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Sugarcane green harvest management influencing soil phosphorus fractions

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ABSTRACT

Few researchers have evaluated phosphorus (P) fractions in soils from humid tropical regions in which sugarcane (*Saccharum spp*) is harvested without prior burning. Aiming to evaluate if that practice may promote substantial changes in the availability of soil P, we analyzed the differences in total P, organic P (P_o), and extractable inorganic P (P_i) fractions in soil samples collected from an Oxisol. A long-term (14 years) randomized block design was employed with six replicates and two treatments: green-harvest (GH) and burned-harvest (BH) in a sugarcane plantation. Soil samples, with six replicates, were collected at depths of 0–0.05 m, 0.05–0.1 m, 0.1–0.2 m, 0.2–0.3 m, and 0.3–0.4 m from the planting row, 0.25 m perpendicular to the row, and in the inter-row. The total P_o fraction had the greatest variation between the GH and BH systems. Total P_o concentration was lower in the 0–0.05 m soil layer of the GH system than that of the BH system. Total P_o had also accumulated in the 0.2–0.3 m layer, which is where P fertilizer was applied at planting. These differences were observed in the planting row and 0.25 m from the planting row, but not in the inter-row. There was also no relationship between Pi fractions and row position or sampling depth in the two harvest systems. Long-term GH management rather than conventional BH sugarcane promoted greater cycling of P_o in the soil, while concentrations of P_i fractions did not differ between harvest systems.

1. Introduction

The predominant soils in Brazil's sugarcane (*Saccharum spp*) producing regions are highly weathered, mostly Oxisols, and the clay fraction consists of variable-charge minerals, such as kaolinite and Fe, Al, and Mn oxides (Fontes and Alleoni, 2006). Given this mineralogy, nearly 90% of the soluble P added to such soils as mineral or organic fertilizer is adsorbed by the solid phase, making the soil predominantly a P sink (Abdala et al., 2012). The need for substantial applications of phosphate fertilizers has led to a search for mechanisms that might reduce or even reverse P sorption in these soils.

Management practices that increase organic matter (OM) contents in soils can increase the biological availability of P (Soltangheisi et al., 2021). Phosphorus can be released from decaying plant residues to soils via mineralization and microorganisms can immobilize available P in soils (Damon et al., 2014). OM decomposition can also release soluble organic compounds that block P adsorption sites and solubilize Fe, Al, and Ca phosphates (Guppy et al., 2005; Heredia and Cirelli, 2007).

The sugarcane mechanical harvest without burning (green- harvest - GH) led to an accumulation of large amounts of sugarcane straw on the soils (Cherubin et al., 2018). With this management, up to 14 t ha^{-1} year^{-1} or more of plant residues are deposited in the field (Carvalho et al., 2017; Bordonal et al., 2018). This residue is commonly incorporated into the soil every six to eight years, when replanting the sugarcane crop.

Increases in soil OM content (Galdos et al., 2010; Razafimbelo et al.,

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Abbreviations: BH;, burned-harvest; CDB, citrate-dithionite-bicarbonate; GH, green-harvest; ICP-AES, inductively coupled plasma-atomic emission spectrometry; NV, natural vegetation; OM, organic matter; P_i, inorganic phosphorus; P_o, organic phosphorus; Al-P, aluminum-bound inorganic phosphorus; Ca-P, calcium-bound inorganic phosphorus; Fe-P, iron-bound inorganic phosphorus; P-occluded, reductant soluble Pi or occluded in Fe oxides; recalcitrant $P_i + P_o$, residual P not extracted in previous steps.

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2006; Robertson and Thorburn, 2007) and improvement in fertility parameters (Correia and Alleoni, 2011; Canellas et al., 2010) have been reported in soils under GH management. Conde et al. (2005) reported that the P content in sugarcane plant residues was between 10.4 and 15.6 kg ha^{-1}, depending on cultivar and specific management practices. However, P is the most slowly mineralized macronutrient (Fortes at al, 2012). In contrast, under the burned-harvest (BH) system, P is immediately released to the soil in the ash (Panosso et al., 2011).

The GH management and fertilizing ratoon cane promote better physical, chemical, and biological conditions in the soil next to the planting row than in the soil of the inter-row, 0.75 m from the planting row (Graham and Haynes, 2006). Phosphate fertilizer is applied directly to the bottom of the furrow where sugarcane is planted, typically at a depth of about 0.3 m, decreasing P adsorption, so that the P is positionally available to the growing roots. This favors the accumulation of P in both inorganic and organic fractions at that depth (Santos et al., 2018). Correia and Alleoni (2011) reported that soil P availability increased under GH compared to the BH system, especially at depths of up to 0.2 m. However, soil P concentrations determined by Mehlich-1 extraction were higher under BH than under GH only in the surface layer (0–0.05 m).

An improved understanding of the nature and distribution of P fractions, by chemical fractionation, in soils cultivated with sugarcane under the GH system will help to clarify how maintaining sugarcane plant residues on the soil surface affects P dynamics and availability. Fractionation methods derived from Chang and Jackson (1957) have been widely used to study Al-P, Fe-P, occluded-P, and Ca-P fractions based on differences in solubility by NH_4F, NaOH, CDB (citrate-dithionite-bicarbonate) and H_2SO_4, respectively (Zhang and Kovar, 2009).

