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UMI®
Assessing soil phosphorus status under different agronomic land use

by

Carlos Henriquez

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Soil Science (Soil Fertility)

Program of Study Committee:
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Iowa State University
Ames, Iowa
2002

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Graduate College
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Carlos Henriquez

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Major Professor

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For the Major Program
I would like to dedicate this work to the Spirit that makes the human being dreams become possible.

To my daughter Sofia who is part of this dream and was always my best motivation
TABLE OF CONTENTS

LIST OF FIGURES vi

LIST OF TABLES viii

ABSTRACT x

CHAPTER 1. GENERAL INTRODUCTION 1
  Introduction 1
  Dissertation Organization 2
  References 2

CHAPTER 2. CHANGES IN SOIL P FORMS AFTER ORGANIC AND INORGANIC
  P FERTILIZATION UNDER SUGAR CANE 4
  Abstract 4
  Introduction 5
  Materials and Methods 8
  Results and Discussion 12
  Conclusion 26
  Acknowledgements 27
  References 27

CHAPTER 3. EFFECT OF LAND USE ON SPATIAL DISTRIBUTION OF SOIL P
  FORMS AND OTHER SOIL CHARACTERISTICS ON AN ANDISOL IN COSTA
  RICA 30
  Abstract 30
  Introduction 31
  Materials and Methods 33
  Results and Discussion 37
  Conclusion 50
  Acknowledgements 51
  References 51

CHAPTER 4. SOIL P FORMS AND P UPTAKE UNDER INTENSIVE PLANT
  GROWTH IN AN ANDISOL WITH DIFFERENT LAND USE 54
  Abstract 54
  Introduction 55
  Materials and Methods 57
  Results and Discussion 61
  Conclusion 73
  Acknowledgements 73
  References 73
LIST OF FIGURES

CHAPTER 2.
Figure 1. Scheme of modified Hedley et al. (1982) soil P fractionation methodology. 11
Figure 2. Percentages and amounts (mg kg⁻¹) of P forms at two depths on a Typic Hapludand. Juan Viñas, Costa Rica. 15
Figure 3. Relation between accumulated sugar cane yield (Var. 611721) and P applied as fertilizer on an Andisol. Juan Viñas, Costa Rica. 22
Figure 4. Relation between accumulated sugar cane yields (Var 611721) and labile-Pi and NaOH-Pi on an Andisol. Juan Viñas, Costa Rica. 23
Figure 5. Total P uptake curve by sugar cane (Var. 611721) on a Typic Hapludand. Juan Viñas, Costa Rica. 24
Figure 6. Relationship between log time and log accumulated desorbed P on an Andisol. 26

CHAPTER 3.
Figure 1. Management areas (a), contour slope lines (b), and grid sampling points (c) on the area of study, Juan Viñas, Costa Rica. 35
Figure 2. Interpolated maps for different soils properties for three crop/soil management areas in a Typic Hapludand. 39
Figure 3. Transect representation for Ca, Mg, and K through three management areas. 40
Figure 4. Interpolated maps of soil P forms in top soil (0-20 cm) of three management areas in a Typic Hapludand. 44
Figure 5. Interpolated maps of soil P forms in subsoil (20-40 cm) of three management areas in a Typic Hapludand. 45
Figure 6. Transect representation of available P forms across the three management areas. 46
Figure 7. Overall and particular linear relation for labile-Pi and NaOH-Pi in three management areas. 49

CHAPTER 4.
Figure 1. Effect of P application on soil P forms in a Typic Hapludand during five sampling times. 63
Figure 2. Changes in soil P forms in three different land use areas in a Typic Hapludand during five sampling times. 65
Figure 3. General trends of soil P forms in soils from three different land use areas in a Typic Hapludand 66
Figure 4. Relationship between total dry matter and P uptake in sorghum (Sorghum bicolor) in a Typic Hapludand under three land use. 68
Figure 5. Accumulated P uptake by sorghum (Sorghum bicolor) during four sampling times in soils from three land use areas. 68
Figure 6. P uptake response by sorghum to P application in soils from three land use areas in a Typic Hapludand. 69
| Figure 7. | Total dry matter accumulation in sorghum during four harvest evaluations in three different land use areas in a Typic Hapludand. |
| Figure 8. | Accumulated P desorbed in soils from three different land use areas in a Typic Hapludand. |
| Figure 9. | Relationship between the log of accumulated P desorbed and log of time in soils from three different land use areas in a Typic Hapludand. |
| Figure 10. | Rate of P desorption in soils from three land use areas in a Typic Hapludand. |
LIST OF TABLES

CHAPTER 2.
Table 1. Estimated amounts of nutrients applied as fertilizer on sugar cane (Var. 611721 over four years on a Typic Hapludan at Juan Viñas, Costa Rica. 9
Table 2. Andic properties of a Typic Hapludand at the experiment site, Juan Viñas Costa Rica. 13
Table 3. Selected properties of the soil used in the study. Juan Viñas, Costa Rica. 13
Table 4. Amounts and relative percentages of P forms obtained by using the modified Hedley et al. (1982) methodology on a Typic Hapludand. Juan Viñas Costa Rica. 14
Table 5. Pearson correlation coefficients between P applied as fertilizer to sugar cane and various P forms in soil. 16
Table 6. Pearson's correlation coefficients for P forms extracted by a modified Hedley scheme (only coefficients significant at less than P 0.05 are shown, n=30). 21
Table 7. Sugar cane (H-611721) yields obtained after two growth cycles during four years on a Typic Hapludand, at Juan Viñas, Costa Rica. 22

CHAPTER 3.
Table 1. Andic properties of a Typic Hapludand at Juan Viñas, Costa Rica. 34
Table 2. Balance between the amounts of nutrients removed and applied in the coffee and sugar cane plantation in the study area, Juan Viñas, Costa Rica (Bertsch et al., 2002). 37
Table 3. Selected chemical properties of the top soil (0’20 cm). Juan Viñas, Costa Rica 37
Table 4. Selected chemical and physical properties of the top soil (0-20 cm). Juan Viñas, Costa Rica. 38
Table 5. Percentages of P forms obtained by using a modified Hedley et al. (1982) methodology at two sampling depths (0-20 and 20-40 cm) on a Typic Hapludand. 41
Table 6. Amounts and relative percentages of P forms obtained by using a modified Hedley et al. (1982) methodology on the top soil (0-20) of a Typic Hapludand, Juan Viñas, Costa Rica. 42
Table 7. Pearson's correlation coefficients for P forms extracted by a modified Hedley scheme (only coefficients significant at P<0.05 are shown, n=30). 48

CHAPTER 4
Table 1. Selected soil chemical properties in samples from three different land use areas used in the greenhouse experiment. 62
Table 2. Changes of percentages of labile-Pi, NaOH-Pi, and HCl-Pi forms in top soil (0-20 cm) from three different land use areas in a Typic Hapludand during five sampling times 63
Table 3. Changes of percentages of extractable-Po and residual-P forms in top soil (0-20 cm) from three different land use areas in a Typic Hapludand during five sampling times

Table 4. Plant response variables obtained during four harvests of sorghum (*Sorghum bicolor*) in soils from three different land uses areas on a Typic Hapludand, Costa Rica.
ABSTRACT

The study of the availability of soil phosphorus (P) to crops has been an important issue for years in different agroecosystems around the world. Because of the complex P cycling in soils this has been studied from different points of view. The study of soil P forms has been seen as a possible way to explain many processes and changes occurring in plant-soil interactions. The purpose of this research was to characterize soil P forms under different land uses and evaluate the relationship between different land use areas and the spatial distribution of soil P forms. The study was carried out in Costa Rica on a Typic Hapludand under coffee plantation (Coffea arabica), sugar cane plantation (Saccharum spp.), and secondary forest. A modified Hedley soil P fractionation methodology was used for determining the soil P forms. Means of the relative content of P forms were 0.43% labile-Pi, 6.44% NaOH-Pi, 9.20% HCl-Pi, 32.55% extractable organic P and 51.37% residual-P. Inorganic fertilization was correlated with labile-P, NaOH-Pi, and HCl-Pi forms. In the first experiment the sugar cane yields were correlated with labile-Pi and NaOH-Pi. Organic fertilizer increased the extractable organic P suggesting an accumulation in this form. In the second descriptive study a spatial relationship was found with soil management areas. Sugar cane soil accumulated more P in HCl-Pi, extractable organic P, and residual-Pi forms. Coffee soil had the highest values in labile-Pi and NaOH-Pi that were correlated with the higher rate of fertilizer application. Secondary forest had intermediate values between these two cropped areas. The third experiment showed that under greenhouse conditions P uptake was closely related to labile-Pi and NaOH-Pi suggesting also that a sparingly available P form could be related to P uptake by plants in time. Extractable organic P and residual-P were suggested to act as a sink of the available P forms. It is concluded that under a sustainable crop production framework the adequate input of P is necessary in order to maintain the adequate nutrient supply through time.
CHAPTER 1
GENERAL INTRODUCTION

Introduction

Soil phosphorus (P) availability depends on different processes that occur intensively in soils and involve changes in various inorganic and organic soil P forms. Despite the fact that these processes occur naturally, they are greatly modified by the agronomic practices usually applied in crop production systems (Killorn, 1985; Beauchemin and Simard, 2000; Reddy et al., 1999). It is thought that the biggest changes affecting the availability of P in time are produced mainly by inorganic and organic fertilizer application (Neufeldt et al., 2000; Guo et al., 2000).

The use of fertilizers has been mentioned as the most important method to increase the inorganic and easily available soil P forms. It accomplishes the task of keeping enough P available for crops (Sample et al., 1980; Beauchemin and Simard, 2000). In many soil conditions a large percentage of the P applied is rapidly fixed or immobilized in organic forms and converted to other unavailable forms of P. This reflects the intensive changes in P forms after the fertilization or manure application.

