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SOIL P FORMS AND P UPTAKE UNDER INTENSIVE PLANT GROWTH IN THE GREENHOUSE[1/]

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Keywords: Soil P forms, fractionation of P, Hedley methodology, P uptake.
Palabras clave: Formas de P en el suelo, fraccionamiento de P, metodología de Hedley, absorción de P.

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RESUMEN

Formas y absorción de P en plantas creciendo intensivamente en invernadero. La concentración del P disponible es una función del equilibrio existente entre las diferentes formas y reacciones del elemento en el suelo. El objetivo de este estudio fue examinar los cambios en las formas de P y la absorción bajo condiciones de extracción intensiva en suelos dedicados a diferente uso agronómico. Con el fin de establecer un experimento bajo condiciones de invernadero, se tomaron muestras representativas de 0 a 20 cm de un Typic Hapludands, separadas y provenientes de 3 campos adyacentes entre sí. Un campo estuvo dedicado al cultivo del café (*Coffea arabica* var Catuai), otro a caña de azúcar (*Saccharum* spp. var 611721) y el tercero con bosque secundario. Sorgo (*Sorghum bicolor* var Glazer 41) fue sembrado en macetas de 1 litro y cosechado 4 veces en forma consecutiva. Los tratamientos fueron sin P y con P (100 mg kg^{-1}) para cada uno de los 3 diferentes suelos. Se determinó peso seco de raíces y parte aérea, así como absorción de P. Se tomaron muestras de suelo de las macetas antes y después de cada uno de los 4 ciclos de crecimiento y se analizaron de acuerdo a la metodología de fraccionamiento de P de Hedley *et al.* (1982). Se determinó Pi-lábil, Pi-NaOH, Pi-HCl, Po-orgánico extraíble y P-residual. La aplicación de P aumentó el Pi-lábil,

ABSTRACT

The concentration of available soil (P) is a function of the equilibrium established among different soil P forms through numerous and different reactions in soil. The objective of this study was to examine the changes in P forms and P supply under exhaustive extraction conditions in soils from 3 different land use areas. In order to establish a greenhouse experiment, representative soil samples (0-20 cm) were taken from three fields located adjacent to one another, in a Typic Hapludands in Costa Rica. One field was a coffee plantation (*Coffea arabica* var Catuai), the second a sugar cane plantation (*Saccharum* spp. var 611721), and the third a secondary forest. Sorghum (*Sorghum bicolor* var Glazer 41) was planted in 1-liter pots and harvested 4 times consecutively. Treatments were no P and P application (100 mg kg^{-1}) for each of the different land-use soil samples. Shoot and root dry matter and total P uptake were determined. Soil samples were taken before and after each of the 4 plant growth cycles and analyzed using a modified Hedley *et al.* (1982) soil P fractionation methodology. Labile-Pi, NaOH-Pi, HCl-Pi, extractable-Po, and residual-P were determined. Applied P increased labile-Pi, NaOH-Pi and HCl-Pi. Statistical changes were not observed in extractable organic P and residual-P due to P application. The NaOH-Pi and HCl-Pi seemed to

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Pi-NaOH y Pi-HCl. No se observaron cambios en el Po-orgánico extraíble y el P-residual debido a la aplicación de P. El Pi-NaOH y el Pi-HCl parecieron actuar como un reservorio temporal del P aplicado. En el tiempo se observó una posible participación del P-residual en la recuperación del Pi-lábil y del Pi-NaOH. La cantidad de P absorbida estuvo cercanamente relacionada a la cantidad inicial del Pi-lábil y fue más alto en el suelo del café que del bosque y la caña de azúcar. Durante el experimento se observaron cambios rápidos en las formas reversiblemente disponibles como el Pi-NaOH y el Pi-HCl. Los resultados sugieren la ocurrencia de cambios rápidos y dinámicos entre las formas disponibles y no disponibles de P en el suelo, en respuesta a la aplicación de fertilizante y absorción por parte de la planta, apoyando la idea de una interacción dinámica, o *continuum*, entre las formas de P.

act as a temporary pool of applied P. The possible participation of residual-P in replenishment of labile-P and NaOH-Pi was observed. The amount of plant P uptake was closely related to the initial amount of labile-Pi and was higher in coffee than in forest and sugar cane soils. The labile-P was depleted by plant uptake. Rapid changes in reversibly available soil P forms (NaOH-Pi and HCl-Pi) were observed during the experiment. Our results suggest the occurrence of very rapid and dynamic changes between available and unavailable soil P forms in response to fertilizer application and plant uptake, supporting the idea of a *continuum* among the P forms.

INTRODUCTION

Labile phosphorus (labile-P) is thought to be the form readily available form to plants and soil microorganisms and is composed basically of various pH-dependent orthophosphate ions; which are related through different types of interactions with both the soil solution and solid phase (Mattingly 1974, Morel *et al.* 2000). Because soil inorganic labile P (labile-Pi) and crystalline P reaction products coexist in soils, they are affected by chemisorption, ligand exchange, physical adsorption, surface precipitation and precipitation of separate solid phase; it is thought the opposite reactions occurs in soils as well (Sample *et al.* 1980). Hence, this so called soil labile P consist of P in both intensity and quantity factors simultaneously (Olsen and Khasawneh 1980). The amount of P present in the soil solution and other readily available P is a small fraction of plant needs. It is thought that the remainder of the amount required by plants must be obtained from the solid phase by a combination of abiotic and biotic processes (Frossard *et al.* 2000). The sources that supply labile-P come mainly from the replenishment of both organic and inorganic P compounds or from other out of soil sources such as fertilizer application and organic residues.

Several authors have attempted to explain the labile-P content and corresponding P supply to plants through the process of compartmentalizing soil P in different forms with variable availability to plants in amount and time (Chang and Jackson 1957, Hedley *et al.* 1982, Guo and Yost 1998). There is evidence that plant uptake produces an unbalanced state in soil solution, depleting P from the surrounded root zone and inducing the forced replenishment from other P sources in the soil. The reactions related to these soil P transformations can vary depending on soil type, climatic conditions and management practices (Zhang and MacKenzie 1997).