We hypothesized that harvesting sugarcane without burning would change the distribution of soil inorganic and organic P fractions, especially in the uppermost soil layer and in the planting row. We aimed here to evaluate the differences in total P, organic P (P_o), and extractable inorganic P (P_i) fractions in soil samples collected at different sampling positions and depths from an Oxisol in GH and BH sugarcane plantations.

2. Materials and methods

This study was conducted in an experimental plot established in 1995, located in Pradópolis, São Paulo, Brazil (21°23′S; 47°59′W; 620 m a.s.l.), at a site with a slope less than 3% in which sugarcane has been cultivated continuously since 1950. The soil is a clayey Typic Hapludox (Soil Survey Staff, 1999). The sand concentration in the soil is 217 g kg^{-1}, the silt concentration is 127 g kg^{-1}, and the clay concentration is 656 g kg^{-1}, as quantified by the densitometer method (Gee and Or, 2002). According to the Köppen classification, the climate is Aw, tropical with rainy summers and dry winters, average annual temperature of 22.5 ºC and average annual rainfall of 1470 mm.

Before the first sugarcane burning and harvest in 1996, the soil chemical properties at 0–0.2 m and 0.2–0.4 m depths were evaluated, with results, respectively: pH in 0.01 M $CaCl_2$ (1:2.5 soil:solution) = 4.7 and 4.9; OM = 37 and 33 g dm^{-3}, estimated by multiplying organic C obtained by Walkley-Black method (Walkley and Black, 1934) by 1.724, as a factor based on an assumed percentage of C in organic matter (Nelson and Sommers, 1982); labile P = 13 and 19 mg dm^{-3} (extracted with ion-exchange resin (Raij et al., 1986); exchangeable cations, $K^+ = 2$ and 7 mmol$_c$ dm^{-3}; $Ca^{+2} = 23$ and 26 mmol$_c$ dm^{-3}; $Mg^{+2} = 6.7$ and 7.5 mmol$_c$ dm^{-3} (extracted with ion-exchange resin); extractable $Al^{+3} = 2$ and 1 mmol$_c$ dm^{-3} (extracted with 1 M KCl); exchangeable H +Al = 47 and 42 mmol$_c$ dm^{-3} (extracted with 0.5 M calcium acetate at pH 7.0); cation exchange capacity (CEC) = 79 and 77 mmol$_c$ dm^{-3}; and base cation saturation (BS) percentage = 40% and 46%.

The experimental design was a randomized block with six replicates of each treatment of green-harvested - GH and burned-harvested - BH management of sugarcane. Each plot contained 22 rows, 50 m long. A central area of 10 rows, 30 m long, was harvested. The site had gone through two previous cycles of plant cane and ratoon (stubble) crops (1995–2003 and 2003–2009). Tillage in the planting year included harrowing, subsoiling, and leveling. At the beginning of each cycle, 2 t ha^{-1} of limestone were applied to the soil and incorporated uniformly in the first 0.3 m-layer.

In the first cycle, 500 kg ha^{-1} of a 10–25–25 N-P_2O-K_2O dry blend, equivalent to 50, 55, and 105 kg ha^{-1} of N, P, and K, respectively, were applied at the bottom of the planting furrow (0.2–0.3 m). In the subsequent ratoon crops, 600 kg ha^{-1} of 15–05–25 N-P_2O-K_2O dry blend, equivalent to approximately 90, 13, and 126 kg ha^{-1} of N, P, and K, respectively, were applied each year, at 0.2 m beside the planting row. In the second cycle, 28, 24, and 70 kg ha^{-1} of N, P, and K, respectively, were applied at the bottom the planting furrow as a 10–20–30 N-P_2O-K_2O dry blend. An average of 104 and 92 kg ha^{-1} year^{-1} of N and K, respectively, were applied to the ratoon crops in the same way as in the first cycle of sugarcane.

Twenty soil cores were collected and composited from each plot in January 2009 at three sampling positions (in the planting row, 0.25 m from the planting row, and in the inter-row, i.e., 0.75 m from the planting row). Soil cores were divided into five depth increments (0–0.05 m, 0.05–0.1 m, 0.1–0.2 m, 0.2–0.3 m, and 0.3–0.4 m). To serve as a control for comparing changes related to sugarcane management, six composite samples (five subsamples for each replicate) were also collected at the same depths from an adjacent site with natural vegetation (Ombrophilous Atlantic Forest).

Soil samples were sieved to 2 mm, and a portion of each was air dried and subjected to chemical characterization, carried out at Soil Fertility Laboratory (Department of Soil Science- ESALQ/USP, Piracicaba, SP, Brazil). There, total carbon (total C) obtained by dry combustion was analyzed in an elemental autoanalyzer (Nelson and Sommers, 1982), after the samples had been grounded and sieved in a 0.1 mm mesh; to pH 0.01 mol L^{-1} $CaCl_2$ in the ratio air-dried soil:solution of 1:2.5; and to P-available extracted by the double acid solution of Mehlich-1 (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4) (P Mehlich) (EMBRAPA, 1999), quantified by colorimetry. The results for total carbon, pH and labile P for each treatment and native vegetation are shown in Fig. 1.