In general terms the impact of adding phosphorus fertilizer year after year could be viewed as increasing both available and non-available P forms and increasing the soil total P as well (Hettiarachchi et al., 1997). In some cases neither the total quantity of P nor the available P in soil are well related to plant uptake and yield. Deficiency symptoms are observed in plants and significant yield decreases may also occur even though sufficient levels of P are present in the soil (Guo et al., 2000). Some researchers have found that the deficiency of P in crops is mainly caused by the strong sorption of phosphate to other compounds in soil, which turns P into plant-unavailable forms (Parfit 1978; Sanchez and Uehara, 1980). Andisols show particular high P sorption and high organic matter content aspects strongly related to P cycling. In Costa Rica, important cropped areas are located on Andisols with a large number of crop production systems where P management is an important issue (Bertsch et al., 2000).
Many studies have shown that it is important to gain an understanding of the effect of soil types on P cycling and how this is related to soil management (Guo et al., 2000; Neufeldt et al., 2000; Reddy et al., 1999).

The purpose of this research was to evaluate the changes in soil P forms related with different land use agroecosystems practices in an Andisol in Costa Rica.

**Dissertation Organization**

Each chapter in this thesis is an individual paper. Therefore the chapters include their own individual abstract, introduction, materials and methods, results, discussion, conclusions, and references. A general conclusion is included at the end of the entire document.

Chapter 2 reports the results of a four-year sugar cane experiment where inorganic and organic P fertilizers were applied. A modified Hedley soil P fractionation methodology was used to measure differences in soil P forms compared with a control that was not fertilized.

Chapter 3 reports a descriptive spatial distribution of soil P forms on three different land use areas. Soil P form distribution on the field were described in three different land use areas using geographical information systems tools.

Chapter 4 reports the results of a greenhouse experiment. Soil samples from the same areas used in Chapter 3 were used in order to study the temporal variation of soil P forms under exhaustive plant P extraction.

The general conclusions of this study are in Chapter 5, which also attempts to convey the most practical applications of the results to the field of P management in agroecosystems in Costa Rica.

**References**


CHAPTER 2
CHANGES IN SOIL P FORMS AFTER ORGANIC AND INORGANIC P FERTILIZATION UNDER SUGARCANE

Carlos Henriquez, Randy Killorn, and Floria Bertsch

Abstract

Soil and crop management practices tend to modify soil phosphorus (P) forms impacting P availability in time and intensity. Organic and inorganic fertilization modifies soil P cycling, increasing available P, but more research is needed to explain the changes in other P forms, especially in tropical soils. The purpose of this experiment was to study the changes produced by application of organic and inorganic fertilizers in soil P forms and their relationship with yield response by sugar cane on an Andisol. A field experiment was conducted from 1997 to 2001 on a Typic Hapludand at Juan Viñas, Costa Rica (1000 masl and 2000 mm of rain per year). Sugar cane (Saccharum sp. var. H-61721) was cropped in two cycles during those years. Yields of cane (in Mg ha\(^{-1}\)) and sugar (kg per Mg\(^{-1}\) of fresh cane) were measured. The treatments were 0, 50% and 100% of the recommended inorganic fertilizer in combination with 0 and 8 tons of compost ha\(^{-1}\) arranged in a randomized, complete block design (RCBD) with three replications. Fertilizer was applied at the beginning of each growing cycle. Soil samples were collected at two depths (0-20 and 20-40 cm). Soil samples were ground (<100 mesh) and analyzed using a modified Hedley et al. (1982) soil P fractionation scheme. The soil P determinations by anionic exchange membrane-P (AEM-P), NaHCO\(_3\)-Pi, NaOH-Pi, HCl-Pi, and H\(_2\)SO\(_4\)+H\(_2\)O\(_2\) digestion were related to soluble/labile-Pi, labile-Pi, Fe/Al-phosphates, Ca-phosphates and residual P. Extractable organic P was determined by the difference of total P (determined in digested aliquots of the NaHCO\(_3\) and NaOH extractions) and the Pi initially determined from these extracts. AEM-P and NaHCO\(_3\)-Pi were summed and expressed as labile-Pi. NaHCO\(_3\)-Po and NaOH-Po were summed and expressed as extractable-Po. Soil subsamples (<2 mm) were analyzed for pH (H\(_2\)O), Ca, Mg, K, organic matter, P fixation and ammonium oxalate extractable Fe and Al. Means of the relative content of P forms were 0.43% labile-Pi (composed of 0.11% AEM-P and 0.32% NaHCO\(_3\)-Pi), 6.44% NaOH-Pi, 9.20% HCl-Pi,
32.55% extractable-Po (composed of 2.38% NaHCO$_3$-Po and 30.17% NaOH-Po), and 51.37% residual-P. The total sum of all the P fractions varied from approximately 1500 mg kg$^{-1}$ (control treatment) to 1800 mg kg$^{-1}$ (100% fertilization and 8 tons of compost). All P forms were lower in the control treatment than the fertilized treatments suggesting that depletion occurred in response to crop uptake and enrichment occurred in fertilized plots. Compost application increased the organic P forms 46 mg kg$^{-1}$. Thirty two percent of the total P was extractable-Po, although there was evidence that some organic P could remain in the residual-P fraction. The 100% fertilized treatment had the highest P desorption while compost fertilized treatments had the highest amount of initial P desorbed. Sugar cane yield increased 33% when P was applied as inorganic and organic fertilizers at the higher levels. Sugar cane took up approximately 60 kg P ha$^{-1}$ at an estimated yield of 180 Mg ha$^{-1}$ of cane in 700 days. Yield was positively related to labile-P$_i$ and NaOH-P$_i$. A poor relationship was found between yield and the extractable-Po, HCl-P$_i$, residual-P, and total P fractions. Labile-P$_i$, NaOH-P$_i$ and total sum of P were highly correlated to P applied. The results suggest that the application of both organic and inorganic fertilizers had an important impact on P forms, modifying the amount of P in the soil. Labile-P$_i$ in control remained nearly constant due to replenishment from other, non-available P forms suggesting rapid cycling among P forms. High demand of sugar cane for P and no application of fertilizer resulted in a decrease of nearly all P forms over time.

Introduction

Fertilizer input is an important factor in determining the economical suitability of production of sugar cane and many other crops around the world. Because of its low application efficiency and high cost, appropriate P fertilization has been of high concern (Ball-Coelho et al. 1993; Zhang and MacKenzie, 1997). Both organic and inorganic fertilizers have been utilized as a source of P for crops to increase P availability, although variable crop responses have been noted under different soil conditions (Ball-Coelho et al., 1993; Reddy et al., 1999; Sui et al., 1999). These results suggest a particular cycle of P in
agroecosystems related to the type of soil and crop production system and emphasize the need for more research.

In Costa Rica important areas dedicated to sugar cane production are on soils derived from volcanic ash or Andisols (Bertsch et al., 2000; Alvarado et al., 2001). Andisols are one of the highest P-fixing soils due to adsorption at the active surfaces of allophane and imogolite minerals and also by humus-Al complexes through ligand-exchange reactions (Sanchez and Uehara, 1980; Molina et al., 1991; Espinosa, 1992; Alvarado et al., 2001). This fact complicates the estimation of P availability on these soils because soil tests are not a completely adequate tool for predicting P availability (Beck and Sanchez, 1994; Espinosa, 1992).

Total soil P is composed of different P forms, with each having variable availability to plants. Transformations of the P forms vary depending on soil type, climatic conditions and management practices (Zhang and MacKenzie, 1997). The actual soil P available to plants is determined by a number of different soil and out-of-soil factors and has been modeled by quantity and intensity factors that represent very complex cycling in the soil (Olsen and Khasawneh, 1980). Soil available P is mainly supplied by parent material, decomposition of soil organic matter, and by fertilizer inputs that enrich different forms of soil P. Hence, when available P is depleted, replenishment from other P forms becomes an important process (Zhang and MacKenzie, 1997). Routine soil P tests have been used to estimate a rapid index of plant-available P and fertilizer requirements but they ignore less available inorganic and organic pools (Beck and Sanchez, 1994). Spatial and temporal variability seem to be linked through depletion or replenishment of P. These aspects are not covered by a unique soil P test value.

The importance of non available P forms on plant nutrition has been observed by various researchers (Tiessen et al., 1984; Sharpley, 1985; Reddy et al., 1999; Neutfeldt et al., 2000; Zheng et al., 2002). These results suggest that, depending on type of soil and management practices, non available P forms could, in time, be taken up by plants after, depending on P form, undergoing desorption, weathering, and mineralization processes. Guo et al. (2000) found that in slightly weathered soils residual P, that is thought to be a sparingly available P form, was available to plants on a relatively short time scale. Sui et al. (1999) stated that
HC1-P applied to soils in biosolids could be transformed to more labile forms. Iyamuremye et al. (1996) found that manure and plant residues increased resin-P, bicarbonate-Pi and Po and NaOH-Pi. Magid (1993) stated that vegetation had an important effect on all P forms. Several authors refer to the NaOH-Pi fraction as a sink of applied P fertilizers (Zhang and Mackenzie, 1997; Dobermann et al., 2002; Zheng et al., 2002). On the other hand, several studies have concluded that organic P forms maybe important in providing P to plants when P availability is low (Tiessen et al., 1984; Beck and Sanchez, 1994; Neufeldt et al., 2000).

Different approaches have been developed in order to study the type, amounts, and dynamic of P cycling (Chang and Jackson, 1957; Bowman and Cole, 1978; Hedley et al., 1982; Tiessen and Moire, 1993). The validity of the approaches has been debated (Olsen and Khasawneh, 1980). Beck and Sanchez (1994) pointed out that the procedure proposed by Chang and Jackson (1957) extracts predominately strongly retained P and is not appropriate for studying soil P cycling that influences uptake by plants. Magid (1993) noted the problems of reprecipitation of extracted P, and the similarity in the solubility of Fe- and Al-associated P. Olsen and Khasawneh (1980) in their broad review mentioned the limitations of this methodology and pointed out that more research is needed before drawing conclusions. Hedley et al. (1982) proposed a sequential P fractionation scheme which distinguishes labile and more stable forms of inorganic (Pi) and organic (Po) P in relation to plant availability (Hedley et al., 1982; Sharpley et al., 1985). This fractionation scheme has been used by various researchers working in temperate and tropical conditions (Schmidt et al., 1996; Beck and Sanchez, 1994; Zhang and MacKenzie, 1997; Neufeldt et al., 2000).