However, this perspective of compartmentalizing soil P has been criticized by several researchers (Olsen and Khasawneh 1980, Frossard *et al.* 2000). Frossard *et al.* (2000) mention that it is not reasonable to consider soil P as existing in discrete pools containing available and unavailable forms of P. The kinetic approach states the existence of a *continuum* between forms of Pi that are immediately available and that are very slowly exchangeable. Despite this point of view it is possible to idealize soil P forms or compartments in a temporal state. The important issue here is to try to determine under what conditions it is likely that the unavailable soil P forms become available rapidly enough to avoid P stress in plants.

Buehler *et al.* (2002), summarizing the results from various experiments, pointed out that in tropical soils, the amounts of P in the different forms and the fluxes of P between forms are controlled by both physical-chemical factors (mainly sorption-desorption) and by biological reactions (immobilization and mineralization). These reactions could act rapidly enough to meet plant demands over time supporting the idea of a *continuum* among the unavailable and available P forms. Under intensive growth conditions is possible to simulate strong and rapid changes in soil P forms and measure the crop response to these changes (Wagar *et al.* 1986, Hedley *et al.* 1994). The sequential soil P fractionation procedure has proven to be useful for measuring small changes in soil P that occur during short-term experiments (Headley *et al.* 1982, Hedley *et al.* 1994, Buehler *et al.* 2002).

Anionic exchangeable membrane-P (AEM-P) is considered the freely exchangeable P and it is thought to represent P in the soil solution (Tiessen and Moire 1993). Inorganic P extracted by bicarbonate ($NaHCO_3$-Pi) is loosely adsorbed to the surfaces of clays, sesquioxides and carbonates. The HCO_3^- ion competes with Pi for sorption sites and also extracts the most labile forms of organic P (Po). This extraction jointly with AEM is considered to be labile inorganic P (labile-Pi) (Magid 1993). Because AEM-P and $NaHCO_3$-Pi are labile and recognized as the most available for plant growth, it is expected that they should reflect short-term seasonal changes in plant available Pi (Hedley *et al.* 1982).

Other soil P forms seem to be closely related to reactions with labile-Pi. These other forms, classified as reversibly available P (Fe and Al phosphates, Ca phosphates, organic forms) and sparingly available P (residual P, more stable organic forms, occluded P), are thought to participate in the replenishment of labile-Pi (Guo and Yost 1998). In fertilized systems the NaOH inorganic P (NaOH-Pi) acts as a sink of fertilizer P and also as a source of P to labile-Pi (Beck and Sanchez 1994). Ca phosphates extracted by HCl (HCl-Pi) are thought to be available in the short term as well (Sui *et al.* 1999). Organic P is an important source of P in non-fertilized systems (Sharpley 1985, Beck and Sanchez 1995). Sharpley (1985) found that most labile-Po was maintained at a constant level possibly by mineralization and formation from moderately labile organic P. Both forms are called extractable-Po.

Few studies have been carried out about the importance of soil P forms related to P transformations under different land use systems and still remains largely unstudied in andisols of the tropics (Soto 1998). The objective of this research was to examine the changes of soil P forms and evaluate their plant availability under exhaustive extraction conditions in andisols from different land uses in Costa Rica.

MATERIALS AND METHODS

Site description and soil sampling

A greenhouse experiment was conducted to evaluate the effect of different land-use systems and their related crop and soil management practices on soil P forms and proportions. Three separate samples of approximately 50 kg of soil were taken from 3 different but adjacent land-use areas. One area has been a coffee plantation (*Coffea arabica* var Catuai), another a sugar cane plantation (*Saccharum* spp. var 611721), and the third a secondary forest for more than 25 years. The field was located in Juan Viñas, Costa Rica (9º55'N and 83º44'W). The soil was a sandy loam to loam well drained Typic Hapludands derived from andesitic volcanic ashes (USDA 1994, Bertsch *et al.* 2000). Samples were taken from the top 20 cm and were a composite of 20 subsamples collected randomly at different points from each of the fields. Soils samples were air dried and sieved to pass a 2mm screen.

Greenhouse experiment and treatments

Two treatments, no P and 100 mg P liter^{-1} (–P and +P treatments respectively) were applied. Five separate subsamples of 1 liter from each type of land use were placed in plastic bags. The +P treatments were applied to the soil, mixed, and incubated for 2 weeks. Five other subsamples received no P but the same amount of water as the +P treatments and were also incubated. After incubation the soil was placed into 1 liter plastic pots. The experiment was arranged in a randomized complete block design (RCBD) with 5 replications. Pots were placed on hollow wooden pans located over plastic containers filled with water in order to maintain constant soil moisture content. The water was supplied through capillarity by a filter going through the wooden pan and entering the soil via a hollow in the center of each pot. The entire experiment received base fertilization of nitrogen (50 mg l^{-1} with NH_4NO_3) and potassium (78 mg l^{-1} with KCl) which was repeated at the beginning of each of the 4 growth cycles.

In order to measure the P uptake and plant response, sorghum (*Sorghum bicolor* var Glazer 41) was grown. Fourteen seeds of sorghum were sowed. After emergence the plants were thinned to 7 plants per pot. After 30 days the entire plants were taken out of the pots, washed, divided into shoot and root, and oven dried at 60 ºC. Dry matter productin was determined, 0.5 g of dry and ground tissue was digested by a wet nitric-perchloric acid digestion (5:1 nitric acid and perchloric acid). P was determined by colorimetric absorption spectrophotomery. P uptake was calculated from the weight of dry matter and the tissue P content.

The soil was transferred again to pots and the process repeated a total of 4 times. At the beginning of the experiment and at each harvest time 3 g of soil were taken for soil P fractionation analysis.

Soil analysis

Selected chemical properties related to soil fertility were determined according to the methodology of Diaz-Romeu and Hunter (1978). Ca and Mg were extracted with 1M KCl and available P and K were determined by a 0.5M $NaHCO_3$ extraction (1:10 soil:solution). Ca, Mg, and K were determined by atomic absorption spectrophotometry and P by colorimetric absorption spectrophotometry. Acidity was extracted with 1M KCl and pH was determined in water (1:2.5 soil:solution). Organic matter was determined by Walkley and Black (1938) methodology.