Other part of the samples was kept at the field humidity level, packed in plastic bags and stored in a cold chamber, at a temperature of 2° C, until the moment of analyses for total P, total organic P and fractionation of inorganic P, carried out from August to October 2009 at the National Laboratory for Agriculture and Environment, USDA/Agricultural Research Service (ARS), Ames, IA, USA.

Total P was extracted in aqua regia ($HCl:HNO_3 = 4:1$) following the method of Crosland et al. (1995). Phosphorus in digests was determined by inductively coupled plasma atomic emission spectrometry (ICP-AES). Total organic P was determined by the ignition method (Kuo, 1996), in which organic P in the soil is converted to inorganic P by oxidation at 550 °C. Total organic P was then calculated from the difference between total P from ignited samples (Pi) and total P from unignited samples. Phosphorus concentrations in the digests were determined colorimetrically by the phosphomolybdate procedure (Watanabe and Olsen, 1965).

Inorganic P was fractionated following the method described by Zhang and Kovar (2009). Extracts were filtered through a 0.45-µm membrane to remove organic particles in suspension, and P determination was carried out by inductively coupled plasma emission spectroscopy (ICP-AES). The residual P (recalcitrant Pi + Po) was calculated as the difference between Total P and the other P fractions (Total organic P + Inorganic P fractions).

There is some uncertainty about the specific inorganic P forms at each stage of P fractionation methods (Condron and Newman, 2011), but we assumed that the P extracted with NH_4Cl, NH_4F, NaOH, sodium citrate-dithionite-bicarbonate – CDB, and H_2SO_4 reflected soluble-P, Al-bound P, Fe-bound P, occluded P and Ca-bound P, respectively (Zhang and Kovar, 2009). More advanced analytical technologies for

