International Journal of Agriculture, Environment and Bioresearch

Vol. 06, No. 05; 2021

ISSN: 2456-8643

BIOAVAILABILITY OF PHOSPHORUS ON HIGHLY WEATHERED OXISOILS OF THE BRAZILIAN MID-WEST

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https://doi.org/10.35410/IJAEB.2021.5664

ABSTRACT

Soils from mid-west Brazil show strong phosphorus (P) fixation, which can reduce the efficiency of P fertilizers. Under this condition, soil competes with the plant for the applied P adsorbing it strongly in its mineral fraction. Nevertheless, in areas where crops are grown and fertilizers are added for many years, soil fertility status has increased over time, making these soils non-responsive to P. The objective of this study was to evaluate how P availability changes with soil use. Forty soil samples were collected under different types of land use: native forest, pasture, no-tillage, and areas with periodic tillage. P fractionation was performed to determine the amount of P in the organic and inorganic fractions with high, medium, and low lability under each land use. Corn was cultivated in a greenhouse experiment to evaluate P uptake and values correlated with different P fractions. The results showed differences in the P fraction relations among different land uses. Cultivated areas (no tillage and periodic tillage) accumulated greater amounts of P in all fractions than pastures and the native forest. A higher proportion of labile organic P was observed under no tillage than under periodic tillage. NaHCO3 and NaOH 0.1 mol L-1were the most relevant P fractions for shoot P uptake. No tillage promoted the accumulation of available P fractions, suggesting that it is a good management strategy to ensure fertilizer use efficiency.

Keywords: Keywords: Phosphorus Fractionation, No tillage, Land use, Phosphorus uptake, Organic Phosphorus.

1. INTRODUCTION

The Oxiosoils are highly weathered soils that have great importance for tropical agriculture, it occupies about 23 percent of the land surface of the tropics (Beinroth et al., 1996). In Brazil Oxisoils cover approximately 39 per cent of the Brazilian territory and it represents the few remaining agriculture frontier in the country and all over the world (Ferreira et al., 2010; Beinroth et al., 1996).

In highly weathered soils, soil mineral binds with P very strongly, making the soil act as a sink for P (Walker and Syers, 1976; Gatiboni et al., 2007). Due to tropical soil P sink characteristics, Roy et al. (2016) claimed that it is unsustainable to spend P fertilizer finite sources of phosphate rocks, just to assist and intensify Brazilian agriculture with P-fixing soils. However, some researchers suggest otherwise. Withers et al. (2018) identified many soils that have been cultivated for many years, which do not respond to P fertilization. These soils have reached an entirely new level of P status mainly because of years and years of P fertilization and a good management system, which the authors termed as soil P legacy.

Soil management influences the P dynamics, P bioavailability, and equilibrium between inorganic and organic P (Zhang and MacKenzie, 2004). Understanding the buffering capacity of organic and inorganic P and the correlation between these sources and plant P uptake is useful for planning soil fertility management (Tiecher et al., 2012; Gatiboni et al., 2013). The P fractionation method proposed by Headley et al. (1982) is helpful for evaluating the distribution of organic and inorganic P and assessing P bioavailability by their correlation with P uptake.

Many studies compared no-till with conventional till management in terms of their effect on P availability and fractionation (Pavinato et al., 2009; Rheinheimer et al., 2001). This study aims to distinguish P fractions under no till and minimum until compared to pasture and native vegetation, how the management and long-term fertilization interferes with the P fractions, and which fraction is plant available on these soils.

2. MATERIAL AND METHODS

Forty soil samples were collected from municipalities of Rio Verde and Caiapônia, southwest of the state of Goiás, located in the Brazilian mid-west (Figure 1). The samples were collected from a depth of 0–20 cm. All soil samples were highly weathered oxisoils locally classified as Latossolos vermelhos distroferricos according to Santos et al. (2018).