Soil P fractionation methodology

Soil P fractionation methodologies are selective dissolution techniques that use the sequential application of a series of solutions to the soil in order to extract different soil P compounds. It is thought that these soil P compounds are related to different soil P forms and therefore could have variable availability to plants (labile P, Fe and Al phosphates, Ca phosphates, occluded P, organic P, etc.). Dried, ground, and sieved (<100 mesh) soil samples were analyzed by a modified version of the Hedley *et al.* (1982) soil P fractionation methodology. The P contained in aggregates and microbial biomass (sonification and chloroform steps) was determined. The methodology makes use of different steps of extraction (water+anion exchange membrane (AEM), 0.5M $NaHCO_3$, 0.1M NaOH, and 1M HCl) and digestion (a mixture of concentrated H_2SO_4 and H_2O_2) applied in sequence to a single soil sample (Fixen and Grove 1990). 0.5 g of soil was weighed into 50 ml screw-cap centrifuge tube and analyzed by the sequential scheme with periods of 16 hours of shaking and 2 to 8 hours of digestion. Constant volumes of 50 ml of solution (1:100 soil:solution) were used during the extraction step. The AEM holds the extracted P in a reversible bond allowing P to be recovered from the membrane by extraction using 0.5M HCl. AEM-P is soluble P. The 0.5M $NaHCO_3$ extracts another portion of labile P fraction. Because both forms are thought to be readily available P they were summed and called labile-Pi. The 0.1M NaOH is supposed to extract both Al and Fe phosphates, with variable binding energy. Separate portions of $NaHCO_3$ and NaOH extracts were digested. P in the digest is a combination of inorganic P (Pi) and extractable organic P (Po). The difference between the amount of P in the $NaHCO_3$ and NaOH extracts and the P in the digest is an estimate of the extractable Po. The sum of these determinations was called extractable-Po. The 1M HCl extracts the Ca phosphates of different nature and source in soil (apatites, monocalcium, dicalcium and other phosphates etc.). The remaining soil was digested with concentrated H_2SO_4 and H_2O_2 for 8 hours. The P determined after this digestion was called residual-P and corresponds to a mixture of occluded P, Ca phosphates, and according to Tiessen and Moire (1993) a portion of non extractable organic P as well. An additional sulfuric-peroxide digestion was performed on separate soil samples in order to determine total P which, when compared to the sum of P in the various fractions allowed calculation of P recovery. Recovery values varied from 105% to 109%. During the entire process the P was determined by the molybdate-ascorbic acid procedure of Murphy and Riley (1962) and determined by colorimetric absorption spectrophotomery.

Data analysis

Data were analyzed using an analysis of variance (ANOVA) (SAS Intitute 1996). The experiment was analyzed as factorial (3 soils x 2 treatments). Correlation coefficients were determined among the variables. Separation of means was performed using least squared mean contrasts. Regression analyses were also carried out on the data.

RESULTS AND DISCUSSION

Selected chemical properties are presented in table 1. The different soil and crop management practices along with the specific crop nutrient requirements produced 3 soils that varied in their fertility properties. Comparing the soil analysis with the critical levels established by Diaz-Romeu and Hunter (1978), the sugar cane soil was low in cations and consequently low effective cation exchange capacity that was reflected in low fertility as well. This was related to uptake by crops and low application rates of fertilizer and lime. As will discuss below, this impacted the P uptake by plants in this particular soil. The coffee soil had better soil fertility characteristics due possibly to a more intensive fertilizer and lime application program compared to the sugar cane soil (Bertsch *et al.* 2002). The soil from the forest had values more similar to the coffee soil than sugar cane soil except for available P.

Table 1. Selected soil chemical properties in samples from 3 different land use areas used in the greenhouse experiment.

Areas	P	pH H_20	Ca	Mg	K	Acidity	O.M.
	mg kg^{-1}		cmol(+) kg^{-1}				g kg^{-1}
Sugar cane	7.0	5.2	1.46	0.39	0.24	0.15	124
Coffee	7.6	5.4	6.80	1.15	0.26	0.20	132
Forest	5.9	5.3	6.40	1.97	0.27	0.17	141
Critical level	10	5.5	4	1	0.20	<0.5	-

Characterization of soil P forms and their variation in time

In the first sampling the labile-Pi was 7 mg P kg^{-1} in sugar cane soil, 17 mg P kg^{-1} in coffee soil, and 15 mg P kg^{-1} in forest soil. This was different than the available P (extracted by the routine method with $NaHCO_3$ and presented in table 1). The labile-Pi values were significantly different ($p > F < 0.01$). The NaOH-Pi was 151, 278, and 199 mg P kg^{-1} in the same order and probability than labile-Pi (both set of data not shown). The higher values of these 2 soil P forms observed in the coffee soil were related to the higher fertilization this crop received during the years as compared with sugar cane plantation (Beauchemin and Simmard 2000, Zheng *et al.* 2002). Sugar cane had lower values compared to forest. Because of variations inherent in the fractionation methodology, that were reported also by Paniagua *et al.* (1995), the soil P forms changes in time will be discussed below as percentages instead of absolute values (Tables 2 and 3).

The application of P rapidly increased the readily (labile-Pi) and reversibly (NaOH-Pi and HCl-Pi) available soil P forms (Table 2 and Figure 1). This increase was observed even in the first sampling; which was made 15 days after P application. The trend was obvious during the entire 164 days of the experiment. This finding suggests that those 3 soil P forms represent most of the exchangeable P and that they are affected by P fertilization in the short term. NaOH-Pi and HCl-Pi seem to act as a sink for applied P (Zheng *et al.* 2002).

Sharpley (1985) and Neufeldt (2000) reported that although no consistent seasonal variation in inorganic P content was observed, increases were measured in available P forms after fertilizer P addition. According to Wagar *et al.* (1986) and Buehler *et al.* (2002), resin-P, $NaHCO_3$-Pi, and NaOH-Pi increased with P fertilization (the first 2 are called labile-Pi in this research). The greatest increase was found in NaOH-Pi (Buehler *et al.* 2002). Important amounts of active Fe and Al in andisols are related to intensive chemisorption reactions with applied P although exchangeable Ca could be also involved (Sanchez and Uehara 1980, Parfit 1989, Molina *et al.* 1991).

The fact that an important proportion of the applied P rapidly becomes part of NaOH-Pi and HCl-Pi is important for defining those forms as sinks of applied P in a relatively short time (Beck and Sanchez 1994). Whether these forms participate in supplying P to replenish depleted labile-Pi is another important issue.