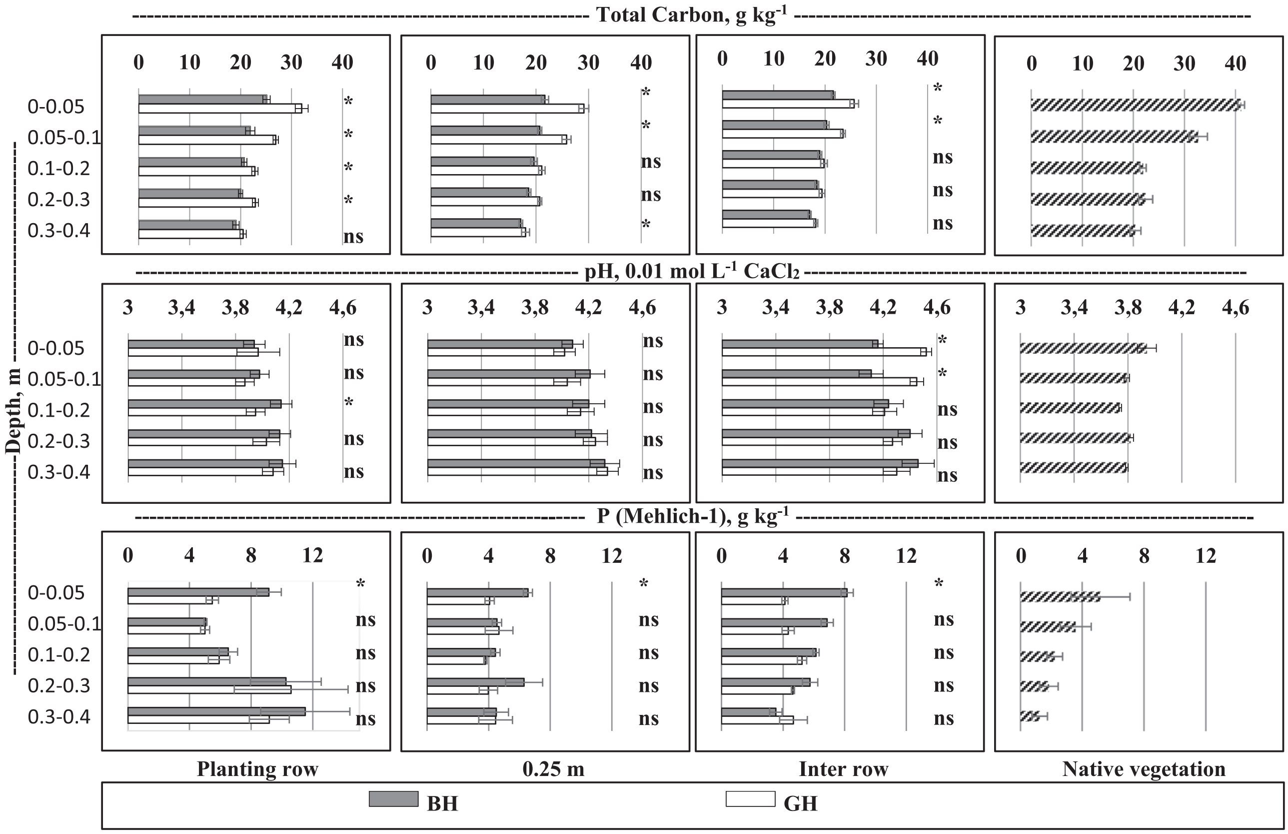

Fig. 1. Contents of total carbon, pH and available P (Mehlich-1) in a Typic Hapludox cultivated with sugarcane under burn-harvested (BH) and Green-harvested (GH) management systems as a function of soil depths and soil sampling positions (planting row, 0.25 m from the planting row, inter-row – 0.75 m from the planting row). Soil samples from an adjacent area under native vegetation were also evaluated. Means from BH and GH management systems for each soil depth were compared by Tukey test ($p < 0.05$): *significant; ns=not significant. Bars represent standard errors.
Adapted from Correia and Alleoni (2011).

elucidating the specific P link to mineral and/or organic compounds in the soil, such as nuclear magnetic resonance (NMR) or x-ray absorption near-edge structure analysis (XANES) (Liu et al., 2017), were not available for our study.

Analyses of variance (ANOVA) were performed following a factorial model (2 ×3×5), with two harvest systems, three sampling positions, and five soil layers (depths). Statistical analyses were carried out with the MIXED procedure of SAS, with replicate x management and replicate x management x row position as random effects, and management, row position, and depth as fixed effects (SAS Institute, 1997).

In a separate analysis, data from the natural vegetation (NV) site were compared with inter-row data from the GH and BH management

Table 1
Concentrations† of total phosphorus (total P) and total organic phosphorus (total P_o) at different sampling positions and depths in a Typic Hapludox cultivated with burn-harvest (BH) and green-harvest (GH) management of sugarcane and at an adjacent site with natural vegetation (NV).

Depth	BH						GH						NV	
(m)	Planting row		0.25 m		Inter-row		Planting row		0.25 m		Inter-row			
	mg kg^{-1}													
	Total P (10)#													
0–0.05	1152†	a	1105	A	1099	A	1129	a	1072	a	1112	a	1229	a
0.05–0.1	1009	b	983	Bc	946	B	1029	ab	937	b	986	b	1168	ab (*, *)
0.1–0.2	1064	ab	1009	Ab	984	B	965	b	951	b	973	b	1163	abc (*, *)
0.2–0.3	1065	abA	956	bcAB	895	bB	1028	abA	953	bAB	947	bAB	1039	c
0.3–0.4	952	b	883	C	978	B	933	b	921	b	959	b	1010	c
	Total P_o (21)													
0–0.05	260	A	228	AB	222	AB	159	cBC	142	cC	250	A	317	a (*, ns)
0.05–0.1	264		268		272		299	ab	251	b	263		392	a (*, *)
0.1–0.2	283		276		267		332	ab	309	ab	299		333	a
0.2–0.3	253	C	256	BC	253	C	350	aA	324	aAB	288	BC	337	a (*, ns)
0.3–0.4	303		279		284		265	b	242	b	269		363	a (*,*)

†Mean values (from 6 replicates) in columns followed by the same lowercase letter and in rows followed by the same uppercase letter are not different (Tukey, $p < 0.05$). #Coefficient variation (%). #For comparison of the NV treatment with BH and GH harvest management (Tukey, $p < 0.05$), “ns” is not significant and “* ” is significant.

systems. The effects of management and soil profile depth were evaluated using the GLM procedure of SAS (SAS Institute, 1997). In all cases, means were compared by Tukey's test ($p < 0.05$).

3. Results and discussion

3.1. Soil total P

Across all parameters evaluated (harvest management, distances from row and distinct soil layers), total soil P ranged from 883 to 1228 mg kg^{-1} (Table 2). Total P in the NV soil was higher ($p < 0.05$) than in BH and GH managed soils at the 0.05–0.1 m layer (Table 1), reflecting P removals by sugarcane harvests for more than six years without P fertilization, since no P was added to the ratoon crops during the second crop cycle (2003–2009). Conversely, Tiecher et al. (2012) reported lower concentrations of total P in soils under native vegetation than under no tillage or conventional tillage cultivation after 23 years with summer-winter annual crop rotation. According to Tiecher et al. (2012), higher total P levels were the result of the annual application of phosphate fertilizers in cropped areas as compared to native vegetation.

At the same distance from the row, total P concentrations in soil samples under GH management did not differ from those under BH management at each depth evaluated (Table 1). Redel et al. (2007) also reported no differences in soil total P between no tillage and conventional tillage systems in an Ultisol from Chile under oat–wheat and white lupine–wheat crop rotations for five years. Similarly, Zamuner et al. (2008) also observed no effect of tillage system in total P content after eight years of annual crop rotation in a Mollisol in Argentina.

In our study, similar amounts of P were supplied to the soil, at the planting fertilization stage six years prior to the soil sampling, and plant residues regardless of management system. Under BH management, P in the ashes left after burning was periodically incorporated into the soil with tillage. Under GH, P was also returned to the soil with residue decomposition. Conversely, Canellas et al. (2010) evaluated samples of an Entisol (370 g kg^{-1} clay) that had been managed for 55 years under GH and BH and observed total P concentrations that were 234% higher in the surface layer (0–0.2 m) and 160% higher in the subsurface layer (0.2–0.4 m) under GH than under BH management.