The samples were collected under different land uses: three samples from native Cerrado forest (NF), four samples from low background P and lime fertilization pastures (PA), 19 samples from no-tillage cropping areas (NT), and 14 samples from minimum tillage cropping areas (MT). The NT and MT were cultivated with grain crops for 30 years. However, the NTs had not been tilled for 28 years, whereas for the MTs, a leveling harrow was used to facilitate planting every year, and they had been periodically tillage with two heavy harrows and one leveling harrow in sequence (every 3 or 5 years depending on yield and soil fertility status). The under-cropped areas were cultivated with soybean (summer), corn (winter), bean (summer), and cotton (winter). Most of the year, soybean and corn are cultivated in sequence in the same crop season and sometimes cultivated with the four crops in rotation in two crop seasons (soybean/corn in the first season and bean/cotton in the second season). The under-cropped samples were collected based on the same fertilizer formula application background, the pastures and Cerrado forest samples were collected next to the under-cropped samples to avoid parent rock materials and soils classification variations.

All soil samples were air dried and sieved through a 2-mm mesh. Exchangeable calcium (Ca), soil pH, $CaCl_2$ and clay content, organic matter (OM), and available P extracted by Mehlich-1 were determined according to Teixeira et al. (2017). Each soil sample was sequentially fractionated to determine the different fractions of organic P (Po) and inorganic P (Pi) according to the method proposed by Hedley et al. (1982), modified by Codron and Goh (1989). The extraction sequence was: resin; $NaHCO_3$, 0.5 mol L^{-1}; NaOH, 0.1 mol L^{-1}; HCl, 1 mol L^{-1}; NaOH 0.5, mol L^{-1}; we also used a digestion method proposed by Brookes and Powlson (1982), using $H_2SO_4 + H_2O_2 + MgCl_2$ to determine the residual P.

Although Cross and Schlesinger (1995) and Yang and Post (2011) found a discrete P compound for each extractant of the Headley procedure, such as P extract by NaOH related to P adsorbed by Fe and Al oxides and hydroxides and P extract by HCl correlated with P bound to Ca found in primary minerals (apatite) or neo formation of calcium phosphates, some researchers like Barrow et al. (2020) disagree with the possibility that soil P occurs in discrete forms.

We interpreted the results not as individual Pi and Po compounds according to the extractants, but we used the lability of the different extractors that Hedley et al. (1982) and Gatiboni et al. (2007) proposed: P extracts by resin and $NaHCO_3$ represent the labile P ($NaHCO_3$ also extracts labile Po), NaOH (0.1 mol L^{-1}) represents labile/moderately labile Pi and Po, HCl and NaOH 0.5 mol L^{-1} represent less moderately labile P (NaOH 0.5 mol L^{-1} extracts also Po), and residual P represents recalcitrant occluded P (sparingly labile Pi and Po).

The Po was fractionated in the following way: half parts of $NaHCO_3$, 0.5 mol L^{-1}, NaOH, 0.1 mol L^{-1}, and NaOH, 0.5 mol L^{-1} extraction were determined immediately to obtain the Pi. The other half parts were subjected to digestion for determination of the total P (Pt) with H_2SO_4 and $(NH_4)_2S_2O_2$ in an autoclave. The Po values were determined by the difference in the Pt–Pi of each extractant. All P values were determined using the ascorbic acid-molybdenum blue method, according to Murphy and Riley (1962). Fractionation was performed in two replicates.

A completely randomized experiment was conducted in four replicates in a greenhouse at the University of Rio Verde with 40 soil samples. Pots were filled with 2 kg of soil samples and four corn seeds were sown in the samples. After 7 days, two seedlings were thinned. The pots were fertilized with nutrient solution (without P). Each kg of soil received 50 mg of N, 80 mg of Ca, 40 mg of Mg, 50 mg of S, 80 mg of K, 1 mg of B, 4 mg of Cu, 8 mg of Mn, and 8 mg of Zn. The pots were watered daily to maintain 90% of the soil's field capacity. After 25 days, the shoots were collected, dried in an oven at 65 °C until reaching constant mass weight, ground, and analyzed after nitric perchloric digestion according to Teixeira et al. (2017). Shoot dry mass (SDM) and shoot P content (SPC) were determined, and shoot P uptake (SPU) was calculated by multiplying SDM and SPC.

