Geoderma Regional 14 (2018) e00184

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

Phosphorus transformations in alfisols and ultisols under different land uses in the atlantic forest region of Brazil

Tarciana de Oliveira Viana [a], Antonio Carlos Gama-Rodrigues [a,*], Emanuela Forestieri Gama-Rodrigues [a], Seldon Aleixo [a], Renato Valadares de Souza Moreira [a], Marcus Vinícius da Silva Sales [a], José Raimundo Bonadie Marques [b]

[a] Laboratório de Solos, Universidade Estadual do Norte Fluminense Darcy Ribeiro - UENF, Campos dos Goytacazes, RJ CEP 28013-602, Brazil
[b] Centro de Pesquisas do Cacau, CEPLAC/CEPEC, Itabuna, BA CEP 45700-000, Brazil

ARTICLE INFO

Article history:
Received 31 October 2017
Received in revised form 27 June 2018
Accepted 28 June 2018
Available online xxxx

Keywords:
Agroforestry systems
Soil organic phosphorus
Sequential extraction method
Structural equation modeling
Ultisols
Alfisols

ABSTRACT

This study examined the impact of land use changes on phosphorus (P) transformations in soils of different pedogenesis with little or no addition of P in the humid tropical region. The sequential extraction method was used to determine P fractions, and structural equations modeling was employed to investigate the P cycle in soils under plantations of rubber tree (*Hevea brasiliensis*), rubber tree + cocoa (*Theobroma cacao*), rubber tree + acai palm (*Euterpe oleracea*), rubber tree + cupuassu (*Theobroma grandiflorum*) and cocoa + erythrina (*Erythrina glauca*) as well as pastures (*Brachiaria decumbens*) and natural forests. The distribution of P fractions in soil appears to be affected by land use in all soil orders. Agroforestry systems of rubber tree + acai palm and rubber tree + cocoa showed high capacity to increase the concentrations of all the P fractions in soil compared to natural forest in soils of advanced stage of weathering. Pastures and rubber plantations provided higher concentrations of inorganic P fractions. The P fractionation method revealed the potential of labile fractions (resin-Pi + $NaHCO_3$-Pi + Po) to supply appropriately the demand of all vegetation types evaluated in all soil orders. The structural model enabled to identify functional pools of P in soil, and to identify transformation processes of P in soil, in which organic P pool was the main P source for the available P pool and which part of the occluded P pool (recalcitrant) can be available for the plants.

1. Introduction

Cacao (*Theobroma cacao L.*) and the rubber tree (*Hevea brasiliensis* Muell. Arg) are among the main commodities in many tropical countries (Hartemink, 2005; Langenberger et al., 2017), but the rising fertilizers prices have raised concerns about the sustainability of these crops, once they are usually planted on low fertility soils (Müller and Gama-Rodrigues, 2012; Marques et al., 2012). In consequence, the soil fertility under rubber tree and cocoa plantations is maintained by nutrient recycling (Fontes et al., 2014; Marques and Monteiro, 2016). Thus, the nutrient quantities exported from the agroecosystem through harvesting are not replaced by mineral fertilizers by most farmers. In this context, it is necessary to find alternatives to reduce fertilizer costs and to establish soil fertility management strategies for a low-input production system.

In Brazil, the rubber tree + cocoa agroforestry system is undergoing expansion with the purpose of diversifying and increasing farmers' income to replace the traditional cocoa + erythrina agroforestry system or the monoculture rubber tree plantations (Marques and Monteiro, 2016). As an alternate to land use, other multistratified agroforestry systems have also been tested, such as rubber tree + acai palm or rubber tree + cupuassu, but still at pilot scale. However, as these agroforestry systems are predominantly distributed over highly weathered soils, phosphorus (P) deficiency is considered to be the main limiting nutritional factor in agricultural productivity (Oberson et al., 2006; Yang and Post, 2011).