The methodology sequentially extracts a soil sample with different reagents in order to determine the soil P form related to those specific extraction conditions. Resin soluble P (or anionic exchange membrane AEM) and bicarbonate Pi are both considered labile forms of P which are thought to consist of Pi in solution and adsorbed on surfaces or more crystalline P compounds, sesquioxides or carbonates (Tiessen et al., 1984). Hydroxide-extractable P is related to amorphous and some crystalline Fe and Al phosphates and its availability to plants is assumed to be low, although some researchers have shown relevant participation of this fraction in plant nutrition (Tiessen et al., 1984; Dobermann et al., 2002; Zheng et al., 2002). Extractable organic P (Po) can be estimated from bicarbonate (labile organic P) and sodium
hydroxide (moderately labile organic P) extraction. Sharpley et al. (1987) mention that organic and inorganic P forms are closely related and strongly affected by fertilizer application according to soil characteristics. Both P fractions are affected by soil and crop management practices. The dilute acid extraction is thought to dissolve mainly different Ca phosphates or apatites (Beck and Sanchez, 1994). The remnant residue of soil digested by strong sulfuric acid/peroxide is thought to contain forms of P related to occluded P, other Ca phosphates and non-extracted organic P. An additional non-extracted soil sample is digested by strong acid/peroxide in order to determine a percentage of recovery compared to the total sum of all the P fractions (Tiessen et al., 1984). Hedley et al. (1982) mention that this fractionation procedure has identified important differences between the P status of pasture and cultivated soils. Olsen and Khasawneh (1980) and Magid (1993) strongly suggest that sequential fractionation only represents chemical extractability and cannot quantitatively define specific P forms. Therefore, the results of fractionation should be interpreted with care. Little work has been done comparing the types of fertilizers and their effect on soil P forms in Andisols in tropical areas.

The goal of this study was to measure the changes in soil P forms after applying organic and inorganic fertilizers in an Andisol under sugar cane production. The relationship between soil P forms and yield response was also measured.

Materials and Methods

Site of experiment and treatments

The experiment was located in Juan Viñas, Costa Rica, on a Typic Hapludand (9°54'N and 83°43'W). The site is 1000 m above sea-level and receives 2000 mm of rain annually but distributed mainly from May to November. Sugar cane (Saccharum sp. var. H-611721) was planted in 120 m² plots during two periods of 22 months. Treatments were arranged in a randomized, complete block design (RCBD) with three replications. The sugar cane was grown for two cycles (plant cane and ratoon) through 4 years. Yield variables were Mg of fresh cane production per ha and kg of sugar per Mg of harvested fresh cane. The treatments were 0, 50%, and 100% of rate of fertilization applied by the farmer in combination with 0
and 8 accumulated Mg of compost per hectare (4 Mg ha^{-1} in plant cane and 4 Mg ha^{-1} in ratoon). Estimated amounts of nutrients applied in the experiment are presented in Table 1. The fertilizers used during the four years were 10-30-10, 25-0-0-5, 14-9-25-4, 25-15-25 and 22-0-22 (in percentages of N, P_2O_5, K_2O and MgO according the type). The compost was produced from sugar cane and coffee residues and was 0.95% N, 0.21% P, 0.54% K, 4.70% Ca, 0.36% Mg and 22.36% organic carbon with 40% moisture. Excluding the 10-30-10 fertilizer (which was banded with the seed piece in 1997), all the other sources, including compost, were broadcast.

Table 1. Estimated amounts of nutrients (N, P, and K) applied as fertilizer on sugar cane (Var. H-611721) over four years on a Typic Hapludand at Juan Viñas Costa Rica.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Nitrogen</th>
<th>Phosphorus</th>
<th>Potassium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Organic</td>
<td>Mineral</td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>kg ha^{-1}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compost</td>
<td>Nitrogen</td>
<td>Phosphorus</td>
<td>Potassium</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>50%</td>
<td>245</td>
<td>245</td>
</tr>
<tr>
<td>0</td>
<td>100%</td>
<td>245</td>
<td>490</td>
</tr>
<tr>
<td>8 Mg ha^{-1}</td>
<td>50%</td>
<td>291</td>
<td>291</td>
</tr>
<tr>
<td>8 Mg ha^{-1}</td>
<td>100%</td>
<td>291</td>
<td>490</td>
</tr>
</tbody>
</table>

Soil Samples

Soils were sampled at the end of the four year cycle at two depths, 0-20 cm and 20-40 cm. Five cores were taken from each plot and composited for each sample. One portion of the samples was dried at 50°C, ground, sieved (<2 mm) and analyzed for various nutrients according to the methodology of Diaz-Romeu and Hunter (1978) as following. Calcium and Mg were extracted with 1M KCl and P and K with 0.5M sodium bicarbonate (1:10 soil:solution). Calcium, Mg, and K were determined by atomic absorption spectrophotometry and P by colorimetric absorption spectrophotometry. Organic matter was determined by the Walkley and Black (1938) method. Total extractable acidity was extracted with 1M KCl (1:10 soil:solution determined by titration) and pH was determined using deionised water (1:2.5 soil:solution). Additionally, soil P fixation, bulk density, and Fe and Al extracted with ammonium oxalate were used to determine andic properties (USDA and NRCS, 1996). The results are presented in Table 2.
**Phosphorus Fractionation**

In order to determine the different P forms in the soil, a selective dissolution technique and sequential extraction procedure was used. A modified methodology of Hedley et al. (1982) was used and is sketched in Figure 1. Sonification and the use of chloroform steps were omitted from the original methodology. Dried, ground, and sieved (<100 mesh) soil samples from each plot were sequentially extracted using four different extractants. Samples of 0.5 g of soil were weighed into 50-ml screw-cap centrifuge tubes. Initially 30 ml of deionized water was added along with a 1.5x1.5 cm anion exchange membrane (AEM) strip and shaken for 16 hr. After the shaking period, the membrane was removed, the rest of sample centrifuged (2500 rpm), and the supernatant water discarded. The Pi on the membrane was recovered using 20 ml of 0.5M HCl. Thirty ml of 0.5M NaHCO₃ were added to the remnant soil and the shaking and centrifugation process was repeated as explained before. The same procedure was done sequentially with 30 ml of 0.1M NaOH and 30 ml of 1M HCl. Separate portions of NaHCO₃ and NaOH supernatant were acidified with 4M sulfuric acid to precipitate extracted organic matter before determining Pi. Additionally, two organic P fractions were determined indirectly by digestion of separate aliquots of NaHCO₃ and NaOH supernatant and subtracting this value from the Pi initially determined. After the extraction the remnant soil was transferred to glass tubes and digested with concentrated H₂SO₄ and H₂O₂ for 8 hours at 270 °C. The Pi was determined by the molybdate-ascorbic acid procedure of Murphy and Riley (1962). For the following discussion, AEM-P and NaHCO₃-Pi were summed and referred to as labile-Pi. Also, NaHCO₃-Po. and NaOH-Po forms were summed and referred to as extractable-Po.

**Phosphorus uptake by sugar cane**

To estimate P uptake by sugar cane, two linear m of row were selected in nearby fields and biomass samples collected in triplicate at various sampling times during the growth cycle. The collected biomass was divided into leaves and shoots and weighed as fresh matter. A subsample was taken to determine dry matter, water content, and P in the tissue. The tissue analysis was carried out using wet digestion with perchloric/nitric acids and P determined by colorimetric absorption spectrophotometry (Diaz-Romeu and Hunter, 1978). The estimation
of uptake of P was calculated based upon the area sampled, dry matter production, and the concentration of P in the tissue.

Figure 1. Scheme of modified Hedley et al. (1982) soil P fractionation methodology.

**Phosphorus desorption curves**

A modified Soto (1998) desorption curve methodology was used. A 3-gram subsample of dried soil (<2 mm) was weighed into 50 ml screw-cap centrifuge tubes in triplicate. Thirty ml of deionised water were added along with one 1.5x1.5 cm AEM strip and three drops of chloroform. The tubes were continuously shaken for different times (0.5, 1.5, 3.5, 7.5, 12.5, 24.5, 48, 96, 144, and 192 hours). After each shaking time the AEM was removed and replaced by a new AEM. Twenty ml of 0.5M HCl was used to recover the Pi adsorbed to the AEM. The Pi was determined by the molybdate-ascorbic acid procedure of Murphy and Riley (1962).

In order to compare the treatments, the log of time was graphed with log of accumulated P (mg kg\(^{-1}\)) desorbed during the time of study. The data were fitted to a linear function (\(y =\))
This allowed calculation of two constants that represented the rate of desorption of P in time and the initial P status. These constants were the slope \((b)\) and the intercept \((a)\) of the linear equation. The constants were then substituted into the equation \(q=at^b\) that represents the real behavior of the desorption process. In this equation, \(q\) is the amount of P desorbed at time \(t\), \(a\) is a constant related to the initial P status in the soil and \(b\) is a constant related to the rate of desorption. Hence, \(b\) allowed quantification of the rate of desorption whereas \(a\) allowed us to relate the initial P desorbed to initial P content in the soil. Desorption curves were calculated for each treatment.

**Data analysis**

Data were analyzed using SAS (SAS Institute, 1996). Variables were compared using correlation and regression analysis. Separation of means was performed by least significant difference (LSD).