For P fractionation, SDM, SPC, and SPU, a t-test LSD ($p<0.05$) was performed to compare the means. An F selector package (Romanski and Kotthof, 2018) on R was used to calculate the weight distribution of the variables for SPU according to the random forest algorithm for all soil samples. A decision tree plot for SPU was also used for all soil samples with the Party package (Hothorn et al., 2006) in R. A decision tree is a non-parametric analysis used for classification and regression. It is an analysis that uses data to approximate a sine curve using an if-than-else algorithm to determine the decision rules. According to the rules, the analysis determines which variables are relevant to the tree (Sehra, 2018). All statistical analyses were performed using R software (R Core Team, 2018).

3. RESULTS AND DISCUSSION

P Fractionation

Regardless of tillage management, under-croppedsamples showed higher P concentrations of all the P fractions than uncropped NF and PA samples (Table 1). The under-cropped areas included in this study were successively fertilized with P above the P exportation rate. This practice led to significant P accumulation in all cropping area fractions (Table 1), and the high rates of P fertilization for long periods contributed to P surplus, significantly increasing the amount of available P in low P status areas in Brazil, creating a P legacy (Withers et al., 2018).

The uncropped areas had similar P values for fractionation (Table1). Livestock activity in Brazil is characterized by low fertilizer input (Lilienfein et al., 2003; Withers et al., 2018). Over the years of P extraction without adequate nutrient replacement, P levels have been declining, starting from more to less labile P pools in the soil. This led to PA areas with low P levels in almost all samples compared to those in under-cropped areas, showing similarity with the levels in the NF (Table 1). The results for resin P levels inMT samples were similar to those in uncropped samples. In addition, the under-cropped samples did not differ in tillage management, but NT samples showed higher levels of resin P than the uncropped samples, while MT samples showed equal levels (Table 1).

Many studies have been conducted to explain how NT can improve the efficiency of P fertilization by increasing the available P. Since there is no till, a high concentration of P near the fertilizer site application is observed, saturating the adsorption sites and making available the recently applied P (Beauchemin et al., 1996; Rheinheimer and Anghinoni, 2001). Another benefit of no tillage is the high soil organic matter content (OM) on that land type (Table 2). Humic substances may bind to the clay adsorption sites of the soil, delaying the adsorption of Pi, which may cause the soil to hinder phosphate fixation and increase P bioavailability (Bedrock et al., 1997; Yang et al., 2019).

Concerning the labile P extracted by $NaHCO_3$, the inorganic and organic portions of this fraction were similar in the uncropped samples. Regarding the under-cropped samples, the difference in tillage management was reflected by the inorganic and organic fractions. The Pi fraction of the MT sample was greater than those in the uncropped samples, while the Po fraction of the NT sample was greater than those in the uncropped samples (Table 1). The inversion of Pi and Po between the under-cropped areas was probably due to the high accumulation of OM in the NT (Table 2) and high rate of OM mineralization in the MT samples.

Regarding the no till samples, 60% of the total $NaHCO_3$ P was extracted in the organic fraction, while for the MT samples, only 40% was extracted (Table 1), confirming that no till allows the accumulation of the crop residues on the soil surface, thus increasing the levels of organic matter and labile Po. This does not happen in the MT because tilling the soil can destroy the soil aggregate stability, exposing the OM to be mineralized by microorganisms, thus turning Po into Pi (Gatiboni et al., 2007; Oliveira et al., 2020). Although the soil is not disturbed every year in the MT, only periodic plow can prevent OM accumulation.

In addition, high lime doses are applied to the MT to correct the soil profile by incorporating nutrients with tillage. The high pH (Table 2) and base saturation of the MT due to high lime doses contribute to increased microbiological activity, which may enhance OM mineralization (Gatiboni et al., 2007; Sá, 1999). Another consequence of liming is the increase in the concentration of Ca. Table 2 shows that the mean Ca level in MT sampleswas higher than that in NT samples. A high amount of Ca can make some phosphorous organic compounds soluble, thus facilitating mineralization (Tate and Newman, 1982; Codron et al., 1989).