Highly-weathered tropical soils such as Latosols and Argisols present high reactivity and high retention of P added as mineral fertilizer in its solid phase, mainly with iron (Fe) and aluminum (Al) oxides, limiting its bioavailability. In this soil environment, P availability is highly dependent on the mechanisms plant roots use to access the range of P sources in soil, both organic and inorganic (Gama-Rodrigues et al., 2014). The method of P fractionation proposed by Hedley et al. (1982) has been more widely used to describe the transformations of P occurring in soil (Condron and Newman, 2011), involving sequential extraction of labile, moderately labile and recalcitrant fractions of P. In a recent review, Negassa and Leinweber (2009) evaluated the effectiveness of sequential P fractionation in demonstrating how the distribution of

* Corresponding author at: UENF/CCTA/Laboratório de Solos, Av. Alberto Lamego 2000, Campos dos Goytacazes, RJ CEP 28013-602, Brazil.
E-mail address: tonygama@uenf.br (A.C. Gama-Rodrigues).

https://doi.org/10.1016/j.geodrs.2018.e00184
2352-0094/

labile and moderately labile fractions of P in soil is affected by soil management and land use.

Specifically for agroforestry systems in humid tropical regions, the distribution of the P fractions in soil was affected by agroforestry type, species composition, soil order and management practices with little or no P addition, revealing which P fractions acted as a sink or a source of available P in medium and long term (Lehmann et al., 2001; Szott and Melendez, 2001; Cardoso et al., 2003; Aleixo et al., 2017). Nevertheless, Mehlich-1 extractor is still widely used in estimating available P for the monoculture rubber tree plantations, and rubber and cocoa agroforestry in soils of different pedogenesis in the Atlantic Forest region of Bahia in Brazil (Chepote et al., 2012), without considering other P forms in the soil that may be P sources for plants. In addition, the P values obtained by Mehlich-1 are very low in soils with high acidity-buffering capacity (Novais and Smyth, 1999). Thus, the current recommendation for P fertilization is likely to overestimate the need for phosphate fertilizer application in rubber tree plantations and rubber and cocoa agroforestry, especially in low input production systems.

Our general hypothesis was that the concentrations and proportions of P fractions will show strong variation due to land use in different soil orders. The specific hypothesis was that in strongly weathered soils the conversion from natural forest to monoculture of rubber tree or pastures or agroforestry of rubber tree + cocoa or rubber tree + acai palm will negatively affect the fractions of labile and moderately labile P, particularly the organic P (Po) fractions, since in these production systems there was little or no input of mineral P. Thus, the objectives of the present study were (1) to evaluate the relationship between the distribution of the different P fractions and the dissimilarity between the land use systems in different soil orders; (2) to build a structural model of the soil P cycle to provide quantitative estimates of the transformation processes of soil P, based on the source-sink relationships of P pools.

2. Materials and methods

2.1. Description of sites

This study was performed in the areas of the Experimental Station Djalma Bahia (EDJAB) and in the farms Bolandeira and Juerana in the municipality of Una (15° 17′ 20.44" S, 39° 3′ 39.44" W), and in the Cocoa Research Center (CEPEC) located at the Executive Committee of the Cocoa Plantation Plan (CEPLAC) in the municipality of Ilhéus (14° 47′ 1.47" S, 39° 13′ 37.80" W). All the areas studied are located in South of the State of Bahia, Brazil. The region's climate is type *Af*, according to the Köppen classification; it is characterized by a mean annual rainfall of 2000 mm, no water deficit, and a mean annual temperature of 26 °C (Climatological Station of CEPLAC, unpublished data). Three sites with Dystrophic Yellow Argisols (Ultisols), five sites with Dystrophic Grayish Argisols (Ultisols) and three sites with Eutrophic Haplic Nitosols (Alfisols) under rubber tree plantation, and agroforestry of rubber tree and cocoa, natural forests and pastures were selected. Description of the eleven sites is shown in Table 1. In each soil order, the sites selected were equidistant from each other and in a flat relief, in order to try to achieve the same environmental condition for all of them. In the Nitosol order there were no fragments of natural forest and pasture near the sites of the selected agroecosystems. In each site, four fixed plots of 900 m^2 were delimited for soil sampling; the plots were separated by at least 100 m. A sample composed of soil between the row planting, formed of 15 single soil samples taken at 0–10 cm depth, was collected from each plot in April 2012.