**Results and Discussion**

According to data presented in Table 2 and based upon field observations and geomorphological map information, the soil was classified as a Typic Hapludand (USDA 1994). The top 40 cm of soil at the site had a bulk density of less than 900 kg m\(^{-3}\), more than 2\% Al+1/2Fe extracted with ammonium oxalate and more than 80\% P fixation. Therefore the soil meets the established criteria for an Andisol (USDA, 1994; USDA and NRCS, 1996). This is supported by the fact that eruptions of Irazu and Turrialba volcanoes, located no more than 20 km from the site, have affected the area several times (Alvarado et al., 2001).

The soil had low levels of Ca, Mg, K and P and high organic matter content (Table 3). Changes occurred in Ca and Mg contents and extractable total acidity after applying dolomite (1.5 Mg ha\(^{-1}\)) in 1998 that improved the fertility status of the soil although the levels were still low according to critical levels presented in Table 3. The available P extracted with 0.5M NaHCO\(_3\) increased slightly even in the control treatment between 1997 and 2001 suggesting replenishment from other P forms in the soil.
Table 2. Andic properties of a Typic Hapludand at the experiment site, Juan Viñas Costa Rica.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Bulk Density kg m$^{-3}$</th>
<th>Amorphous Al†</th>
<th>Amorphous Fe†</th>
<th>Al + 1/2Fe†</th>
<th>P Fixation‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compost</td>
<td>Fertilization</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>830</td>
<td>3.90</td>
<td>0.65</td>
<td>4.23</td>
</tr>
<tr>
<td>0</td>
<td>50%</td>
<td>850</td>
<td>5.70</td>
<td>0.70</td>
<td>6.05</td>
</tr>
<tr>
<td>0</td>
<td>100%</td>
<td>880</td>
<td>5.20</td>
<td>0.67</td>
<td>5.53</td>
</tr>
<tr>
<td>8 Mg ha$^{-1}$ 50%</td>
<td>850</td>
<td>4.90</td>
<td>0.71</td>
<td>5.26</td>
<td>99</td>
</tr>
<tr>
<td>8 Mg ha$^{-1}$ 100%</td>
<td>830</td>
<td>5.20</td>
<td>0.96</td>
<td>5.68</td>
<td>99</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>850</td>
<td></td>
<td>5.35</td>
<td>98</td>
</tr>
</tbody>
</table>

† Extracted by ammonium oxalate
‡ USDA and NRSC (1996)

Table 3. Selected properties of the soil used in the study. Juan Viñas, Costa Rica.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>pH H$_2$O</th>
<th>P mg kg$^{-1}$</th>
<th>Ca cmol(+) kg$^{-1}$</th>
<th>Mg cmol(+) kg$^{-1}$</th>
<th>K cmol(+) kg$^{-1}$</th>
<th>Acidity</th>
<th>O.M. g kg$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compost</td>
<td>Fertilization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil analysis in 1997 † ‡</td>
<td>5.0</td>
<td>3.0</td>
<td>2.19</td>
<td>0.19</td>
<td>0.11</td>
<td>1.1</td>
<td>-</td>
</tr>
<tr>
<td>Soil analysis in 2001 ‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>5.2</td>
<td>4.6</td>
<td>4.65</td>
<td>0.30</td>
<td>0.09</td>
<td>0.17</td>
</tr>
<tr>
<td>0</td>
<td>50%</td>
<td>4.9</td>
<td>4.8</td>
<td>5.85</td>
<td>0.33</td>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td>0</td>
<td>100%</td>
<td>4.8</td>
<td>5.5</td>
<td>3.49</td>
<td>0.23</td>
<td>0.10</td>
<td>0.27</td>
</tr>
<tr>
<td>8 Mg ha$^{-1}$ 50%</td>
<td>4.8</td>
<td>5.5</td>
<td>4.49</td>
<td>0.28</td>
<td>0.09</td>
<td>0.17</td>
<td>158</td>
</tr>
<tr>
<td>8 Mg ha$^{-1}$ 100%</td>
<td>4.9</td>
<td>5.8</td>
<td>3.91</td>
<td>0.11</td>
<td>0.11</td>
<td>0.22</td>
<td>172</td>
</tr>
<tr>
<td>Critical Level</td>
<td>5.5</td>
<td>10.0</td>
<td>4.00</td>
<td>1.00</td>
<td>0.20</td>
<td>&lt;0.5</td>
<td>-</td>
</tr>
</tbody>
</table>

† Initial soil sampling previous the installation of the experiment
‡ 1.5 Mg ha$^{-1}$ of dolomite was applied in 1998

Soil P fractionation

According to Hedley et al. (1982) the fractionation procedure permits separation of soil P forms which vary in the extent of their availability to growing plants. Nearly all the P forms were affected by organic and inorganic fertilizer application during the four years of experimentation. This finding agreed with results of other studies (Tiessen et al., 1984; Magid, 1993; Garcia-Montiel et al., 2000). Significant differences were found in absolute concentrations of P (mg kg$^{-1}$) rather than in relative proportions (Table 4). The total sum of all the P fractions for all the treatments varied from approximately 1500 mg kg$^{-1}$ (control) to 1800 mg kg$^{-1}$ (100% fertilization and 8 Mg of compost). Overall proportions of soil P forms (Table 4) were 0.43% labile-Pi (composed of 0.11% AEM-P and 0.32% NaHCO$_3$-Pi), 6.44%
NaOH-Pi, 9.20% HCl-Pi, 32.55% extractable-Po (composed of 2.38% NaHCO₃-Po and 30.17% NaOH-Po), and 51.37% residual-P. Similar results are reported by Soto (1998). Only labile-Pi differed between the 0-20 cm and 20-40 cm depth (data not presented), although the top layer was higher in all the forms except in residual P (Figure 2). Additionally, the total sum of P was not statistically different between the two depths which reflects the homogeneity of these soils. According to Ball-Coello et al. (1993) this is a reflection of limited mixing of broadcast applications and limited movement of P from topsoil to subsoil. Richards et al. (1995), on the other hand, suggest that subsoil P could be involved in the P cycle. We could suggest that the top layer is supporting the major root biomass and the more active demand for readily and reversibly available P (labile-Pi, NaOH-Pi, and HCl-Pi) than sparingly available P (residual-P).

Table 4. Amounts and relative percentages of P forms obtained by using the modified Hedley et al. (1982) methodology on a Typic Hapludand, Juan Viñas Costa Rica.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>labile P</th>
<th>NaOH Pi</th>
<th>HCl Pi</th>
<th>Extrac-Po</th>
<th>Residual P</th>
<th>Total sum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg kg⁻¹ of P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>6.2b</td>
<td>78c</td>
<td>118c</td>
<td>517</td>
<td>813</td>
</tr>
<tr>
<td>0</td>
<td>50%</td>
<td>6.7ab</td>
<td>103c</td>
<td>133bc</td>
<td>525</td>
<td>860</td>
</tr>
<tr>
<td>0</td>
<td>100%</td>
<td>7.6a</td>
<td>139a</td>
<td>196a</td>
<td>553</td>
<td>916</td>
</tr>
<tr>
<td>8 Mg ha⁻¹</td>
<td>50%</td>
<td>7.7a</td>
<td>104cb</td>
<td>158abc</td>
<td>564</td>
<td>878</td>
</tr>
<tr>
<td>8 Mg ha⁻¹</td>
<td>100%</td>
<td>8.3a</td>
<td>125ab</td>
<td>180ab</td>
<td>592</td>
<td>871</td>
</tr>
<tr>
<td>Significance</td>
<td>*</td>
<td>**</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
<td>*</td>
</tr>
</tbody>
</table>

Means within the same column followed by the same letter are not significantly different (P<0.05) by LSD test.
Figure 2. Percentages and amounts (mg kg\(^{-1}\)) of P forms at two depths on a Typic Hapludand. Juan Viñas, Costa Rica.

a) Labile Pi (AEM-P and NaHCO\(_3\)-Pi)

Because AEM-P and NaHCO\(_3\)-Pi are recognized as being the most available for plant growth, they were summed and are referred to as labile-Pi in the following discussion (Kamprath and Watson, 1980; Olsen and Khasawneh, 1980; Hedley et al., 1982). This fraction is thought to consist of Pi in the soil solution and Pi adsorbed on surfaces of more crystalline P compounds, sesquioxides or carbonates (Tiessen et al., 1984). In terms of mg P kg\(^{-1}\), labile-Pi in organic and inorganic fertilized treatments was higher than in the control treatment even though this was not occurred in terms of percentage (Table 4). According to Buehler et al. (2002) and Dobermann et al. (2002), fertilization increased both components of labile-Pi (AEM-P and NaHCO\(_3\)-Pi) which agrees with the high correlation found between this fraction and P applied as fertilizer (Table 5). However, the relative difference of 25% among treatments due to fertilization was less than that found in NaOH-Pi and HCl-Pi (43% and 40%, respectively). This is opposite to the results of Neufeldt et al. (2000) who mention
that the increase due to fertilization was more notable in the labile-Pi forms than in other forms. Table 4 shows that the difference in this form among the treatments was 2 mg kg\(^{-1}\). Based upon the small difference between the control treatment and the other fertilized treatments is possible to suggest that a replenishment from non available P forms occurred acting as a buffer keeping a relatively constant amount of labile-Pi in this treatment.

b) Sodium hydroxide-extractable Pi

Soil NaOH-Pi represents P that is held strongly by chemisorption to Fe and Al components of soil surfaces. It is considered to be moderately labile-Pi (Zhang and MacKenzie, 1997). It was 6.44% of the total P (Table 4). This fraction had the greatest difference between the control and high P rate + compost treatments, 60 mg kg\(^{-1}\), which was a 43% difference (Table 4). The treatments with 100% of inorganic fertilization had higher NaOH-Pi values compared with the other treatments suggesting the close relationship between this P fraction and applied P (Table 5). Chemisorption between P and Al and Fe oxides is the first "fixation" process and could result in NaOH-Pi becoming a sink for labile and applied P (Buehler et al., 2002; Tiessen et al, 1984; Zhang and MacKenzie, 1997). Some evidence suggests that this fraction is not only acting like a sink but as a P supplier to labile-P. Guo et al. (2000) mention that this fraction seems to act as a buffer for labile Pi in highly weathered soils. This suggests the strong dynamic nature of this pool whether gaining P from fertilizer sources or enduring depletion for maintaining the labile P form. This form is as strongly affected by fertilization as are labile-Pi and HCl-Pi forms (Buehler et al. 2002). Taking in to account the amount of P withdrawal by the crop and the status of this P fraction in the other treatments, we suggest that this pool endured depletion while acting as source of P for the labile-Pi pool.