The results from the third extractant NaOH 0.1 mol L^{-1} showed that this extractant could remove more P than any other residual P, similar to results found by Gatiboni and Codron (2021). All the areas, regardless of use and management, accumulated most of the Pi and Po on the NaOH 0.1 mol L^{-1} (Table 1). Cross and Schlesinger (1995) and Tate and Newman (1982) claimed that NaOH 0.1 mol L^{-1} primarily removes P bound to kaolinite, iron (Fe), aluminum (Al) hydroxide and oxide, monoester, diester, and polyphosphates. Brazilian oxisoils are highly weathered soils that contain a great amount of secondary minerals such as kaolinite, oxides, and hydroxides of Fe and Al, which are responsible for adsorbing a large part of the total soil P (Walker and Syers, 1976; Yang and Post, 2011).

The NaOH 0.1 mol L^{-1}fractions of the under-cropped samples did not differ from each other and were greater than those of the uncropped samples (Table 1). Under-cropped areas have been P fertilized for long years; when P is added for a long period on these highly weathered soils, all the fractions increased, but NaOH 0.1 mol L^{-1} increases at a large scale. This effect can be attributed to the fact that highly weathered tropical Brazilian soils present a large number of P adsorption sites with kaolinite, aluminum oxides, aluminum hydroxides, iron oxides, and hydroxides. NaOH 0.1 mol l^{-1} can primarily remove Pi bound to the adsorption sites mentioned above (Codron and Goh, 1989; Bunemann et al., 2004).

Pavinato et al. (2009) compared the NaOH 0.1 mol L^{-1} fraction between no-tillage and conventional tillage and found an increase in Pi from conventional tillage in red oxisoil, while Rheinheimer and Anghinoni (2001) did not find differences between conventional and no-tillage management. Selles et al. (1997) found no differences in Pi between the MT and NT. These differences might have occurred because of the large variation in the sequential extraction by the fractionation method. The Hedley P fractionation method is complex, and the large amount of modification of the original method along with the variation caused by the sequential extraction can make the results of the studies differ from each other. The results should be compared with caution regarding the P fractionation method, mainly because of the great variation that the method presents (Gatiboni et al., 2013; Codron and Newman, 2011).

The organic fraction of NaOH 0.1 mol L^{-1} in the under-cropped samples did not differ from each other, but the fractions of the MT samples were higher than those of the uncropped areas, while those of the NT samples were equal to those of the PA samples (Table 1). Tillage exposes the adsorption sites, contributing to the adsorption of inorganic and organic P compounds. Monoester phosphates, such as inositol, are Po compounds that can be easily adsorbed by the clay fraction (Dao, 2003; 2004). Meanwhile, no tillage enhances the soil OM content, which facilitates the desorption of Po by ligand exchange (Dao, 2003). In addition, NT promotes microorganism activity, increasing the release of phosphohydrolases by plants and microorganisms to solubilize Po into Pi, thus making it available. Pavinato et al. (2010) showed that NT could increase the desorption and solubilization of inositol monoester phosphate compared to conventional tillage.

HCl P had the lowest fractionation value. If Cross and Schlesinger (1995) are true about the origin of the HCl P being related to calcium and P primary minerals, small values of this fraction are explained by the highly weathered tropical soils, which do not have P from primary minerals. The millions of years of weathering transformed the primary mineral in tropical soils, resulting in the P being released to the soil solution, which was consequently taken up by the plants and microorganisms or adsorbed by the secondary minerals of the soil (Walk and Syers, 1976; Yang and Post, 2011). Nevertheless, the under-cropped samples showed a greater P value for this fraction than the uncropped samples. In cropped areas, lime is used to increase pH, Ca, and Mg (Table 1) levels, leading to the formation of calcium phosphate (P-Ca); the same results were found by Beck and Sanchez (1994) and Guo et al. (2000). Although Gu et al. (2020) showed that HCl P extraction could overestimate calcium-bounded P by the dissolution of some Fe and Al oxides as well as by the redistribution of P after alkaline steps of the fractionation, our under-cropped samples presented a higher amount of HCl P fraction than the uncropped samples and might not be related to P bound to calcium. Nevertheless, this fraction is negligible in terms of P bioavailability in highly weathered soils.

