with no obvious signs of productivity decline. All farms were located within a 30 km radius of Florencia and experienced similar management histories (i.e., forest cleared >40 years earlier).

2.2. Soil sampling, preparation and preliminary measurements

In July of 2011, four soil sub-samples in each pasture type on all nine farms were taken from regularly spaced sampling points, 3 m distance from a central point in each pasture. These samples were carefully collected to a depth of 10 cm using a soil knife, so as not to disrupt aggregates or disturb soil structure, and combined (yielding one sample for each pasture type per farm, or 18 samples in total). Samples were gently stored in plastic bags and kept cool for transport. Immediately upon return to the laboratory, the field moist subsamples from each pasture were dry-sieved by gently breaking soil clods along natural planes of weakness, so that they passed through an 8 mm sieve. Soils were then dried at 50 °C for shipping and further processing at International Center for Tropical Agriculture (CIAT) and the Swiss Federal Institute of Technology (ETH Zurich).

2.3. Vegetation and productivity estimates

Litter deposition in the pastures was assessed in July of 2011 by collecting dead plant material lying on the ground and senesced aerial plant biomass still affixed to the stems within an area of