The long-term accumulation of sugarcane plant residues without burning may favor the return of P to soils. Moreover, the damaging effect of burning can compromise crop development by interfering with factors other than P availability, both suppressing yield and P turnover in the soil. In our study, carried out on a clayey Hapludox, the GH management was established for 14 years, and this period may not have been sufficient to increase total P concentration in the soil to the extent observed by Canellas et al. (2010).

In both harvest treatments and at the NV site, concentrations of total P were higher in the uppermost soil layer (0–0.05 m) than in the other layers and decreased gradually with depth (Table 1). Under BH, this is attributed to the deposition of ashes on the soil surface. The effect may have extended down to 0.3 m because sugarcane had been burned for years, and the ashes were periodically incorporated with tillage carried out at each seasonal planting. On the other hand, the same effect under GH was observed only in the uppermost (0–0.05 m) layer, at the 0.25 and inter-row positions, as a result of the straw deposition.

Araújo et al. (1993) reported decreasing total P with depth in samples of an Oxisol cultivated with sugarcane under BH management. More recently, Oliveira Filho et al. (2021) found similar results for an Inceptisol following 37 years of sugarcane production under BH management. Araújo et al. (1993) attributed the effect to (i) the annual application of soluble phosphate fertilizer to the ratoon, (ii) the recycling of P from crop residues and ashes after burning, and (iii) the low mobility of P in the soil profile. It is common for total P concentrations to decline with depth, as has been reported by several authors with diverse soils, crop species and management practices (Schroeder and Kovar, 2006; Jiménez-Cárceles and Álvarez-Rogel, 2008; Assis et al., 2010; McLaughlin et al., 2011; Tiecher et al., 2012).

3.2. Organic P

Soil total organic P (P_o) varied little with harvest management, soil depth, or sampling position relative to the planting row (Table 1). Soil under BH management had higher concentrations of total P_o than that under GH management in the 0–0.05 m layer of the planting row and at 0.25 m from the planting row (Table 1). This uppermost surface layer received the greatest organic inputs, and because the total carbon concentration was greater under GH management (Fig. 1), the lower total P_o was not expected.

Our results suggest that P in the ashes was quickly released to the soil solution and may have been directly immobilized in organic forms thereafter (Scheuner et al., 2004), leading to an increase in P_o similar to surface horizon P in soils under forests that are managed with burning (Cade-Menun et al., 2000). In the present study, burning did lead to an increase in labile Mehlich-P concentrations, as reported by Correia and Alleoni (2011) (Fig. 1), because the ashes could provide continuous, long-term inputs of P. The greater concentration of P_o in the uppermost layer under BH management could also result from the physico-chemical stabilization of P_o caused by the linkage of phosphate monoesters to Fe and Al oxides in the soil (Condron et al., 2005; Celi and Barberis, 2005).

At the 0 – 0.05 m depth, the plant residue decomposition under GH seems to happen so slowly that a depressing effect on organic P concentrations was observed after two full crop cycles (14 years). Sugarcane residues typically mineralize slowly (Gava et al., 2005). Fortes et al. (2012) reported that the trend of nutrient release rate from post-harvest sugarcane straw was K > Ca > N > Mg > S > P after three years; only 23% of the residue P had been mineralized after three years. So, we hypothesize that mineralization did not release enough P to promote an increase in total P_o concentrations. Moreover, a very high organic C:P ratio (204) was observed in the 0–0.05 m of the planting row and at 0.25 m from the row. The lack of an effect of plant residues on P immobilization as organic P is consistent with other related studies, as observed by Dick (1983) in soil with a C:P ratio of 121–129 and managed under a no-till system for 18 years, and by Umrit and Friesen (1994) in *Setaria sphacelata* residues with a C:P ratio of 227.

The opposite was observed at the 0.2 – 0.3 depth, where the total Po concentration in GH was higher than BH. At the same depth, phosphorus fertilizer was placed in the planting furrow in both the GH and BH management systems but in GH, a higher total carbon concentration was found (Fig. 1). The phosphate fertilizer applied at the bottom of the planting furrow may have immobilized as P_o, pushed by a higher level of OM in that layer. Increased levels of total P_o as result of phosphate fertilization were also found by Tiessen et al. (1992) in Brazilian semi-arid soils. This could have occurred as a result of migration of organic complexes from the uppermost layer, which received OM inputs, to the deeper layers that hold residual fertilizer P.

There was no difference ($p < 0.05$) between harvesting systems in P_o concentrations of samples collected in the inter-row (Table 1). It is possible that the inter-row receives too little ash from burning and fertilizers to create different levels of accumulation, i.e., not enough to lead to differences in the total P_o fraction (Beck and Sanchez, 1994).