The sparingly available P forms (extractable-Po and residual-P) did not change when P was applied even though, as will be discussed below, both P forms seem to participate in the replenishment of labile-Pi (Table 3 and Figure 1). Surface associated or poorly crystalline clay bound Pi replenishes labile-Pi while more stable crystalline species act as a sink as well as long term reservoir of P (Tiessen *et al.* 1984). This result has been reported by various authors

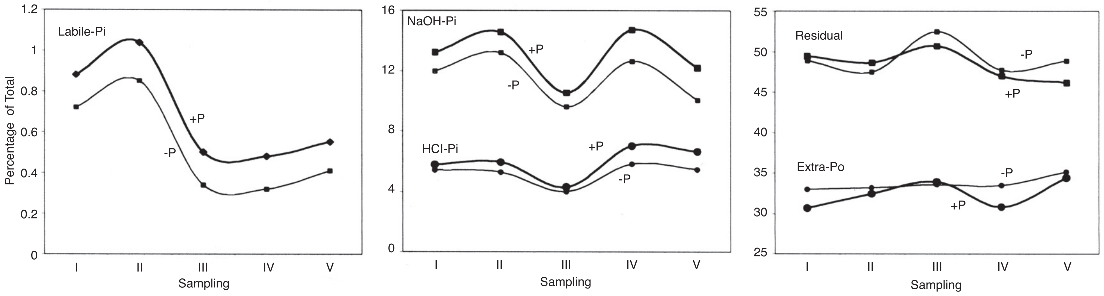

Fig. 1. Effect of P application on soil P forms in a Typic Hapludands, during 5 sampling times.

Table 2. Changes of percentages of labile-Pi, NaOH-Pi, and HCl-Pi forms in top (0-20 cm) soils from 3 different land use areas in a Typic Hapludands during 5 sampling times.

P forms	%Labile-Pi					%NaOH-Pi					%HCl-Pi				
Sampling	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
S.C.	0.48b	0.78b	0.27b	0.15b	0.34c	9.80c	13.17b	8.56c	9.86c	9.40c	7.26a	7.09a	5.46a	4.57b	7.81a
C.	0.97a	1.00a	0.47a	0.54a	0.61a	15.56a	15.36a	11.56a	18.33a	13.40a	6.01b	5.92b	4.38b	10.13a	6.39b
F.	0.96a	1.05a	0.53a	0.51a	0.49b	12.42b	13.10b	10.09b	12.84b	10.58b	3.50c	3.82c	2.57c	4.55b	3.98c
Significance	**	**	**	**	**	**	ns	**	**	**	**	**	**	**	**
+P	0.88a	1.04a	0.50a	0.48a	0.55a	13.21a	14.57	10.54a	14.72a	12.20a	5.77	5.95a	4.29a	7.02	6.64
–P	0.72b	0.85b	0.34b	0.32b	0.40b	11.97b	13.19	9.60b	12.64b	10.05b	5.42	5.27b	3.99b	5.82	5.48
Significance	**	**	**	**	**	**	ns	*	**	**	ns	*	*	*	**
S.C. +P	0.53c	0.81bc	0.37c	0.21c	0.40d	10.52e	13.79ab	9.07cd	11.76c	10.23c	7.48a	7.30a	5.87a	5.21c	9.28a
S.C. –P	0.43d	0.75c	0.17d	0.09d	0.29e	9.09f	12.54b	8.05d	7.95d	8.57d	7.04ab	6.87a	5.04b	3.93c	6.33b
C. +P	1.06a	1.17a	0.53ab	0.61a	0.71a	16.67a	16.17a	12.67a	18.42a	14.19a	6.50b	6.60a	4.65b	11.11a	6.37b
C. –P	0.88b	0.83bc	0.41c	0.47b	0.51c	14.45b	14.56ab	10.46b	18.26a	12.19b	5.53c	5.24c	4.11b	9.16b	6.41b
F. +P	1.06a	1.14a	0.61a	0.61a	0.55b	12.45c	13.74ab	9.89bc	13.99b	12.18b	3.32d	3.95d	2.33d	4.75c	4.28d
F. –P	0.87b	0.97b	0.46bc	0.41b	0.42d	12.38c	12.47b	10.30bc	11.70c	8.98d	3.68d	3.69d	2.81d	4.35c	3.69d
Significance	ns	ns	ns	ns	*	*	ns	*	**	**	*	ns	**	ns	**

Sugar cane (S.C.), coffee (C.), and forest (F.).

ns	not significant.
*	Significance at 0.01 to 0.05.
**	Significance at <0.01.

The treatments with the same letter are similar according LS means at p <0.05.

Table 3. Changes of percentages of extractable-Po and residual-P forms in top (0-20 cm) soils from 3 different land use areas in a Typic Hapludands during 5 sampling times.

	%Extrac-Po					%Residual P				
	I	II	III	IV	V	I	II	III	IV	V
S.C.	27.88c	30.32b	28.96c	28.57b	31.81c	54.58a	48.65a	56.76a	56.85a	50.64a
C.	30.18b	30.93b	32.10b	29.37b	33.41b	47.29b	46.79ab	51.49b	41.61b	46.19b
F.	37.46a	37.28a	40.25a	38.55a	39.23a	45.66b	44.74b	46.55c	43.55b	45.71b
Significance	**	**	**	**	**	**	**	**	**	**
+P	30.68b	32.47	33.95	30.82	34.45	49.46	45.98	50.72	46.96	46.15b
–P	32.99a	33.22	33.59	33.51	35.18	48.89	47.47	52.48	47.72	48.89a
Significance	**	ns	ns	ns	ns	ns	ns	ns	ns	**
S.C. +P	27.56d	29.86b	27.07d	29.24cd	31.46c	53.91a	48.24	57.63	53.59	48.62
S.C. –P	28.19d	30.79b	30.84c	27.91cd	32.16bc	55.26a	49.06	55.89	60.11	52.65
C. +P	28.38d	30.27b	32.78c	25.84d	33.21b	47.41b	45.79	49.37	44.02	45.52
C. –P	31.97c	31.59b	31.42c	32.91bc	33.62b	47.17b	47.78	53.60	39.21	46.89
F. +P	36.10b	37.28a	42.01a	37.39ab	38.69a	47.06b	43.89	45.16	43.27	44.30
F. –P	38.82a	37.28a	38.49b	39.71a	39.77a	44.26c	45.59	47.94	43.84	47.14
Significance	ns	ns	**	ns	ns	ns	ns	*	ns	*

Sugar cane (S.C.), coffee (C.), and forest (F.).

ns not significant.

