Science of the Total Environment xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

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

Legacy phosphorus and no tillage agriculture in tropical oxisols of the Brazilian savanna

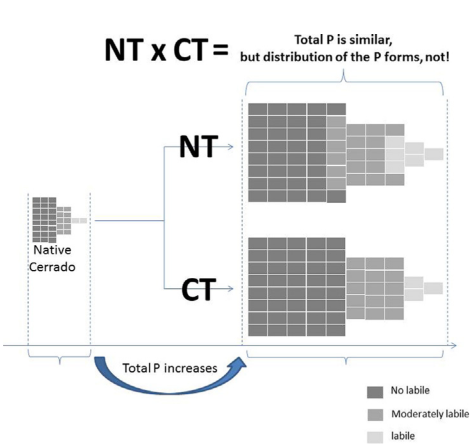
Marcos Rodrigues [a], Paulo Sergio Pavinato [a,*], Paul John Anthony Withers [b], Ana Paula Bettoni Teles [a], Wilfrand Ferney Bejarano Herrera [a]

[a] University of São Paulo, "Luiz de Queiroz" College of Agriculture, Soil Science Department, Pádua Dias Av., 11, Box 9, Zip code 13418-900 Piracicaba, SP, Brazil
[b] School of Environment, Natural Resources and Geography, Bangor University, Bangor LL57 2UW, UK

HIGHLIGHTS

- P fractionation is useful to investigate the soil P-cycling changes under tillage systems.
- The land use change from native vegetation to agriculture increases all P fractions in the soil.
- The no tillage promotes organic P accumulation in topsoil (0-10 cm) and increases all inorganic P fractions.
- NT increases the labile organic and inorganic P pools whereas CV only in the moderately labile P pool.
- The contribution of biological P in tropical Oxisols increases after conversion to agriculture.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 December 2014
Received in revised form 31 July 2015
Accepted 20 August 2015
Available online xxxx

Keywords:
Phosphorus fractionation
Inorganic P
Organic P
No tillage

ABSTRACT

Crop production in the Brazilian Cerrado is limited by soil phosphorus (P) supply without large inputs of inorganic P fertilizer, which may become more costly and scarce in the future. Reducing dependency on fertilizer P requires a greater understanding of soil P supply in the highly weathered soils in this important agricultural region. We investigated the impact of no tillage (NT) and conventional tillage (CT) agriculture on accumulated (legacy) soil P and P forms in four long-term sites. Compared to the native savanna soils, tilled soils receiving regular annual P fertilizer inputs (30–50 kg P ha^{-1}) increased all forms of inorganic and organic P, except highly recalcitrant P associated with the background lithology. However, 70–85% of the net added P was bound in moderately labile and non-labile forms associated with Fe/Al oxyhydroxides rather than in plant available forms. Under NT agriculture, organic P forms and labile and non-labile inorganic P forms were all significantly ($P < 0.05$) increased in the surface soil, except for one site with maize residues where labile inorganic P was increased more under CT agriculture. The contribution of organic P cycling in these tropical soils increased after

* Corresponding author.
E-mail address: pavinato@usp.br (P.S. Pavinato).

http://dx.doi.org/10.1016/j.scitotenv.2015.08.118

Cerrado
Brazilian savanna

conversion to agriculture and was proportionally greater under NT. The results highlight the large amounts of unutilized legacy P present in Brazil's Cerrado soils that could be better exploited to reduce dependency on imports of finite phosphate rock. No tillage agriculture confers a positive albeit relatively small benefit for soil P availability and overall soil function.

1. Introduction

Phosphorus (P) is an essential fertilizer element to maintain or increase the productivity of cropped ecosystems (Condron and Newman, 2011; Johnston et al., 2014). However, recent and predicted future increases in P fertilizer costs, linked to increasing global P demand and declining reserves of mineable phosphate rock (PR) (Cordell et al., 2009; Elser et al., 2014) have raised serious concerns about the efficient use of this non-renewable resource. To reduce the growing pressure on global PR reserves, fertilizer P must be better managed in agricultural systems (Childers et al., 2011; Withers et al., 2015), especially in emerging economies such as Brazil, where future P demand is expected to be high.

In 2010, Brazil imported around 51% of its total PR demand of 1.4 Tg P $year^{-1}$ (3.2 Tg P_2O_5 $year^{-1}$) for fertilizer use. This usage equates to an average application of 29 kg P ha^{-1} $year^{-1}$ (66 kg P_2O_5 ha^{-1} $year^{-1}$), and is projected to increase by 5% per year for the next 5 years (ANDA, 2011). Average P use is high compared to many other countries due to the need to compensate for the rapid immobilization of soluble by secondary Fe/Al compounds in the highly weathered soils of the region (Novais et al., 2007; Sattari et al., 2012). Improving the efficiency of P use in Brazils' cropping systems and reducing dependence on high rates of fertilizer requires a better understanding of how soil, crop and fertilizer management practices influence long-term P availability in soils, and requires access to long-term experiments (Rowe et al., 2015).