2.2. Physical-chemical characterization of soil

Total carbon (C) was determined by oxidation with $K_2Cr_2O_7$ 1.25 mol L^{-1} in an acid medium (Anderson and Ingram, 1996) and total nitrogen (N) by Kjeldahl method. Granulometry and other chemical attributes were determined according to Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA (1999). Briefly, granulometry was performed using the pipette method after pre-treatment with 35% H_2O_2 and 1.0 mol L^{-1} HCL to remove organic matter and carbonates. The pH was measured with a glass electrode in a 1:2.5 water suspension. Exchangeable Ca, Mg, and Al were extracted with 1.0 mol L^{-1} KCl, and K was extracted with Mehlich-1. The concentrations of Ca^{2+}, Mg^{2+} e Al^{3+} in the extracts were determined by atomic absorption spectrophotometer, and K concentrations were determined by flame emission spectrophotometer. The potential acidity (H + Al) was extracted with Ca acetate at pH 7. The sum of bases (SB) corresponded to the sum of the concentrations of $Ca^{2+} + K^{+} + Mg^{2+}$ and the cation exchange capacity at pH 7 (CEC) by SB + (H + Al). The total P was determined by digesting 5 g of macerated soil in $H_2SO_4 + H_2O_2$ (Hedley et al., 1982). The results of physical and chemical analyses of soils under different land uses are shown in Table 2.

2.3. Fractionation of soil P

Fractions of P in soil samples were extracted sequentially using the Hedley method with the modifications proposed by Condron et al. (1985). The extraction procedure was begun by weighing 0.5 g of air dried soil in 15-mL Falcon tubes. P fractions of soil were extracted

Table 1
Brief description of different sites selected in three soil orders.

Site	Soil order	Land use	Age (years)	Management
1	Dystrophic Yellow Argisols	Natural forest	–	Unfertilized Atlantic Forest fragment
2		Pasture	30	Unfertilized *Brachiaria decumbens* replacing a natural forest,
3		Rubber tree (monocrop)	35	Rubber tree (*Hevea brasiliensis* Muell. Arg.) spacing was 7 × 3 m, without inorganic fertilization since 1982
4	Dystrophic Grayish Argisols	Natural forest	–	Unfertilized Atlantic Forest fragment
5		Pasture	10	Unfertilized *Brachiaria decumbens* replacing a natural forest, without inorganic fertilization
6		Rubber tree (monocrop)	35	Rubber tree spacing was 7 × 3 m, without inorganic fertilization since 1982
7		Rubber tree + açaí palm	30	Rubber tree and açaí palm (*Euterpe oleracea* Mart) spacing was 7 × 3 m, without inorganic fertilization since 1987
8		Rubber tree + cocoa	35	Cocoa rows (*Theobroma cacao* L.) spacing was in double rows of 2 × 2 m. Lines L1 and L2 were planted at a distance of 2.5 m from the hevea hedgerows. Rubber tree spacing was 7 × 3 m, without inorganic fertilization since 1982
9	Eutrophic Haplic Nitosols	Cocoa + erythrina	35	Erythrina (*Erythrina glauca* Lour.) spacing was 25 × 25 m, distributed in a quincunx that totaled 32 trees per hectare, cocoa tree spacing was 3 × 3 m, without inorganic fertilization since 1990
10		Rubber tree + cocoa	12	Cocoa rows spacing was in four rows of 2 × 2.5 m. Lines L1 and L4 were planted at a distance of 2.5 m from the hevea hedgerows. Double hevea hedgerows at a density of 7 × 4 × 3 m, without inorganic fertilization since 2006
11		Rubber tree + cupuassu	40	Rubber tree and cupuassu (*Theobroma grandiflorum* (Willd. ex Spreng.) K. Schum.) spacing was 7 × 3 m, without inorganic fertilization since 1980