* Significance at 0.01 to 0.05.

** Significance at <0.01.

The treatments with the same letter are similar according LS means at <0.05 of probability.

who refer to these soil P forms as stable and not modified by fertilizer application (Sharpley 1985, Reddy *et al.* 1999, Neufeldt *et al.* 2000).

A particular and unique increase occurred in labile-Pi at the second sampling time just after the first harvest (Figure 1 and 2). The increase was also observed in the NaOH-Pi form. It is thought that the optimal moisture in pots favored both physical-chemical reactions and biological processes that promoted the release of P from other forms and consequently increased these fractions. This increase was observed in both readily and reversible available P forms that are shown in figures 1 and 2.

The increase in labile-Pi and NaOH-Pi at the second sampling time was accompanied by a slightly decrease in residual P in coffee and forest soils but it was most evident in the sugar cane soil (Figure 2). Buehler *et al.* (2002) found that the organic and recalcitrant inorganic forms contained almost no exchangeable P although it is possible to involve those P forms in the replenishment of the labile-Pi and the other reversible available P (Guo and Yost 1998). Following the increase discussed above, labile-Pi decreased at a steady rate until the end of the study (Figure 2). After the 5 samplings the initial level of labile-P was not reached again, maybe due to high plant uptake.

General trends of the soil P forms are presented in figure 3. An increase in labile-Pi was accompanied by a proportional and significant increase in NaOH-Pi in the 3 soils. Similar results are reported by Dobermann *et*

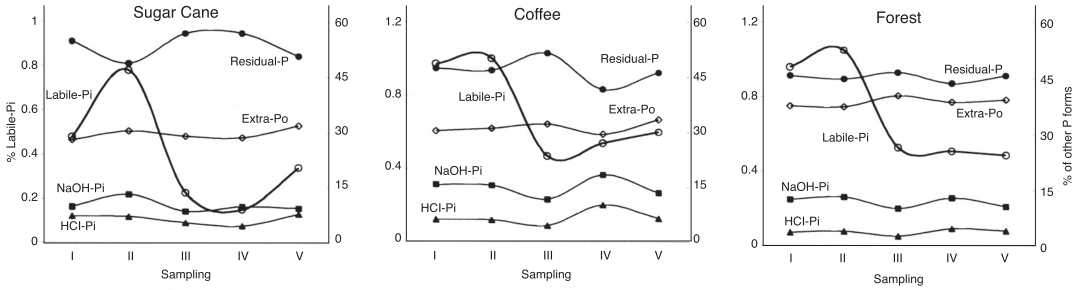

Fig. 2. Changes in soil P forms in 3 different land use areas in a Typic Hapludands, during 5 sampling times.

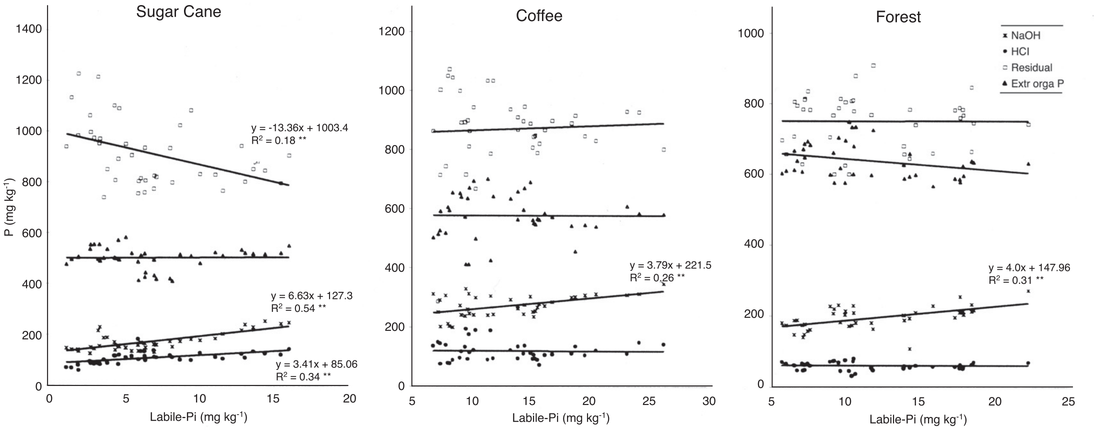

Fig. 3. General trends of soil P forms in soils from 3 different land use areas in a Typic Hapludands.

al. (2002). This supports the observation that both P fractions seem to be related through desorption/adsorption processes.

A negative relationship between labile-Pi and residual-P was observed in the sugar cane soil. The negative slope of the residual-P line suggests a possible replenishment relationship. The soil from the forest had a small and non significant decrease in extractable-Po in response to the increase in labile-Pi (Figure 3). This suggests the participation of this fraction in the replenishment of readily and reversibly available P that has been reported by other authors in unfertilized systems (Beck and Sanchez 1994). Buehler *et al.* (2002) using ^{33}P found that in soils with low or no P fertilization more than 14% of this P was recovered in NaOH-Po and HCl-Po (this last form was not determined in this study), showing that organic P dynamics are important when soil Pi reserves are limited. Paniagua *et al.* (1995) found that the immobilization and mineralization of Po is strongly controlled by the supply of P and depends on inorganic fertilization; they also suggest that organic additions without synthetic fertilizers may decrease soil organic P. Linquist *et al.* (1997) found that in the zero applied P treatment, $NaHCO_3$-Po was correlated with labile-Pi, soybean dry matter, yield, and P uptake, suggesting that mineralized Po is an important source of plant P in unfertilized systems. This result is supported by the studies of Beck and Sanchez (1994) and suggests that in unfertilized cropping systems, Po mineralization may be a major source of plant P.

Plant P uptake and relation with soil P forms

The results presented in table 4 and figure 4 suggest a significant relationship between total dry matter (g pot^{-1}) and plant P uptake (mg P kg^{-1}). Therefore, and based on the assumption that under the conditions of this study both variables act the same, P uptake will be used in discussing plant response variables and assumptions will make for both variables as sharing the same behavior.