The MT samples had higher levels of Pi extracted with NaOH 0.5 mol L^{-1} than the uncropped samples but did not differ from the NT samples (Table 1). This can be explained by tillage, as deep plowing of the soil may contribute to P adsorption by exposing the adsorption sites, resulting in high P accumulation on the compartments that are less labile than others (Selles et al., 1997). The Po levels extracted by NaOH 0.5 mol L^{-1} were not significantly different between the management treatments (Table 1),Pavinato et al. (2009) and Rheinnheimer and Anghinoni (2001) found no differences in the Po levels of this fraction between conventional tillage and no-tillage samples. It seems that this non-labile occluded Po extracted by NaOH 0.5 mol L^{-1} is unresponsive to management and land use.

The residual fractions showed no difference between the samples, regardless of land use. Silva et al. (2003) and Negassa and Leinweber (2009) found that residual P levels do not change over time, even with fertilizer application. These less labile fractions did not change over time because when P fertilizer was added to the soil for a long time, P was equalized in all soil compartments but to a large extent in the labile and moderately labile P fractions. It is possible that a considerable part of the P was already extracted on the first three extractants, so the differences in the types of management of the last extractant (residual P and Po NaOH 0.5 mol L^{-1}) are not significant (Crews and Brookes, 2014).

P-bioavailability

The SDM, SPC, and SPU were the lowest for the NT, followed by the PA. No differences were observed between the different types of under-cropped samples, but these values were higher for the under-cropped samples that for the uncropped samples (Table 3). The low values of SDM, SPC, and SPU for the NF samples are explained by the native Cerrado soil, which is an acidic soil with high rates of aluminum, low base saturation, and low available P; therefore, nutrient uptake and plant growth are limited (LOPES and COX, 1977). Low pH can dissociate Al forms that are toxic to plant roots, restraining nutrient uptake, such as P, causing yield losses (Pavlů et al., 2018; Caires et al., 2015). In addition, the highly weathered native Cerrado soil presents most of its P in unavailable forms strongly bound to amorphous Al or Fe oxides and hydroxides (Rheinheimer et al., 2008; Parfitt, 1979; Walker and Syers, 1976).

Although Brazil is one of the largest exporters of cattle meat (Vargas et al., 2020), most of the livestock areas in the country are native pasture lands with low P fertility (Bai et al., 2008; Pereira et al., 2013). Only 1.5% of P fertilizer consumption in the country is attributed to livestock pastures, and many of these areas are in degraded conditions (Soares-Filho, 2016; Withers et al., 2018). Although the pasture soils sample in this study had received P fertilization before, it was not enough to raise P concentration as in the under-cropped areas. Because of low background fertilization and lack of nutrients, including P, small values of SDM, SPC, and SPU were observed for this type of land use.

The under-cropped samples had the highest SDM, SPC, and SPU values. High investments in fertilizers are made every year to raise and maintain yields in soybean agricultural areas. The cost of fertilizers accounts for one-quarter of the total production costs of soybean production in Brazil (USDA Foreign Agricultural Service, 2012). The fertility status of those areas is at another level compared to the status of the NF, as shown in Tables 1 and 2.

In addition, some studies showed better P efficiency uptake and yield gains in no-tillage than in conventional tillage (Oliveira et al., 2019; and Oliveira et al., 2020) land; we could not find differences between the NT and MT with regard to SDM, SPC, and SPU. In field conditions with other variables acting in the system, NT might be more efficient land use than MT, owing to the better benefits regardless of soil P fertility that this system provides, such as good physical soil properties and accumulation of organic matter (Souza et al., 2016; Sales et al., 2016).

In addition, minimum tillage cannot be considered a conventional tillage, but we think that if P fertilization stops, the differences between P availability would be large, with the NT showing better yield and P uptake because of its tendency of greater accumulation of labile Pi and Po than the MT (Table 1). The same results were found by Oliveira et al. (2019; 2020) for conventional tillage and no-tillage lands. As shown in Tables 1 and 2, the under-cropped areas showed accumulation of high levels of labile P. With the adoption of new technologies to improve agronomic practices, a sustainable intensification of those areas to increase yields with efficient use of P is perfectly possible, and high rates of P fertilization are not necessary (Sattari et al., 2016; Withers et al., 2018).