3.3. Inorganic P fractions

In the present study, the concentrations of inorganic P extracted by NH_4Cl (P-NH_4Cl) were below the limit of detection for soil samples evaluated (i.e., <1 mg kg^{-1}). Olibone and Rosolem (2010) reported P-NH_4Cl concentrations ranging from 7 to 12 mg kg^{-1} to a depth of 0.1 m, but no detectable concentrations were found below that layer in a sandy loam soil (220 g kg^{-1} clay) under a no-tillage system. Moreover, very low concentrations of P-NH_4Cl (0.3–2.7 mg kg^{-1}) have also been reported for 16 New Zealand grassland soils with 40 – 310 g kg^{-1} of clay (Chen et al., 2003).

The concentrations of P_i-NH_4F (Al-P) were higher in the three deepest layers from 0.1 to 0.4 m of the cultivated inter-row than in the soil under native vegetation (NV) (Table 2). This trend reflects the long-term management of soil fertility in the sugarcane production systems. Pavinato et al. (2009) also reported higher concentrations of moderately labile P in a P-fertilized Oxisol cultivated with soybean under both no-till and conventional management than in a comparable soil under NV. This suggests that residual P from fertilization can be retained in weakly labile fractions in Oxisols under agricultural production.

Values of P_i-NH_4F under BH and GH managements were not different at all depths when comparing the same sampling position (Table 2). However, under BH management and in the planting row, there was considerably more P_i-NH_4F at 0.3 – 0.4 m than in the overlying soil (Table 2). This suggests that the distribution of the P_i-NH_4F fraction under BH management was driven by the spatial distribution of the mineral fertilizer applied to the crop. In contrast, there were no differences in P_i-NH_4F among depths under GH management, perhaps due to the prevalence of interactions between Al sorption sites and organic matter (Celi and Barberis, 2005) given that total carbon content was higher in the GH system than in the BH system (Fig. 1).

The highest P_i-NaOH (Fe-P) concentrations were detected in the uppermost layer (0–0.05 m) of the NV soil (Table 2), a result of OM mineralization from long-term plant litter deposition, as also reported by Alleoni et al. (2012). Under BH and GH harvest systems, the highest P_i-NaOH concentrations in the surface layer, compared with other layers at the same position, were observed in samples collected in the planting row, due to the addition of ash under the BH system and crop residues under GH system (Table 2). There was no difference ($p < 0.05$) in P_i-NaOH concentrations between GH and BH managements at different sampling positions, except at the depths of 0.2–0.3 m for the BH planting row (Table 2), which may reflect residual P from fertilization. Olibone and Rosolem (2010) reported a corroborating increase in the P_i-NaOH fraction in samples of a coarse-textured Oxisol under triple superphosphate fertilization. Pavinato et al. (2009) also reported higher P_i-NaOH concentrations in two P-fertilized Oxisols under both no-till and conventional management.

Lower concentrations of P_i-CDB (P-occluded) were measured in soils cultivated with sugarcane than under NV at depths of 0–0.05 m and 0.05–0.1 m (Table 2). This suggests that long-term management practices, such as the addition of lime, that increases the pH, the localized application of fertilizer, and the recycling of plant residues could promote a release of P from occluded sites (Damon et al., 2014). On the other hand, as with P-NaOH, there were no differences in P-CDB concentrations between BH and GH managements. With respect to soil depths, the P-CDB concentration was less at 0.2–0.3 m and 0.3–0.4 m in the 0.25 m position and at 0.3–0.4 m in the inter-row position under BH compared to the planting row; this was not the case under GH management.

In most cases, there were no differences ($p > 0.05$) in the concentrations of the more recalcitrant fraction, P_i-H_2SO_4 (Ca-P), between harvest systems (BH and GH), between the cultivated soils and NV, nor across depths analyzed. The exception was a higher concentration in the uppermost layer (0–0.05 m) of the BH treatment at the planting row position (Table 2), possibly due to the presence of calcium phosphate in the ashes of the burned straw (Ball-Coelho et al., 1993). Under GH treatment, values of P_i-H_2SO_4 reflected Ca introduced into the system by mineralization of residues (Canellas et al., 2010). Despite long-term sugarcane cultivation, there was no difference in P_i-H_2SO_4 between production systems (BH and GH) and NV that could be explained by the lime added to the plots (Tokura et al., 2002).

Table 2

Concentrations† of inorganic P fractions from different sampling positions and depths in a Typic Hapludox cultivated under burn-harvest (BH) and green-harvest (GH) sugarcane management and at an adjacent site with natural vegetation (NV).