The amount of P uptake by plants was strongly dependent on the amount of labile-Pi in the soil. This result agrees with data reported by

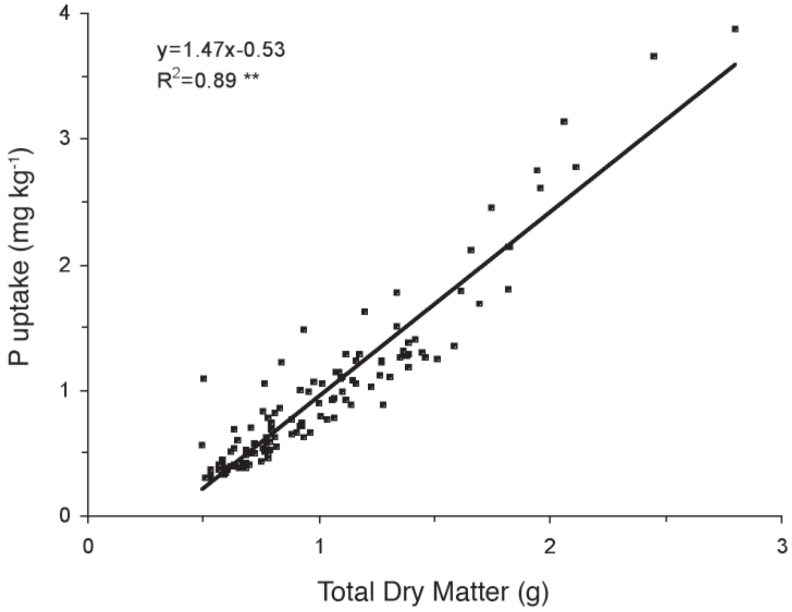

Fig. 4. Relationship between total dry matter and P uptake in sorghum (*Sorghum bicolor*) in Typic Hapludands soils, from 3 land use areas.

Table 4. Plant response variables obtained during 4 harvests of sorghum (*Sorghum bicolor*) in soils from 3 different land use areas on a Typic Hapludands, Costa Rica.

Variable	P uptake				Shoot weight				Root weight				Total dry matter			
	mg kg^{-1}				g per pot				g per pot				g per pot			
Harvest	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
S.C.	0.83b	0.42b	0.39c	0.47b	0.39c	0.41b	0.43c	0.49b	0.32b	0.21b	0.18c	0.22b	0.71c	0.62b	0.61c	0.71c
C.	0.80b	1.80a	1.49a	1.00a	0.51b	0.92a	0.92a	0.74a	0.41a	0.66a	0.55a	0.44a	0.92b	1.58a	1.47a	1.17a
F.	0.99a	1.74a	1.04b	0.82a	0.65a	0.82a	0.64b	0.54b	0.43a	0.61a	0.46b	0.39a	1.09a	1.42a	1.10b	0.93b
Significance	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
+P	1.10a	1.83a	1.09a	0.84	0.61a	0.89a	0.68	0.61	0.45a	0.58a	0.40	0.35	1.06a	1.47a	1.08	0.96
–P	0.64b	0.81b	0.85b	0.69	0.42b	0.54b	0.64	0.57	0.33b	0.40b	0.40	0.35	0.75b	0.95b	1.04	0.92
Significance	**	**	*	ns	**	**	ns	ns	**	**	ns	ns	**	**	ns	ns
S.C. +P	1.02b	0.45c	0.43bc	0.52b	0.41cd	0.42c	0.43c	0.51bcd	0.35b	0.20c	0.18b	0.22c	0.76cd	0.62c	0.61c	0.73c
S.C. –P	0.64c	0.38c	0.35c	0.42b	0.36d	0.40c	0.43c	0.46cd	0.29b	0.21c	0.17b	0.23c	0.65d	0.62c	0.60c	0.69c
C. +P	1.02b	2.31a	1.54a	0.90ab	0.59b	1.13a	0.92a	0.67ab	0.48a	0.77a	0.55a	0.41ab	1.06b	1.91a	1.47a	1.08ab
C. –P	0.57c	1.29b	1.43a	1.09a	0.44cd	0.70b	0.92a	0.80a	0.34b	0.54b	0.55a	0.46a	0.78c	1.24b	1.47a	1.27a
F. +P	1.26a	2.72a	1.30a	1.09a	0.84a	1.12a	0.69b	0.65abc	0.51a	0.76a	0.46a	0.41ab	1.35a	1.87a	1.15b	1.06ab
F. –P	0.71c	0.75bc	0.78b	0.55b	0.46c	0.52bc	0.59bc	0.43d	0.36b	0.46b	0.46a	0.37b	0.82c	0.98bc	1.05b	0.80bc
Significance	ns	**	ns	ns	**	ns	ns	ns	ns	*	ns	ns	**	ns	ns	ns

Sugar cane (S.C.), coffee (C.), and forest (F.).

ns	not significant.
*	Significance at 0.01 to 0.05.
**	Significance at <0.01.

The treatments with the same letter are similar according LS means at <0.05 of probability.

Linquist *et al.* (1997) and Guo *et al.* (2000). Strong differences in this variable could be seen in sugar cane soil compared to the coffee and forest soils. The highest P uptake was measured for plants in the coffee and forest soils. P uptake by plants in the sugar cane soil was low and followed a different pattern over time (Figure 5 and Table 4).

Plant P uptake response to applied P was statistically different among the 3 soils (Figure 6). The total amounts of applied P absorbed by plants were 35%, 30%, and 127% of the total in sugar cane, coffee and forest soils, respectively. The low recovery observed in the sugar cane soil was related to poor plant growth due something other than P availability and consequently poor P absorption even though the supply of P was adequate (100 mg P kg^{-1}). It is likely that the general low fertility observed in this soil had more effect on plant growth than the application of P itself. Ca and Mg contents for instance, were visibly lower in this soil as compared with the other 2 soils (Table 1).

The response to P by plants growing in the forest soil was probably due to the favorable physical and chemical characteristics of this soil that when P was applied promoted good plant growth. This is supported by the trend in dry matter accumulation by plants growing in coffee and forest soils which were different from the trend observed in plants growing in the sugar cane soil (Figure 7). The rate of response in figure 7 agrees with the observed in figure 6. It is possible to relate the behavior of total dry matter accumulation in plants in coffee and forest soils with the changes in labile-Pi over the time of the study (comparing Figures 2 and 6). This is an evidence of the strong relationship between labile-P and plant response reported by other authors as well (Hedley *et al.* 1994, Morel *et al.* 2000, Guo *et al.* 2000).