Variables most important on P uptake

In order to find the most important variables that had a greater influence on plant P uptake on highly weathered Brazilian oxisoils, the weights of the variables using a random forest algorithm with the F selector package in R for all soil samples were calculated (Romanski and Kotthof, 2018). The top five variables that influenced P uptake were Po $NaHCO_3$ at a weight of 15.99, Pi NaOH 0.1 M l^{-1}, of 14.91, calcium, of 11.51, clay, of 11.48, and P Mehlich-1, of 10.85.

The P extracted by $NaHCO_3$ is known to have a significant impact on plant nutrition; it is a labile organic and inorganic fraction. In soils with tropical P sink characteristics, the organic P fraction plays a major role in P availability, providing P to the plants when mineralized and preventing the P from being adsorbed by the minerals of the soil. Of course, not all organic P is labile, some Po forms like phytate with monoester bonds that can interact with the minerals of the soil, such as iron and aluminum oxides, and become physically protected to be mineralized by the microorganism (Dalal, 1977). However, $NaHCO_3$ organic extraction is a labile and important P fraction for plants (Negassa & Leinweber, 2009; Blake et al., 2003). In addition, our decision tree showed the relevance of $NaHCO_3$ Po to SPU (Figure 2). The decision tree showed that if NaOH 0.1 mol L^{-1} Pi was greater than 82.36, the other relevant variable was NaHCO3 Po, and an intermediate SPU was classified with values smaller or equal to 15.7, and a greater SPU when the values are higher than 15.7.

Another important extractant for SPU was NaOH 0.1 mol L^{-1}, considered a moderately labile fraction. This fraction can support P uptake in highly weathered soils (Guo and Yost, 1998; Negassa and Leinweber, 2009; Henriquez and Killorn, 2005; Beck and Sanches, 1994), and it is very important. When this fraction is high, it means P has penetrated into the Al and Fe oxides and hydroxides, changing the overall charges of these minerals, contributing to the subsequent application of P to effectively maintain adequate amounts of P in soil solution (Barrow and Debnath, 2015; Barrow et al., 2014). This can be seen in both the decision tree (Figure 2) and the F-selector weight.

Exchangeable Ca on F selector weighs is also important for P uptake (the third highest weight), but this seems not because P bound to Ca is related to P uptake, even though Henriquez and Killorn (2005) and Beck and Sanches (1994) reported that P bound to calcium may be important for P uptake even in highly weathered soils. In this case, the exchangeable calcium was related to promoting root growth and improving the capacity of P uptake (Marschner, 2011). This can be proven because when the NF and LG soils were excluded from the analysis (which are soils with low exchangeable Ca), the F selector analysis showed a very low Ca weight,which was not in the top five. (data not shown).

The last two selected variables in the F selector analysis were clay and P Mehlich-1 (Mehlich, 1953). Several attributes control P adsorption, and clay content is one of those (Novais and Smyth, 1999). Brazilian oxisoils contain large amounts of kaolinite and oxides of Fe and Al in their clay fraction, which contribute to significant P adsorption that can interfere with SPU (Volksweiss and Raij, 1977). P Mehlich-1 is one of the most commonly used elements for routine analyses of available P in soil in Brazil. It is an effective extractor that provides a good correlation with grain yield (Oliveira et al., 2019).

It is important to highlight that labile Po and moderately labile Pi extracted with $NaHCO_3$ and NaOH 0.1 mol L^{-1}, respectively, might be especially important to supply P to the plants on highly weathered tropical soils, maybe more relevant than Mehlich-1 as it shows on F selector weights, especially when you have high values of P Mehlich-1. When we used only the MT and NT soils (data not shown), (which had high levels of P Mehlich-1), P Mehlich-1 was not among the top five highest weight attributes in the F-selector analysis.

NTs accumulate a large amount of $NaHCO_3$ Po (Table 1) and might be a good land use type to provide plant-available P. Although Po can account for the majority of P uptake in tropical lands (Chen et al., 2008; Tiessen et al., 1994), the evaluation methods to determine the bioavailable Po are unclear because not only is the single value of an extractor important when it comes to available Po, the soil dynamics of roots and microorganism exudation of acids and enzymes to solubilize and hydrolyze Po are also important.