Table 5. Pearson correlation coefficients between P applied as organic and inorganic fertilizer in kg ha\(^{-1}\) to sugar cane and various P forms in soil.

<table>
<thead>
<tr>
<th></th>
<th>AEM-P</th>
<th>Bicarbo-Pi</th>
<th>Labile-Pi</th>
<th>NaOH-Pi</th>
<th>HCl-Pi</th>
<th>Extr-Po</th>
<th>Residual</th>
<th>Total sum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.98 **</td>
<td>ns</td>
<td>0.90 *</td>
<td>0.95 **</td>
<td>0.93 *</td>
<td>ns</td>
<td>ns</td>
<td>0.96 **</td>
</tr>
</tbody>
</table>

ns not significant at \(P < 0.05\)

* Significance at \(P 0.01\) to \(0.05\)

** Significance at \(P < 0.01\)
c) Hydrochloric acid extractable Pi

The HCl-Pi form is related to inherent calcium phosphate minerals or those formed as the soil is fertilized and limed (Magid, 1993). This P form was 9% of the total of the measured P forms. HCl-Pi varied from 118 to 180 mg kg$^{-1}$ among the treatments (Table 4). As slightly weathered soils, Andisols are likely to have an important reservoir of Ca apatites that could also result from enrichment by inorganic fertilizers. Buehler et al. (2002) mention that this fraction is affected by fertilization based on the source of the materials (calcium phosphates). A high correlation (0.93) was found between HCl-Pi and P applied as fertilizer suggesting that fertilizer enriched this form. This result is opposite to that found by Reddy et al. (1999) on a Vertisol. They did not measure changes in this fraction due to organic and inorganic fertilization, maybe because of the high content of calcium phosphate that their soil had initially. Guo et al. (2000) pointed out that HCl-Pi along with NaOH-Pi and residual-P seemed to act as a buffer for the labile Pi forms in slightly weathered soils. Zhang and MacKenzie (1997) found this fraction stable as related to the other soil P forms.

d) Residual P

This unavailable P form may consist of a resistant mixture of occluded P, different Ca-phosphates and certain non extracted organic P (Zhang and MacKenzie, 1997; Tiessen et al., 1984). Residual-P accounted for about 50% of the total P (Table 4). As mentioned by lyamuremye et al. (1996), this value may change depending on the type of soil and soil management. Magid (1993), analyzing soils of Denmark, found that this fraction was up to 78-85% of the total P. Garcia-Montiel et al. (2000) found that this fraction was 40-55% of total P in 20 yr-old pastures and 63-65% in forest in Amazonian soils. Zhang and MacKenzie (1997) reported 21-25% of the total P was this fraction. The control treatment had 813 mg kg$^{-1}$ residual-P whereas the 100% fertilization treatment had 916 mg kg$^{-1}$ (Table 4). Despite this, it is not possible to state whether this difference was due to depletion in the control treatment or to an increase due to fertilization of the other treatments or a combined effect of both. Additionally, no relationship between the residual-P fraction and P applied as fertilizer was found (Table 5). Both treatments with compost (8+50% and 8+100%) had values statistically similar to the 0+50% treatment. Some researchers reported that additions of
inorganic P fertilizer alone or combined with manure significantly increased the soil residual-P fraction suggesting that this fraction also acts as a sink for P applied in Alfisols and Mollisols (Zhang and MacKenzie, 1997; Richards et al., 1995). Dobermann et al. (2002) found no changes in residual-P in Ultisols and Oxisols due to fertilizer application. The previous discussion suggests that as stated above, this fraction is closely related to type of soil and soil management. The mechanism of stabilization of soil P into non extractable forms in this fraction is still not well understood because of the variety of P forms that may be involved. The processes that move P to this pool have been attributed to precipitation of insoluble associations of organic matter and minerals or to occlusion of P in Fe and Al oxides (Magid, 1993). Residual-P seems to be a relevant fraction in Andisols, soils having high P-fixation processes (specific surface adsorption, ligand exchange, and precipitation), and may play an important role in long term agriculture.

e) Organic extractable P (Po)

Extractable-Po is the sum of NaHCO₃-Po and NaOH-Po and includes easily mineralizable labile-Po and more stable forms of Po involved in short and long term transformations of P in soils (Tiessen et al., 1984). This fraction varied from approximately 500 to 600 mg kg⁻¹, which was 30 to 33% of the total P (Table 4). Henriquez et al. (1997) found values up to 1068 mg kg⁻¹ in Andisols from Costa Rica and variations between 22 to 60% of organic P among four different groups of soils. Garcia-Montiel et al. (2000) and Magid (1993) reported the greatest values in pastures compared with forest and fallow areas (29-35%); results that are similar with data in this study. Compost application increased extractable-Po 46 mg kg⁻¹ (8% increase) even though this amount does not correspond to the estimated amount supplied by compost (Table 1). Sharpley (1985) pointed out that Po variation could be due to changes in moderately labile-Po, with more labile and resistant pools remaining constant. Despite the fact that statistical differences were not found in amount of extractable-Po, the treatments with addition of compost had the highest extractable-Po values although this difference was no more than 3% with the 100% fertilized treatment (Table 4). No relationship was found between extractable-Po and P applied as fertilizer (Table 5). Zhang and MacKenzie (1997) found inorganic P applied with manure P
decreased NaHCO₃-Po and moderately increased NaOH-Po, with the result that total extractable soil Po increased. Beck and Sanchez (1994) mention that residual P could contain some occluded organic P compounds resistant to the extraction procedure with bicarbonate and hydroxide. Taking into account the strong relationship between organic matter and allophane and Al- and Fe- humus complexes, it is very likely that a certain amount of Po remained in the residual-P fraction (Espinosa, 1992; Otani and Noriharu, 1999). Several researchers pointed out that Po is important when soil Pi reserves are limited (Beck and Sanchez, 1994; Buehler et al., 2002). Zhang and MacKenzie (1997) mention that extractable-Po acted as sink for added Po and a source for NaOH-Pi and residual-Pi. Sharpley (1985) concluded that Po is an important source of available P in both unfertilized and fertilized soils suggesting the need of including Po in soil-P fertility tests. In a subsequent study the same author pointed out the relationship between organic P and soil test P in highly weathered soils (Sharpley et al., 1987). Otani and Noriharu (1999) mention that in Andisols, the most important strategy for P uptake by plants may be how to release P from Al- and Fe-bound forms of Po as well as Pi. Buehler et al. (2002) conclude that NaOH-Po and HCl-Po (this last one not analyzed in our study) are important in P cycling when soil Pi reserves are limited. Despite the high organic matter content of the soil in this study (approximately 150 g kg⁻¹) only 32% of the total P was related to the extractable-Po form (the sum of NaHCO₃-Po and NaOH-Po forms). The high correlation found between inorganic P forms and plant yield and P applied, suggests the main importance of the mineral P fraction in the short term in plant nutrition in this soil more than organic forms.

f) Total sum of P forms and total P

The total quantity of P and plant-available P often differ greatly in soils of the tropics which typically range in weathering intensity (Guo et al., 2000). A variation of 1500 to 1811 mg kg⁻¹ was found in the total sum of soil P fractions analyzed. Similar results were reported by Soto (1998) in nearby Andisols that also varied in management, suggesting the high reservoir of P existent in these soils. The percentage of recovery from the total sum of P fractions compared with the total from the alternate digestion varied from 105 to 109% with a correlation of 0.66 between both methods (data not presented). Significant differences
among the treatments due to fertilizer application were found in the total sum of P. According to Magid (1993), fertilization produced variable changes in total P.

**Correlation among P forms**

AEM-P, labile-Pi, NaOH-Pi, HCl-Pi, and total sum of P, were well correlated with P applied as fertilizer (Table 5). These soil P forms seem to be related to the rate of fertilizer P and confirm the fact that fertilization could impact total P. Those forms could be classified as readily available P (AEM-P and labile-Pi) and reversibly available forms (NaOH-Pi and HCl-Pi). No significant correlation was found between applied P and extractable-Po, residual-P and NaHCO₃-Pi (Table 5). Labile-Pi (composed of AEM-P plus NaHCO₃-Pi) had a good correlation with applied P due to a very good correlation between AEM-P and P applied. Additionally, a very high correlation was found between NaOH-Pi and P applied (0.95**), which means that a high proportion of P fertilizer became part of this fraction that acted as a sink. Correlations were also determined among the P forms and are presented in Table 6. Only positive correlation values were found validating the close relationship among the soil P forms evaluated in only one type of soil and under the same experimental conditions. A poor relationship was found between NaHCO₃-Pi and AEM-P, explained by the high variability in the NaHCO₃ extraction (data not presented). An acceptable and significant correlation was found between NaOH-Pi and AEM-P, suggesting that both P forms could be related through similar sorption and desorption mechanisms in the soil. More research might be developed to study this aspect. NaOH-Pi and HCl-Pi were well correlated (0.75) suggesting corresponding increases of those P forms. A good relation was found between residual-P and extractable-Po suggesting that a proportion of non-extracted organic P could remain in residual form (Beck and Sanchez, 1994). Contrary to the results of Magid (1993), we found a good correlation between residual P and total P (0.87) probably because most of total P was in residual-P forms (51%).
Table 6. Pearson's correlation coefficients for P forms extracted by a modified Hedley scheme. (only coefficients significant at less than $P < 0.05$ are shown, n=30).