CONCLUSION

P fertilization impacted labile-Pi, NaOH-Pi, and HCl-Pi supporting the readily and reversible available nature of these soil P forms

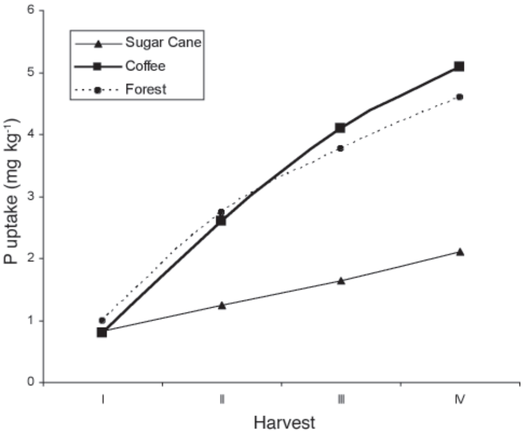

Fig. 5. Accumulated P uptake by sorghum (*Sorghum bicolor*) during 4 sampling times in soils from a Typic Hapludands under 3 different land uses.

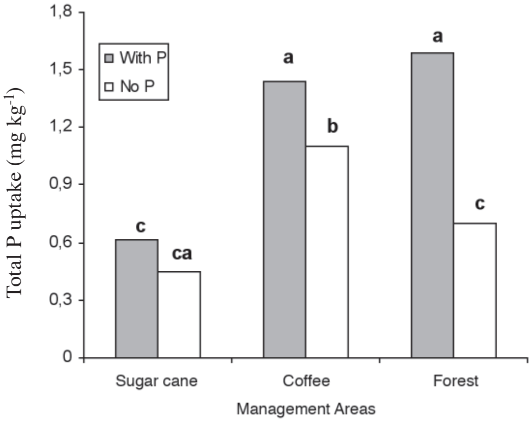

Fig. 6. P uptake response by sorghum (*Sorghum bicolor*) to P application in soils from 3 land use areas in a Typic Hapludands.

that occured during the 120 days, of the study. NaOH-Pi and HCl-Pi seem to act as sinks of applied P when the labile-Pi is not able to keep high amounts of applied P. Residual-P could participate in replenishment of depleted available P forms under certain conditions, *i.e.* low amounts of labile-Pi even though the rate or replenishment may not meet the plant requirements over time. Plant P uptake was related to the amount of

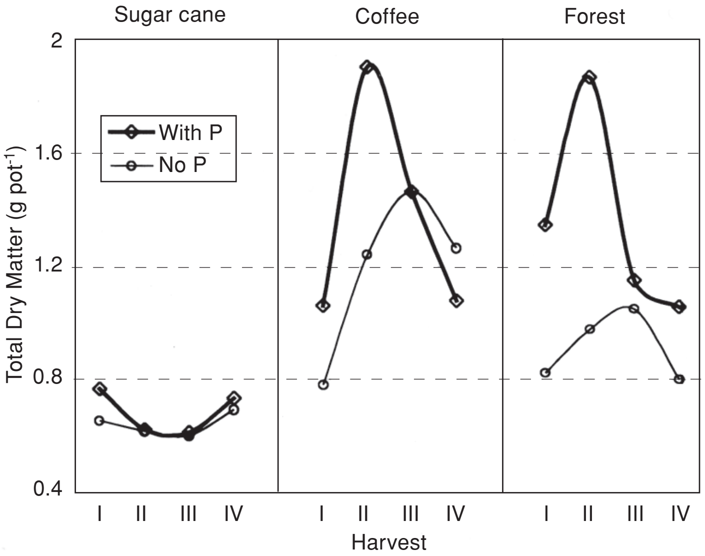

Fig. 7. Plant response in total dry matter accumulation in sorghum (*Sorghum bicolor*) during 4 harvest evaluations in 3 different land use areas in a Typic Hapludands.

available labile-Pi. The initial P desorbed was related to labile-Pi. The forest soil had the higher rate of P desorption as compared with coffee and sugar cane soils even though this was defined under specific time conditions imposed by the methodology.

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CITED LITERATURE

BALL-COELLO B., SALCEDO I.H., TIESSEN H., STEWART J.W.B. 1993. Short- and long- term phosphorus dynamics in a fertilized Ultisol under sugarcane. Soil Sci. Soc. Am. J. 57: 1027-1034.

BEAUCHEMIN S., SIMARD R.R. 2000. Phosphorus status of intensively cropped soils of the St. Lawrence Lowlands. Soil Sci. Soc. Am. J. 64: 659-670.

BECK M.A., SANCHEZ P.A. 1994. Soil phosphorus fraction dynamics during 18 years of cultivation on a Typic Paleoudult. Soil Sci. Soc. Am. J. 58: 1424-1431.

BERTSCH F., ALVARADO A., HENRIQUEZ C., MATA R. 2000. Properties, geographic distribution and management of major soil orders of Costa Rica. *In*: Quantifying sustainable development: The future of tropical economies. Ed. C.A.S. Hall, C. Leon, and G. Leclerc. Academic, San Diego CA. p. 265-294.

BERTSCH F., HENRIQUEZ C., RAMIREZ F., SANCHO F. 2002. Site-specific nutrient management in the highlands of Cartago province. Better Crops International 16(1): 16-19.

BUEHLER S., OBERSON A., RAO I.M., FRIESSEN D.K., FROSSARD E. 2002. Sequential phosphorus extraction of a ^{33}P-labeled oxisol under contrasting agricultural systems. Soil Sci. Soc. Am. J. 66: 868-877.

CHANG S.C., JACSON M.L. 1957. Fractionation of soil phosphorus. Soil Sci. 84: 133-144.

DELGADO A., TORRENT J. 2000. Phosphorus forms and desorption patterns in heavily fertilized calcareous. Soil Sci. Am. J. 64: 2031-2037.

DIAZ ROMEU R., HUNTER H. 1978. Metodología de muestreo de suelos. Análisis químico de suelos y tejido vegetal e investigaciones en invernadero. CATIE. Turrialba, Costa Rica, Bulletin.

DOBERMANN A., GEORGE T., THEVS N. 2002. Phosphorus fertilizer effects on soil phosphorus pools in acid Upland soils. Soil Sci. Soc. Am. J. 66: 652-660.