Although P $NaHCO_3$ is considered a labile organic fraction, it still cannot account for all labile Po (Johnson et al., 2003) because not all $NaHCO_3$ Po is susceptible to enzyme hydrolysis (Hayes et al., 2000; Turner et al., 2003), which is a very important mechanism used by microorganisms and plants to acquire Po (Begum and Tofazzal, 2005). Darch et al. (2016) focused on the best way to measure labile Po and proposed a method based on acid and enzyme hydrolysis. This effort to make a precise determination of available Po might be the key to future P routine analysis and may facilitate accurate fertilizer application, especially in highly weathered tropical soils.

4. CONCLUSIONS

More P was accumulated in almost all extracts of P fractionations of under-cropped samples than of pasture and native soil samples, indicating the presence of a P legacy after successive P fertilization. The NaOH 0.1 mol L^{-1} Pi and $NaHCO_3$ Po are the most important extractants for shoot P uptake in highly weathered tropical soils. A conservative system, such as no tillage, is important to accumulate labile organic P, as this fractions of this soil sample showed high P availability.

Table 1. Hedley modified by Codron & Goh (1989) P fractionation results.

NF	NA	MT	NT
P-resin mg dm^{-3}			
1.33 b	9.1 b	19.76 ab	31.48 a
Pi-NaHCO$_3$ mg dm^{-3}			
1.49 c	5.69 bc	19.36 a	15.29 ab
Po-NaHCO$_3$ mg dm^{-3}			
0.88 b	1.33 b	11.94 ab	23.39 a
Pi-NaOH 0.1 mol L^{-1} mg dm^{-3}			
52.37 b	58.65 b	203.38 a	187.2 a
Po-NaOH 0.1 mol L^{-1} mg dm^{-3}			
65.63 c	102.95 bc	187.19 a	172.07 ab
P-HCl mg dm^{-3}			
2.67 b	3.6 b	11.14 a	12.63 a
Pi-NaOH 0.5 mol L^{-1} mg dm^{-3}			
36.59 b	24.62 b	76.78 a	58.86 ab
Po-NaOH 0,5 mol L^{-1} mg dm^{-3}			
19.41 ns	15.60 ns	34.08 ns	28.88 ns
P-residual mg dm^{-3}			
579.2 a	580.43 a	582.09 a	587.56 a

Means followed by the same letter on the line do not differ by t-test (0.05); NF: natural forest; PA: pasture; MT: minimum tillage; NT: no tillage

Table 2. Mean and range of some attributes from the routine soil analysis according to management.

	NF		PA		MT		NT	
attributes	range	mean	range	mean	range	mean	range	mean
Ca cmolc dm^{-3}	0.24 - 0.79	0.43	1.05 - 2.02	3.43	1.88 - 5.72	3.43	0.99 - 5.24	2.89
pH	4.00 - 4.30	4.13	4.40 - 5.10	5.15	5 - 5.9	5.15	4.40 - 5.60	4.90
Clay g dm^{-3}	420.0 - 670.0	561.0	265.0 - 495.0	532.0	270.0 - 595.0	532.0	220.0 - 645.0	506.0
OM g dm^{-3}	26.30 - 45.40	35.47	19.7 - 45.7	31.96	13.10 - 37.20	30.96	20.40 - 55.40	39.99
P-mel 1 mg dm^{-3}	1.10 - 3.90	2.53	1.7 - 17.4	12.22	7.90 - 53.7	29.63	15.7 - 87.00	46.01

NF: natural forest; PA: pasture; MT: minimum tillage; NT: natural tillage. Ca = calcium, OM = organic matter, and P-mel 1 = P extracted by Mehlich 1

Table 3. Result of SDM, SPC and SPU according to the different management

SOIL MANAGEMENT			
NF	**PA**	**MT**	**NT**
----------SDM (g)----------			
c	3.36 b	7.92 a	8.60 a
----------SPC (g kg^{-1})----------			
0.97 c	1.72 b	2.28 a	2.45 a
----------SPU (mg)----------			
1.60 c	5.78 b	18.05 a	21.07 a