<table>
<thead>
<tr>
<th>Extractant</th>
<th>NaHCO$_3$ inorganic</th>
<th>NaHCO$_3$ organic</th>
<th>NaOH inorganic</th>
<th>NaOH organic</th>
<th>HCl</th>
<th>Extractable Po</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labile $\dagger$</td>
<td>-§</td>
<td>0.35</td>
<td>0.68</td>
<td>0.62</td>
<td>0.58</td>
<td>0.61</td>
<td>ns</td>
</tr>
<tr>
<td>AEM</td>
<td>0.50</td>
<td>0.57</td>
<td>0.71</td>
<td>0.59</td>
<td>0.53</td>
<td>0.60</td>
<td>0.46</td>
</tr>
<tr>
<td>NaHCO$_3$-Pi</td>
<td>-</td>
<td>0.53</td>
<td>0.51</td>
<td>0.49</td>
<td>0.49</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>NaHCO$_3$-Po</td>
<td>0.46</td>
<td>0.76</td>
<td>0.38</td>
<td>-</td>
<td>0.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaOH-Pi</td>
<td>-</td>
<td>0.75</td>
<td>0.64</td>
<td>0.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaOH-Po</td>
<td>0.62</td>
<td>-</td>
<td>0.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCl</td>
<td>0.61</td>
<td>0.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extr-Po $\ddagger$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.63</td>
<td></td>
</tr>
</tbody>
</table>

$\dagger$ Sum of AEM-P and NaHCO$_3$-Pi

$\ddagger$ Sum of extractable organic P from NaHCO$_3$-Po and NaOH-Po

§ Correlation not performed

Yield response and P uptake by sugar cane

The two yield variables measured in this experiment showed different responses (Table 7). Statistical differences were found in amount of fresh cane production per hectare. Significant differences were found in 1999, 2001 and in accumulated yield (sum of 1999 and 2001 yields), comparing the control and the fertilized treatments which support the expected yield response to fertilization in soils with low fertility level (Table 3). The yields varied from 106 to 145 Mg ha$^{-1}$ in the first harvest and from 162 to 257 Mg ha$^{-1}$ in the ratoon. The increase in accumulated yield was 33% higher than the control when the mineral and organic fertilizers (8+100%) were applied at the higher levels. There were no significant differences among the fertilized treatments (Table 7), even though the treatments with 100% of inorganic fertilization always had the highest yield. This was related to the higher amounts of P applied, but it was also due to the higher amount of other nutrients applied in those treatments. This positive response could also due to N and K applications that were applied as well (Table 1).

Statistical analysis showed that there were no differences due to treatment application in the amount of sugar produced per metric ton of fresh cane (Table 7). Despite the fact that there was not a statistical difference, sugar yield tended to increase with applied P in 1999 (Table 7). This trend was not observed in 2001.
Table 7. Sugar cane (H-61721) yields obtained after two growth cycles during four years on a Typic Hapludand, at Juan Viñas, Costa Rica.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>1999 yield</th>
<th>2001 yield</th>
<th>Accumulated yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mg ha⁻¹</td>
<td>Mg ha⁻¹</td>
</tr>
<tr>
<td>Compost</td>
<td>Fertilization</td>
<td>kg sugar Mg⁻¹</td>
<td>Mg ha⁻¹</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>112</td>
<td>106 b</td>
</tr>
<tr>
<td>0</td>
<td>50%</td>
<td>111</td>
<td>134 a</td>
</tr>
<tr>
<td>0</td>
<td>100%</td>
<td>113</td>
<td>142 a</td>
</tr>
<tr>
<td>8 Mg ha⁻¹</td>
<td>50%</td>
<td>115</td>
<td>139 a</td>
</tr>
<tr>
<td>8 Mg ha⁻¹</td>
<td>100%</td>
<td>119</td>
<td>145 a</td>
</tr>
</tbody>
</table>

Significance: ns not significant at P < 0.05  
* Significance at P 0.01 to 0.05  
** Significance at P<0.01  
Means within the same column followed by the same letter are not significantly different (P<0.05) by LSD test.

Rather than a unique response to P, a synergistic effect could have occurred. Hence, we can not say that positive response in yield was due only to P application, although graphically it is possible to relate yield and P added (Figure 3). A non significant increase in accumulated yield was found due to compost application which varied from 3 to 6% (Table 7). Figure 3 shows the relationship between yield and applied P fertilizer expressed as a quadratic model.

![Figure 3. Relation between accumulated sugar cane yield (Var. 617721) and P applied as fertilizer on an Andisol. Juan Viñas, Costa Rica.](image-url)
Yield, which actually represents a biomass accumulation on the field, was positively related to labile-Pi and NaOH-Pi (Figure 4). This relationship reflects the importance of these P forms to plant response. A poor relationship was found between yield and organic, residual and total P fractions. The good relation between yield and applied P, labile-Pi, and NaOH-Pi reflects the expected good relationship between yield and labile-Pi and NaOH-Pi (Table 5 and Figure 4).
The P uptake curve by sugar cane is shown in Figure 5. The total amount of P uptake by sugar cane at a yield of 180 Mg ha\(^{-1}\) in 700 days was approximately 60 kg ha\(^{-1}\) in a growth cycle of two years. Ball-Coelho et al. (1993) reported P uptakes of 37 and 17 kg P ha\(^{-1}\) under mulch and burn treatments in an Ultisol in Brazil.

![Figure 5. Total P uptake curve by sugar cane (Var. 611721) on a Typic Hapludand. Juan Viñas, Costa Rica.](image)

### Phosphorus desorption curves

AEM-P desorption appears to be adequately represented by a sum of simultaneous first-order reactions representing a quantity of adsorbed P with a given energy of desorption (Olsen and Khasawneh, 1980; Soto, 1998). The process represents a group of P pools simultaneously releasing P rather than a distinct chemical compound or physical state of one compound (Olsen and Khasawneh, 1980). Comparison of the control treatment with the fertilized treatments (50% and 100%) in Figure 6a suggests that the 100% fertilization treatment had a higher desorption capacity in time that agrees with the higher labile-Pi in this treatment (slope =0.55). This suggests that despite the high P fixation of this soil and the time since the last fertilization (one year and a half) that part of the P applied as fertilizer continues being desorbed. After its application, fertilizer gradually undergoes different
processes until a portion of it becomes adsorbed or precipitated in unavailable P components in the solid phase from which it may be subsequently released (Delgado and Torrent, 2000). Additionally, comparing Figures 6a and 6b is possible to deduce that compost fertilized treatments had higher initial available P (0.21 and 0.28 log mg P kg$^{-1}$) than the corresponding non compost fertilized treatments (0.09 and 0.14 log mg P kg$^{-1}$). Figure 6b suggests that the application of compost increased the initial amounts of desorbed P and the total amount of P but not the rate of desorption. Sui and Thompson (2000) and Maguire et al. (2000) mention that the combination of organic and inorganic fertilizer produced an increase in desorption.
Figure 6. Relationship between log time and log accumulated desorbed P on an Andisol.

Conclusion

The changes in soil P forms observed among the treatments after four years of study indicate that P cycling is rapid and intensive in response to plant uptake and P fertilizer application. Applied P was correlated mainly with AEM-P, labile-Pi and NaOH-Pi even though the results suggest active participation of nearly all P forms in maintaining labile-Pi levels in this soil. Adsorption-desorption processes act intensively in this soil and it was possible to see the effect of fertilizer in desorbing P for a long time after its application. Crop
production without added fertilizer will, in time, deplete all of the P forms in the soil. More research must be carried out to determine the time required for depletion of the P forms in the soil.

Acknowledgements

The authors acknowledge Dr. Jose Espinosa and the economic support given by the Potash and Phosphate Institute (Northern Latin American-INPOFOS). We also wish to mention the valuable cooperation of the staff and workers from Hacienda Juan Viñas and the Laboratory of Soil and Plant Analysis in Centro de Investigaciones Agronomicas at the Universidad de Costa Rica. Special thanks to Gloria Melendez, Luis Garcia, Pablo Lopez and Ivania Cartin.

References


CHAPTER 3
EFFECT OF LAND USE ON SPATIAL DISTRIBUTION OF SOIL P FORMS AND
OTHER SOIL CHARACTERISTICS ON AN ANDISOL IN COSTA RICA

Carlos Henriquez, Randy Killorn, Floria Bertsch, and Freddy Sancho

Abstract

The relationship between land-use and subsequent changes in soil properties has been the subject of study and discussion for years. Fertilization affects chemical and biological soil properties according to the amount and type of fertilizer applied and frequency of application on a spatial basis. An observational survey was carried out with the objective of studying the spatial distribution of soil P forms jointly with other selected soil chemical properties as related to different land use on a landscape. The whole field was 8.4 ha and was located in Juan Viñas, Costa Rica on a Typic Hapludand. The study area was sections of nearby fields that have been dedicated to production of sugar cane (*Saccharum* spp., 2.1 ha), coffee (*Coffea arabica*, 2.7 ha), and secondary forest (3.6 ha) for more than 25 years. The study area was sampled in 40 m grids at two depths (0-20 and 20-40 cm). Soil samples were analyzed using a modified Hedley et al. (1982) soil P fractionation methodology in order to obtain different inorganic and organic P (Pi and Po) forms. The forms were labile-Pi, NaOH-Pi, HCl-Pi, extractable-Po, and residual-P. Ca, Mg, K, pH, and acidity were also determined jointly with some soil physical properties. The data were analyzed statistically and interpolated using a kriging procedure to provide an estimation of the spatial distribution on the field of soil P forms and the other selected soil properties. Correlations among the variables were also made. Contrasting values were found among the selected soil properties and P forms that were closely related to management zones. These variables followed a spatial distribution pattern related to soil and crop management on the field. The sugar cane area was low in Ca, Mg, and K. This was probably related to plant uptake and little replenishment from lime and fertilization. The extractable acidity was highest in the coffee area and was related to high rates of N fertilization. The forest area was variable in these general fertility indexes. No spatial relationship was found in soil pH. This was due to the high buffer capacity of this variable-charge type soil. No difference was found in soil P forms
between depths. The coffee plantation field had the highest values in labile-Pi and NaOH-Pi due in part to the frequency of fertilization. Sugar cane field had the highest amounts of HCl-Pi, residual P, extractable-Po, and total sum of P. The accumulation of sparingly available P forms in sugar cane field was related to the period between the fertilizer applications (1.5 years). The data suggest that frequency of fertilization and type of crop resulted in a differentiation in the spatial distribution of P forms and the other soil chemical properties that were evaluated in this study. The interpolation method was an efficient technique for detecting areas with low to high values of different variables that corresponded to crop and soil management areas. The spatial analysis approach agreed with the results from traditional statistical analysis by management areas.