FIXEN P.E., GROVE J.H. 1990. Testing soils for phosphorus. *In*: Soil testing and plant analysis. ed. R.L Westerman. Soil Science Society of America. Madison, WI. p. 141-180.

FROSSARD E., CONDRON L.M., OBERSON A., SINAJ S., FARDEAU J.C. 2000. Processes governing phosphorus availability in temperate soils. J. Environ. Qual. 29: 15-23.

GUO F., YOST R.S. 1998. Partitioning soil phosphorus into three discrete pools of differing availability. Soil Sci. 163: 822-833.

GUO F., YOST R.S., HUE N.V., EVENSON C.I., SILVA J.A. 2000. Changes in phosphorus fractions in soils under intensive plant growth. Soil Sci. Soc. Am. J. 64: 1681-1689.

HEDLEY M.J., STEWART J.W.B., CHAUHAN B.S. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Sci. Soc. Am. J. 46: 970-976.

HEDLEY M.J., KIRA G.J.D., SANTOS M.B. 1994. Phosphorus efficiency and the forms of soil phosphorus utilized by upland rice cultivars. Plant and Soil 158: 53-62.

LINQUIST B.A., SINGLETON P.W., CASSMAN K.G. 1997. Inorganic and organic phosphorus dynamics during a build up and decline of available phosphorus in an Ultisol. Soil Sci. 162: 254-264.

MAGID J. 1993. Vegetation effects on P fractions in set-aside soils. Plant and Soil 149: 111-119.

MATTINGLY G.E.G. 1974. Labile phosphate in soils. Soils Sci. 119: 369-375.

MOLINA E., BORNEMISZA E., SANCHO F., KASS D.L. 1991. Soil Aluminum and iron fractions and their relationships with P immobilization and other soil properties in andisols of Costa Rica and Panama. Commun. Soil Sci. Plant Anal. 22(13-14): 1459-1476.

MOREL C., TUNNEY H., PLENET D., PELLERIN S. 2000. Transfer of phosphate ions between soil and solution. Perspectives in soil testing. J. Environ. Qual. 29: 50-59.

MURPHY J., RILEY J.P. 1962. A modified single solution method for the determination of phosphate in natural resources. Anal. Chim. Acta 27: 31-36.

NEUFELDT H., DA SILVA J.E., AYARZA M.A., ZECH W. 2000. Land-use effects on phosphorus fractions in Cerrado oxisols. Biol. Fertil. Soils. 31: 30-37.

OLSEN S.R., KHASAWNEH F.E. 1980. Use and limitations of physical-chemical criteria for assessing the status of phosphorus in soils. *In*: The role of phosphorus in agriculture. ed. F.E. Khasawneh, E.C. Sample and E.J. Kamprath. ASA, CSSA and SSSA. Madison, WI. p. 361-410.

PANIAGUA A., MAZZARINO M.J., KASS D., SZOTT L., FERNANDEZ C. 1995. Soil phosphorus fractions under five tropical agro-ecosystems on a volcanic soil. Australian Journal of Soil Research 33: 311-320.

PARFITT R.L. 1989. Phosphate reactions with natural allophane, ferrihydrite and goethite. J. Soil Sci. 40: 359-369.

REDDY D.D., RAO A.S., TAKKAR P.N. 1999. Effects of repeated manure and fertilizer phosphorus additions on soil phosphorus dynamics under a soybean-wheat rotation. Biol. Fertil. Soils 28: 150-155.

SAMPLE E.C., SOPER R.J., RACZ G.J. 1980. Reactions of phosphate fertilizers in soils. *In*: The role of phosphorus in agriculture. ed. F.E. Khasawneh, E.C. Sample and E.J. Kamprath. ASA, CSSA and SSSA. Madison, WI. p. 263-312.

SANCHEZ P., UEHARA G. 1980. Management considerations for acid soils with high phosphorus fixation capacity. *In*: The role of phosphorus in agriculture. ed. F.E. Khasawneh, E.C. Sample and E.J. Kamprath. ASA, CSSA and SSSA. Madison, WI. p. 471-514.

SAS INSTITUTE. 1996. SAS/STAT user's guide. Release 6.11. SAS Inst., Cary, NC.

SELLES F., CAMPBELL C., ZENTNER R. 1995. Effect of cropping and fertilization on plant and soil phosphorus. Soil Sci. Soc. Am. J. 59: 140-144.

SHARPLEY A.N. 1985. Phosphorus cycling in unfertilized and fertilized agricultural soils. Soil Sci. Soc. Am. J. 49: 905-911.

SOTO J.A. 1998. Formas de fósforo y su liberación en andisoles de la región Central Oriental de Costa Rica. Tesis Doctoral Ph.D. Universidad Superior de Ingenieros Agrónomos y de Montes. España. 155 p.

SUI Y., THOMPSON M.L., SHANG C. 1999. Fractionation of phosphorus in a Mollisol amended with biosolids. Soil Sci. Soc. Am. J. 63: 1174-1180.

TIESSEN H., STEWART J.W.B., COLE C.V. 1984. Pathway transformations in soils of differing pedogenesis. Soil Sci. Soc. Am. J. 48: 853-858.

TIESSEN H., MOIRE J.O. 1993. Characterization of available P by sequential extraction. P 75-86. *In*: M.R. Carter (ed.) Soil Sampling and methods of analysis. Canadian Society of Soil Science. Lewis Publ., Boca Raton, Fl.

USDA. 1994. Keys of soil taxonomy. Sixth edition. USA, Soil Conservation Service.

WAGAR B.I., STEWART J.W.B., MOIR J.O. 1986. Changes with time in the form and availability of residual fertilizer phosphorus on Chernozenic soils. Can. J. Soil Sci. 66: 105-119.

WALKLEY A., BLACK C.A. 1938. An examination of the Degtajareff's method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 37: 29-38.

ZHANG T.Q., MACKENZIE A.F. 1997. Changes of soil phosphorus fractions under long-term corn monoculture. Soil Sci. Soc. Am. J. 61: 485-493.

ZHENG Z., SIMARD R.R., LAFOND J., PARENT L.E. 2002. Pathways of soil phosphorus transformations after 8 years of cultivation under contrasting cropping practices. Soil Sci. Soc. Am. J. 66: 999-1007.