Depth	BH			GH			NV
	Planting row	0.25 m	Inter-row	Planting row	0.25 m	Inter-row	
m	mg kg^{-1}						
	P_i-NH_4F (32)$^{\#}$						
0–0.05	89† b A	47 b B	98 a A	64 AB	62 AB	71 AB	88 a
0.05–0.1	76 b	64 ab	71 ab	74	61	57	46 b
0.1–0.2	78 b	76 ab	69 ab	68	67	68	36 b (*, *)
0.2–0.3	123 b A	96 a AB	75 ab B	87 AB	85 AB	71 B	38 b (*, *)
0.3–0.4	135 a A	74 ab B	57 b B	96 AB	75 B	92 AB	40 b (ns, *)
	Pi-NaOH (12)						
0–0.05	288 a	289	254	301	270	277	306 a (*, ns)
0.05–0.1	232 b B	288 A	272 AB	226 B	260 AB	240 AB	289 ab (ns, *)
0.1–0.2	248 ab	257	231	258	265	258	221c
0.2–0.3	304 a A	253 B	269 AB	242 B	240 B	270 AB	239c
0.3–0.4	285 a	253	255	272	250	267	253 BCE
	Pi-CDB (23)						
0–0.05	113	148 a	130 abc	110 ab	121	144 ab	209 a (*, *)
0.05–0.1	129 AB	139 a AB	152 a A	91 b B	98 B	131 ab AB	214 a (*, *)
0.1–0.2	154	123 ab	145 ab	136 ab	122	164 a	155 b
0.2–0.3	124	90 BCE	101 BCE	122 ab	128	115 b	144 b (*, ns)
0.3–0.4	111 BCE	71c C	88c BC	137 aAB	129 AB	153 a A	119 b
	P_i-H_2SO_4 (20)						
0–0.05	89 a A	48 b B	51 B	49 bB	56 b B	58 b B	46 b
0.05–0.1	78 ab	77 a	74	68 ab	73 ab	74 ab	94 a
0.1–0.2	77 ab	68 ab	63	78 a	72 ab	68 ab	73 a
0.2–0.3	64 b	56 ab	63	75 a	70 ab	85 a	71 a
0.3–0.4	71 ab	66 ab	61	67 ab	80 a	75 ab	79 a

† Mean values (from 6 replicates) in columns followed by the same lowercase letter and in rows followed by the same uppercase letter are not different (Tukey, $p < 0.05$). $^{\#}$Coefficient variation (%). For comparison of the NV treatment with BH and GH harvest management (Tukey, $p < 0.05$): ns = not significant; * is significant.

3.4. *Relative P fractions in the soil*

The relative contribution of P_o to total P (P_o/total P) had different depth patterns in the GH treatment compared with the BH treatment and with NV (Fig. 2). In the 0.1–0.2 and 0.2–0.3 m subsurface layers of the GH soil, the fraction of total P_o was higher than in either the uppermost layer (0–0.05 m) or in the deepest layer (0.3–0.4 m). Higher relative Po fraction contribution in the GH system was favored by the accumulation of OM, as reported by Correia and Alleoni (2011).

The P_o average of three sampling positions (0–0.05, 0.05–0.1, and 0.1–0.2 m) shown in Fig. 2, weighted by the thickness of the sampled zone (1:1:2), accounted for 28% of the total P under GH and 26% of the total P under BH management (Fig. 2). In the subsurface layer (0.2–0.4 m), GH and BH averages were 30% and 28% of total P, respectively. The same trend of P_o concentrations in the subsurface layer was reported by Canellas et al. (2010), who found relative P_o values of 25% at a depth of 0–0.2 m and 28% at 0.2–0.4 m under long-term GH management of sugarcane.