Phosphorus is found in organic and inorganic forms in soil, ranging from ionic forms in solution to highly stable compounds with soil organic matter (SOM) and mineral fractions (Negassa and Leinweber, 2009; Shen et al., 2011). Inorganic P (Pi) can be divided into primary mineral-P (e.g. apatite), secondary precipitates of amorphous and crystalline Fe, Al and Ca, and adsorbed-P, predominantly to 1:1 clay silicates and oxy-hydroxides of Fe and Al (Parfitt, 1978). In Brazilian soils which have a very high P fixation capacity because of their high content of Fe and Al oxides and hydroxides, Pi in the soil solution is often very low and limits crop yield (Novais et al., 2007; Tiessen, 2005). Organic P forms (Po) encompass the soil microbial biomass and SOM decomposition compounds of varying recalcitrance, including phosphomonoesters, phosphodiesters and organic polyphosphates (Nash et al., 2014). This P pool can represent 20–80% of the total soil P and its availability is very variable and dependent on SOM decomposition (Condron and Tiessen, 2005). The dynamics of Po forms in soils are far less understood than inorganic P forms, not least due to analytical limitations (Turner et al., 2005). However, this fraction is highly relevant to the supply of P to crops in highly weathered soils because of the very limited availability of Pi (Nziguheba and Bünemann, 2005; Tiessen, 2005).

Farming systems and soil and fertilizer management alter P dynamics and availability by changing P forms and their relative quantities in soil (Agbenin and Goladi, 1998; Matos et al., 2006). In natural systems on highly weathered soils the mineralization and decomposition of forest litter and SOM are the primary sources of P (Vincent et al., 2010). In agricultural systems, annual additions of inorganic fertilizer become the main P source, increasing total P content in soil. However the form in which P accumulates depends on soil type and soil management. For example, under no-tillage (NT), both Pi and Po accumulates more in surface horizons relative to conventional tillage (CT) because of the lack of regular soil disturbance (Redel et al., 2007; Zamuner et al., 2008). Pi accumulates at the soil surface under NT because higher P affinity adsorption sites become more saturated, lowering P binding energies and increasing P diffusion to the soil solution. Po accumulates due to the concentration of crop residues at the soil surface leading to greater SOM and its decomposition products (Rheinheimer and Anghinoni, 2003). However the relative importance of Pi and Po forms under differing soil and crop management systems is poorly understood, especially in the highly weathered soils of Brazil's intensely farmed areas (Zamuner et al., 2008; Pavinato et al., 2009).

The Cerrado is an important agricultural region of Brazil producing grain and fibre, and has seen the largest increase in cultivated cropping areas over the last 30–40 years. In 2012/13, around 20.6 M ha were cultivated to grow soybean, maize and cotton, and this area is increasing every year. According to FEBRADP (2012) the NT system in Brazil is also expanding rapidly; increasing from around 25 M ha in 2005/06 to 30 M ha in 2011/2012, with more than 7 M ha now in the Cerrado region. Phosphorus fertilizer use in the Cerrado has also changed considerably since the first areas were reclaimed from the natural savanna vegetation and cultivated for agriculture. Typical rates are now 44–87 kg P ha^{-1} $year^{-1}$ (100–200 kg P_2O_5 ha^{-1}) in the first year of cultivation and 26–35 kg P ha^{-1} $year^{-1}$ (60–80 kg P_2O_5 ha^{-1}) once the cropping system has become established.

The objective of this research was to evaluate the effects of long-term NT and CT cultivation systems on the amounts of accumulated (legacy) soil P and the fractionation of soil inorganic and organic P in four Oxisols of the Cerrado biome compared to the native Brazilian savanna. Phosphorus fractionation to separate P forms has been widely and successfully used to study the distribution of labile and non-labile forms of Pi and Po in soils under differing lithologies and agricultural practices (Negassa and Leinweber, 2009; Condron and Newman, 2011).

2. Material and methods

2.1. Sites characterization and experimental treatments

Field experiments were established at four representative sites on oxisol (Ox) soils of the Cerrado biome (Fig. 1): Ox1, Ox2, Ox3 and Ox4.

The climate across the four sites is relatively similar and classified as Aw – tropical, with a well-defined rainy season from October to April and a four to five month dry season with very little rain (Fig. 2).

The sites were established at different times and provide a unique opportunity to study the long-term effects of soil cultivation system on soil phosphorus in this important region. Two sites (Ox1 and Ox3) have run for about 20 years and two sites (Ox2 and Ox4) have run for 13 years (Table 1). The soils are classified as very acid Oxisols, Typic Hapludox (Soil Survey Staff, 2014) and have been previously characterized for granulometry and mineralogy (Table 2). Ox1 and Ox3 both have high clay content (65%), while Ox2 has slightly less clay (45%) and more silt (36%), and Ox4 has a high proportion of sand (70%). Soils Ox1 and Ox2 have both a high content of crystalline and amorphous Fe/Al. Ox3 has less crystalline Fe, but a similar amount of crystalline Al and amorphous Fe/Al to Ox1 and Ox2. Ox4 has much lower amounts of crystalline and amorphous Fe/Al than the other soils.

Prior to experimental establishment, soybean (*Glycine max* L.) and maize (*Zea mays* L.) crops were grown at Ox1 and Ox3 under a continuous CT system for 20 and 15 years respectively. At Ox2, soybean was previously grown under CT in 1997/98, but then soybean and cotton (*Gossypium hirsutum* L.) were grown using NT in succeeding years until the treatments were established in 2001 (Table 1). At Ox4, after Cerrado deforestation in 1990/91, soybean was grown under CT until 1994/95. Thereafter it was cropped to soybean and maize under NT except in one year (1999/00) when it was conventionally cultivated. Since