**Introduction**

Optimizing the application of inputs at the farm level involves reducing agrochemical applications and maximizing crop production with minimal impact on soil, water, and other resources. These have been common goals and topics of many international scientific and political conventions (Nielsen et al., 1995). A baseline measure of the different crop production variables that determine yield is required prior to implementing future management strategies. Examining on-farm soil variability in relation to the crop system allows creating a data base and a register of critical variables. Yield maps have been used for differentiating areas and also for optimizing soil sampling strategies (Nielsen et al., 1995; Franzen et al., 2000; van Groenigen et al., 2000). When collecting spatial data it is important to identify unique and unusual fertility areas in a field and to define boundaries so that they can be treated differently to maximize crop response to fertilizer application (Franzen et al., 1998). Phosphorus (P) is one of the limiting nutrients in many of the agroecosystems around the world; the ability to predict the status of P supply in soils would improve the precision of fertilizer recommendations. Additionally, evaluation of soil P availability in fields is important in resolving management conflicts between the increasing cost of P fertilizers and low fertilizer P efficiency (Zhang and MacKenzie, 1997).

Spatial variation of soil chemical properties, particularly P, has been observed by several authors (Jenkins et al., 2000; Schepers et al., 2000; Simard et al., 2000; Bermudez and
Mallarino, 2002). Most landscapes have natural variations in the soil P content due to variations in parent material, weathering processes, management, and movement of water and sediment across the surface. Special attention has been given to the change produced by organic and inorganic fertilization on soil P forms (Iyamuremye et al., 1996; Linquist et al., 1997; Buehler et al., 2002).

Phosphorus reactions in soils are complex and its availability is affected by a great number of processes. Different approaches have been developed for evaluating soil P cycling (Olsen and Khasawneh, 1980). Tiessen et al., (1984) and Zhang and MacKenzie (1997) suggest that the availability of P to plants depends on the amount of different P forms present in the soil and the way that they are related for replenishing the available P fractions depleted by plant uptake. Magid (1993) found that vegetation affects the distribution of soil P fractions and soil fertility over fields as well. Soil P fractionation methodologies have been applied in both temperate and tropical conditions in order to evaluate the way that P cycling is affected by fertilization, type of soil, and type of crops (Tiessen et al. 1984; Sharpley and Smith, 1985; Beck and Sanchez, 1994; Zheng et al., 2002). In highly weathered soils available P is generally low and may be dependent on mineralization of organic P (Tiessen et al., 1984). Low pH and high Al or Fe activity cause the formation of sparingly soluble, crystalline or occluded Al and Fe phosphates (Sanchez and Uehara, 1980). However, Iyamuremye et al. (1996) found that liming had little or no effect on P distribution among different forms, indicating that redistribution of P forms does not occur with reduction in exchangeable Al and Fe or change in pH.

Variation of soil P forms occurs both vertically and horizontally in soils. Current site specific management techniques allow “targeting” particular areas on a field for unique management practices (Jenkins et al., 2000; Schepers et al., 2000). Topography-based, management zones, and grid sampling are some of the techniques that have been used for soil sampling. Where the management zones and topography variations are clearly defined, partitioning the area could be used instead of grid soil sampling (Franzen et al., 1998; van Groenigen et al., 2000). Since data collected as point observations have to be converted to continuous observations so that the spatial patterns sampled by these measurements can be compared with the spatial patterns of other spatial entities, an interpolation process has to be
performed (Demmers, 1999). In this way data sources sparsely distributed as point samples are converted to discrete and continuous surfaces for mapping the variation of attributes over space (Burrough and McDonnell, 1998). Different types of nonlinear interpolation methods have been used, for instance weighting, trend surfaces, and a geostatistical method popularly known as kriging (Burrough and McDonnell, 1998; van Groenigen et al., 2000). All of these methods have the same final goal, to improve management decisions. They have been used with some success for representing the spatial variation of fields (Petersen et al., 1995; Nielsen et al., 1995; Schepers et al., 2000; Bermudez and Mallarino, 2002). The majority of studies related to soil P fractions have been focused on characterization and possible pathways among the forms but few have been done studying spatial variability on fields related to crop management in tropical conditions. The purpose of this study was to evaluate the spatial distribution of soil P forms and other selected soil properties as related to on three different land-use areas on an Andisol in Costa Rica.

**Materials and Methods**

**Site of study**

The study was located in Juan Viñas, Costa Rica (9°55'N and 83°44'W) on a Typic Hapludand derived from andesitic volcanic ash (USDA, 1994; Alvarado et al., 2001). The soil was a well drained sandy loam to loam. Although allophane is the dominant clay mineral (Alvarado et al., 2001), Soto (1998) reported the presence of ferrihidrite and goethite in Andisols from nearby areas. The site varied in elevation from 1240 to 1340 m above sea level and receives approximately 2000 mm of rain per year distributed mainly from May to November. The study area was approximately 8.4 ha and was divided into three sub-areas that have been dedicated continuously to sugar cane (*Saccharum spp.* var 6111, 2.1 ha), coffee (*Coffea arabica* var Catuai, 2.7 ha), and secondary forest (3.6 ha) for more than 25 years. These three areas share boundaries with one another (Figure 1). The coffee plantation and secondary forest varied from 10% to 20% slope. The sugar cane plantation varied from 0 to 3% slope. The secondary forest had not received any fertilizer application for more than 25 years and was used as a control area.
Soil sampling

A rectangular portion of approximately 280x160 m (4.48 ha) was selected from the total area of 8.4 ha for soil sampling. The sampling area was defined on a 40 m grid base using an aerial ortho-photograph for a total of 40 sampling points. Due to lack of accessibility, soil samples were not taken from two points in the forest area; therefore only 38 points were taken. A GPS was used for geo-referencing the grid points during soil sampling to bring the real position of the each point into the area of study (Figure 1c). Grid sampling points served as a fixed sampling pattern for the interpolation process. The sampling area contained representative portions of each of the three fields under different crop management (Figure 1). At each sampling point, three radial cores were collected spaced at 1 m from the central point. The three subsamples were combined into a single sample representing each grid point. The soil samples were taken at two depths, 0-20 cm and 20-40 cm. The central sampling of each grid point was used to describe soil depth, color, and texture. Penetration resistance under approximately 1.5 Mpa of soil moisture was also determined in the field.

Table 1. Andic properties of a Typic Hapludand at Juan Viñas, Costa Rica.

<table>
<thead>
<tr>
<th>Areas</th>
<th>Amorphous Al†</th>
<th>Amorphous Fe†</th>
<th>Al + 1/2Fe‡</th>
<th>P Fixation‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar cane</td>
<td>5.00%</td>
<td>0.74%</td>
<td>4.23%</td>
<td>98%</td>
</tr>
<tr>
<td>Coffee</td>
<td>4.20%</td>
<td>0.77%</td>
<td>5.26%</td>
<td>97%</td>
</tr>
<tr>
<td>Forest</td>
<td>3.20%</td>
<td>0.59%</td>
<td>5.68%</td>
<td>96%</td>
</tr>
</tbody>
</table>

† Extracted by ammonium oxalate
‡ USDA and NRSC (1996)

Soil analysis

Soil samples were dried and ground to <2 mm. Calcium, Mg, and acidity were extracted with 1M KCl. Potassium, P, and cationic microelements were extracted with 0.5M NaHCO₃ at pH 8.5 (Olsen and Khasawneh, 1980). pH was measured in water (1:2.5 soil:solution) and percentage of organic matter was also determined (Diaz-Romeu and Hunter, 1978). Andic properties are shown in Table 1 and were defined in terms of soil P fixation and iron and aluminum extracted with ammonium oxalate (USDA, 1994). Soil texture was determined as described by Diaz-Romeu and Hunter (1978).
Soil P fractionation

Other portion of the dried soil sample was separated and ground to <100 mesh for soil P fractionation. This methodology is a selective dissolution technique that allows the extraction
of different P forms from the solid phase. A modified Hedley et al. (1982) method was used. Soil samples of 0.5 g were weighed into 50 ml screw-cap centrifuge tubes. Initially 30 ml of deionized water was added with a 1.5x1.5 cm Anion Exchange Membrane (AEM) strip. The samples were shake continuously for 16 hours. After shaking the membrane was removed and the rest of the sample centrifuged (2500 rpm) and the supernatant water discarded. The inorganic P (Pi) on the membrane was recovered by shaking 20 ml of 0.5 M HCl with the membrane for one hour. The inorganic P was determined using the molybdate-ascorbic acid procedure of Murphy and Riley (1962). Thirty ml of 0.5M NaHCO₃ was added to the soil in the tube and it was reshaken for 16 hours then centrifuged to separate the liquid from the soil. The same procedure was sequentially done using 30 ml of 0.1M NaOH and 30 ml of 1M HCl. Separate portions of NaHCO₃ and NaOH supernatants were acidified with 4 M sulfuric acid to precipitate extracted organic matter to eliminate reading interference and then Pi was determined. Additionally, separate aliquots of NaHCO₃ and NaOH supernatant were digested with concentrated H₂SO₄ and H₂O₂ for 1 hour at 240°C to determine the total P in each extract. Organic P (Po) in NaHCO₃ and NaOH (called extractable-Po in the following discussion) was determined by subtracting Pi from the digested total P. After the extraction procedure, the soil was transferred to glass tubes and digested with concentrated H₂SO₄ and H₂O₂ for 8 hours at 270°C. The sonification and the use of chloroform, used in the original methodology, were not performed in this study. For the following discussion, AEM-P and NaHCO₃-Pi were summed and are referred to as labile-Pi. As it was mentioned above, NaHCO₃-Po and NaOH-Po fractions were summed and are referred to as extractable-Po.