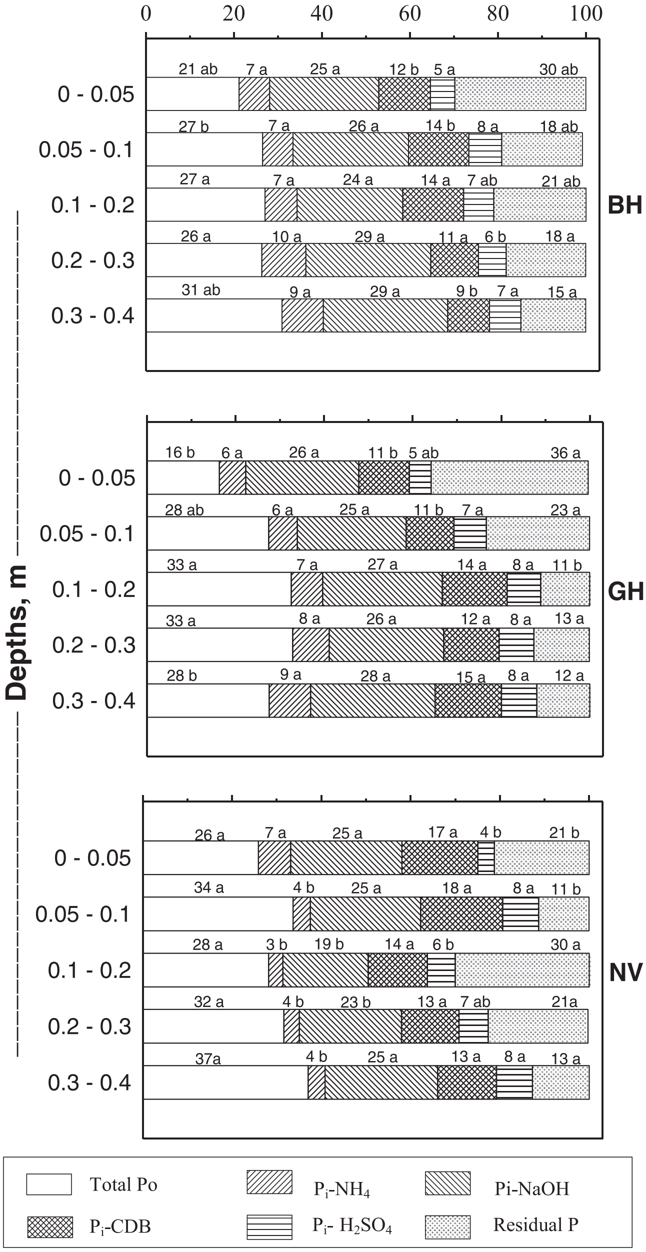

Fig. 2. The relative contributions (%) to total P of the total organic P fraction (P_o total) and the inorganic P (P_i) fractions in a Typic Hapludox cultivated under burn-harvest (BH) and green-harvest (GH) sugarcane management and at a site with natural vegetation (NV). Values are the simple average of the three sample positions (row, 0.25 m from the row and inter-row). Means followed by the same letter vertically within each harvest management (BH and GH) and P fractions are not different (Tukey, $p < 0.05$).

The organic fraction also dominated most soil layers at the NV site (Fig. 2). Soil in both BH and GH managements had lower proportions of P_o than NV at depths of 0–0.05 m (NV = 26% > BH = 21% > GH = 16%), 0.05–0.1 m (34% > 27% = 28%), and 0.3–0.4 m (37% > 31% > 28%). On the other hand, in the 0.1–0.2 m layer, the organic fraction of the fertilized GH system (32%) was higher than NV (28%) while in the 0.2 – 0.3 m layer of the GH system, the organic fraction (33%) was comparable to NV (32%). Beck and Sanchez (1994) reported a reduction in P_o fractions in unfertilized plots and an increase in fertilized plots after 13 years of annual crop cultivation compared to NV. However, at this study, the Po fraction did not increase at BH fertilized depths (Fig. 2). This suggests that the higher carbon substrates from straw decomposition, as found in the GH system, positively affect the accumulation Po (Nziguheba, Bünemenn, 2005). In the GH system, the higher values of P_o in the 0.1–0.2 m and 0.2–0.3 m layers, compared to other layers, were attributed to the residual effect of crop fertilization and to the high content of organic matter.

The relative contributions of the P_i fractions to total P were not strongly affected by harvest management compared to NV. The same could be reported for inorganic P fractions across layers (Fig. 2). Similarly, little effect of crop residue application on soil P_i fractions was described in a 4-year cultivation experiment in a Tanzanian soil (331 g kg^{-1} clay), even with fertilizer application (Sugihara et al., 2012). Zamuner at al. (2008) also reported no differences in P_i fractions after eight years under no tillage and conventional tillage systems in Argentinian soils (310 – 330 g kg^{-1} clay). In general, P_i fractions under GH and BH and under NV were ranked in the following order: P_i-NaOH $>>$ P_i-CDB $>$ P_i-NH_4F $\approx$ P_i-H_2SO_4 at all depths. The predominance of P_i-NaOH is typical for highly weathered soils that often are dystrophic, acidic, poor in C content, and have high levels of Fe oxides in the clay fraction (Novais et al., 2007). The same trend in the predominance of the Fe-P (NaOH), Al-P (P_i-NH_4F) and Ca-P (P_i-H_2SO_4) fractions also was reported in a clayey Oxisol by Alleoni et al. (2012).

As expected for highly weathered soils (Cross and Schlesinger, 1995), Ca-P (P_i-H_2SO_4) on average accounted for only 7% of total P in both BH and GH managements in our study (Fig. 2). Similar results were reported by Canellas et al. (2010) for soils collected from a long-term BH sugarcane plantation. Otherwise, they reported up to 28% of the total P being removed by strong acid (i.e., Ca-P) from a soil (pH > 6.0) under GH sugarcane management. According to those authors, high concentrations of soil Ca explained the relative abundance of Ca-P. On the other hand, the Oxisol in our study was acidic (pH < 5.0) with lower Ca content at most sampling positions and depths (Correia and Alleoni, 2011), thus explaining the results observed here.

Residual P (recalcitrant Pi + Po) accounted for the largest fraction of total P in the surface (0–0.05 m) under both types of harvest management, with 30% under BH and 36% under GH (Fig. 2). In the deeper layers, however, residual P was the third largest fraction of total P, after Po and Pi-NaOH. This fraction has an unknown chemical nature, including several inorganic and organic P components not extracted with the procedure used here. Similarly, Canellas et al. (2010) observed that this residual P fraction was also dominant in an Inceptisol cultivated with sugarcane, accounting for 59% and 36% of total P in BH and GH managements, respectively.

4. Conclusions

The accumulation of straw under green-harvested management promoted mineralization of organic P in the uppermost layer of soil (0–0.05 m) and immobilization of inorganic P at the depth where P fertilizer was applied (0.2–0.3 m) both in the planting row and at 0.25 m from the row.

Higher total P_o contents in the subsoil suggest that residual P from fertilizer placed at the bottom of the furrow has been immobilized and soluble organic complexes may have moved down into the profile.

Our results indicate that long-term sugarcane green-harvested management promotes greater cycling of organic P, which can contribute to crop demand for P.

The inorganic P fractions within the soil profile and relative to the plant row differed little between the two harvest management systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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