Means followed by the same letter on the line do not differ by t-test (0.05). NF: natural forest; PA: pasture; MT: minimum tillage; NT: no tillage; SDM = shoot dry matter; SPC = shoot P content; SPU = shoot P uptake

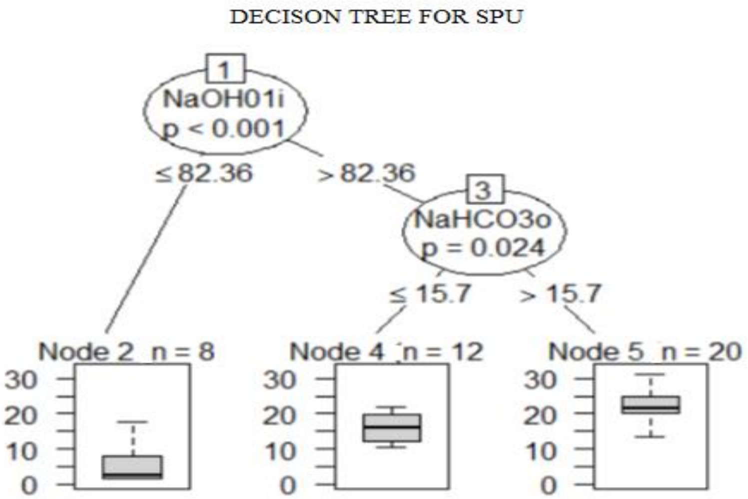

Figure 2. SPU decision tree for all soil samples. NaOH01i stands for Pi extracted by NaOH 0,1 Ml^{-1}. NaHCO30 stands for Po extracted by $NaHCO_3$. n = number of samples that classified on each node.

DATA AVAILABILITY STATEMENT

Some of the data of this study can be found at http://www.unirv.edu.br/producaovegetal/admin/images/pdfs/1910252095.pdf. Raw data can be requested by any authors in particular.

AUTHOR CONTRIBUTIONS

Vinicius and Ernesto conceived this study. All authors contributed to the study design. Sulian, Cassio, and Ernesto conducted the sample collections, P fractionation and greenhouse experiments, and Vinicius, Cassio, and Ernesto performed the statistical analysis. Vinicius was the overall advisor for the study.

ACKNOWLEDGMENTS

We would like to thank the University of Rio Verde for providing the laboratory facilities and chemical reagents for all analyses presented in this work. We would also like to thank everyone who worked in the laboratory of the University for helping with the experimental analysis. Special gratitude to the teachers of the master's program at the University for passing the knowledge forward. Special thanks to the agriculture engineer student Suely Schneider, who helped with the laboratory and greenhouse experiments. We also would like to thank Editage (www.editage.com) for English language editing.Part of the data in this manuscript has previously appeared online in a master's degree thesis, which can be found at http://www.unirv.edu.br/producaovegetal/admin/images/pdfs/1910252095.pdf.

FUNDING

Part of this study was found by EMBRAPA soils.

CONFLICT OF INTEREST

SLC Ágricola currently employs author Sulian Junkes Dal Molin, by the time he was helping in the study his affiliation was UDESC Santa Catarina State University, Lages, Brazil. Therefore, the authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Contribution to the Field Statement

This study aimed to evaluate how phosphorus (P) availability changes with soil use in the context of Brazil. We believe that our study makes a significant contribution to the literature because we found that more P was accumulated in almost all extracts of P fractionations of under-cropped samples than of pasture and native soil samples, indicating the presence of a P legacy after successive P fertilization. The NaOH 0.1 mol L-1 Pi and $NaHCO_3$ Po are the most important extractants for shoot P uptake in highly weathered tropical soils. No tillage promoted the accumulation of available P fractions, suggesting that it is a good management strategy to ensure fertilizer use efficiency A conservative system, such as no tillage, is important to accumulate labile organic P.Further, we believe that this paper will be of interest to the readership of your journal because ensuring a P legacy is very important because P needs to be replenished depending on the importation rates of the harvest crops, and high doses of fertilizer are not always necessary, contributing to efficient and sustainable use of fertilizers. Our findings can provide important data for future research and agricultural settings.