**Statistical analysis and data interpolation**

The data were analyzed using GLM and PROC MIXED (SAS Institute, 1996). Separation of means was performed by least significant difference (LSD). Correlations were calculated among the variables. The soil data were mapped and interpolated with kriging using the ArcView program (Environmental Systems Research Institute 1996).
Results and Discussion

Andisols are soils with a highly variable natural nutrient status depending on the characteristics inherited from the parent material and with high P fixation (Parfit 1989; Alvarado and Boul 1985). This natural fertility status is affected by soil and crop management practices (Soto, 1998; Bertsch et al., 2000).

Table 2. Balance between the amounts of nutrients removed and applied per year in coffee and sugar cane plantations in the study area, Juan Viñas, Costa Rica (Bertsch et al., 2002).

<table>
<thead>
<tr>
<th>Crop</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg ha⁻¹ year⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coffee</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied</td>
<td>216</td>
<td>27</td>
<td>90</td>
<td>94</td>
</tr>
<tr>
<td>Removed</td>
<td>115</td>
<td>8</td>
<td>116</td>
<td>10</td>
</tr>
<tr>
<td>Balance</td>
<td>+101</td>
<td>+19</td>
<td>-26</td>
<td>+84</td>
</tr>
<tr>
<td>Sugar Cane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied</td>
<td>97</td>
<td>25</td>
<td>69</td>
<td>26</td>
</tr>
<tr>
<td>Removed</td>
<td>87</td>
<td>23</td>
<td>187</td>
<td>22</td>
</tr>
<tr>
<td>Balance</td>
<td>+10</td>
<td>+2</td>
<td>-118</td>
<td>+4</td>
</tr>
</tbody>
</table>

The two crop areas received a specific fertilizer application program that is presented in Table 2, while the forest has not been fertilized for at least 25 years. The differences among the areas can be observed in Tables 3 and 4. It was possible to categorize and separate the three management zones selected for this study on the basis of these data. The spatial variation found for soil P fractions and some selected soil chemical and physical variables were also represented graphically by the interpolated maps (Figures 2, 4, and 5).

Table 3. Selected chemical properties of the top soil (0-20 cm). Juan Viñas, Costa Rica.

<table>
<thead>
<tr>
<th>Areas</th>
<th>P</th>
<th>pH H₂O</th>
<th>Ca</th>
<th>Mg</th>
<th>K</th>
<th>Acidity</th>
<th>O.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg kg⁻¹</td>
<td></td>
<td>cmol(+) kg⁻¹</td>
<td></td>
<td></td>
<td></td>
<td>g kg⁻¹</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>5.2b</td>
<td>5.5</td>
<td>1.7b</td>
<td>0.42c</td>
<td>0.15c</td>
<td>0.7b</td>
<td>117a</td>
</tr>
<tr>
<td>Coffee</td>
<td>11.6a</td>
<td>5.4</td>
<td>7.2a</td>
<td>1.49b</td>
<td>0.46a</td>
<td>1.7a</td>
<td>69b</td>
</tr>
<tr>
<td>Forest</td>
<td>3.9b</td>
<td>5.4</td>
<td>8.4a</td>
<td>3.04a</td>
<td>0.27b</td>
<td>1.1a</td>
<td>74b</td>
</tr>
</tbody>
</table>

significance

ns not significant at $P < 0.05$
* Significance at $P 0.01$ to 0.05
** Significance at $P <0.01$

Means within the same column followed by the same letter are not significantly different ($P<0.05$) by LSD test.

The soil analysis and the interpolated maps were also supported by one-dimensional transects presented in Figures 3 and 6. The trend found from the interpolation matched well
with the results of the traditional statistical analysis. According to Nielsen et al. (1995), a concept fundamental to geostatistics and regionalized variable analysis is that of spatial dependence or autocorrelation of soil or crop attributes. The traditional statistical approach does not quantify the variability of the soil and crops in regard to their spatial arrangement but merely treats the values in terms of their magnitudes, independent of their spatial position. However, the results of the traditional statistical analysis were well correlated with the interpolation representation in this study.

Table 4. Selected chemical and physical properties of the top soil (0-20 cm), Juan Viñas, Costa Rica.

<table>
<thead>
<tr>
<th>Areas</th>
<th>Zn</th>
<th>Cu</th>
<th>Fe</th>
<th>Mn</th>
<th>Clay</th>
<th>Penetration Resistance</th>
<th>Depth to A_1 Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg kg(^{-1})</td>
<td>%</td>
<td>MPa</td>
<td>cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar cane</td>
<td>4.8 (a)</td>
<td>8.7 (b)</td>
<td>101 (b)</td>
<td>13 (c)</td>
<td>11</td>
<td>0.26 (b)</td>
<td>25</td>
</tr>
<tr>
<td>Coffee</td>
<td>4.2 (ab)</td>
<td>18.6 (a)</td>
<td>185 (a)</td>
<td>45 (a)</td>
<td>12</td>
<td>0.47 (a)</td>
<td>18</td>
</tr>
<tr>
<td>Forest</td>
<td>2.1 (b)</td>
<td>11.0 (b)</td>
<td>187 (a)</td>
<td>31 (b)</td>
<td>8</td>
<td>0.19 (b)</td>
<td>26</td>
</tr>
</tbody>
</table>

**significance**

- \(\*\) not significant at \(P<0.05\)
- \(\*\) Significance at \(P<0.01\) to 0.05
- \(\*\*\) Significance at \(P<0.01\)

Means within the same column followed by the same letter are not significantly different \((P<0.05)\) by LSD test.

**Variations in selected chemical and physical soil properties**

Data presented in Table 3 show that the soil in the sugar cane field was low in Ca, Mg, K and P which was strongly related to crop uptake rate and low replenishment by fertilizer and lime applications (data presented in Table 2 except for Ca). Coffee, in general, had higher soil fertility characteristics even though higher extractable acidity was noted. This was probably related to the higher nitrogen fertilization rate received during the years (Table 2). Spatial representation of these variables is shown in Figures 2 and 3 and supports the results of Table 3. These trends by type of crop are in agreement with data and discussion presented by Bertsch et al. (2002) for these crops in the same area of study and they were related to changes caused by fertilizer application and the nature of crop nutrient uptake.
Figure 2. Interpolated maps for different soils properties in three crop/soil management areas in a Typic Hapludand.
The forest area had the lowest NaHCO₃ extractable P value among the three (Table 3). Moderate Ca, Mg and K contents were found in it even though no fertilizer was applied during the last 25 years suggesting a relatively closed nutrient cycling system with no significant outputs (Kitayama et al., 2000). Organic matter content was higher in sugar cane than the coffee and forest systems; this was related to biomass accumulation that occurs during harvest under no-burning sugar cane management systems (Ball-Coelho et al., 1993). In spite of the variability of Ca, Mg, and acidity that was found over the entire field, no significant difference in soil pH or the spatial relationship between pH and management areas was found (Figure 2). This is probably due to the high buffer capacity of Andisols (Sanchez and Uehara, 1980; Soto, 1998; Alvarado et al., 2001).

Statistically higher soil strength was found in the coffee field probably because this area has more human traffic related to crop management practices during the year than sugar cane and forest (Table 4). No statistical differences were found in clay content or depth of A₁ horizon (characteristic horizon with moist color 10YR3/4), even though there was a trend found on the coffee area suggesting less thickness of the A₁ horizon that could be related to a steeper slope, less cover, and consequently more erosion (Figure 1).
Differences in soil P forms among management areas

Soil P fractions delineated by the Hedley et al. (1982) methodology roughly correspond to soil P forms; however, the scheme permits estimation of the most important soil P forms and their possible participation in soil P cycling (Hedley et al., 1994; Guo and Yost, 1998). The soil P fractionation methodology used in this research allowed us to accomplish the goal of categorizing the different land-use areas based upon the relative distribution of P forms. Soil and crop management practices applied to the sugar cane plantation, coffee plantation and forest area, characteristically defined the soil P forms among the fields. As reported by other authors, all the soil P forms were significantly affected by the vegetation and fertilization practices (Magid, 1993; Neufeldt et al., 2000; Buehler et al., 2002). One of our objectives was to represent these changes spatially.

Table 5. Percentages of P forms obtained by using a modified Hedley et al. (1982) methodology at two sampling depths (0-20 and 20-40 cm) on a Typic Hapludand.

<table>
<thead>
<tr>
<th>Areas</th>
<th>labile P</th>
<th>NaOH P</th>
<th>HCl P</th>
<th>organic P</th>
<th>residual P</th>
<th>Total sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 20 cm</td>
<td>percentage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar Cane</td>
<td>0.30c</td>
<td>14.32b</td>
<td>7.72a</td>
<td>29.66</td>
<td>47.91a</td>
<td>100</td>
</tr>
<tr>
<td>Coffee</td>
<td>1.84a</td>
<td>24.33a</td>
<td>3.00b</td>
<td>30.14</td>
<td>40.69b</td>
<td>100</td>
</tr>
<tr>
<td>Forest</td>
<td>0.70b</td>
<td>20.74a</td>
<td>5.91a</td>
<td>27.90</td>
<td>44.74b</td>
<td>100</td>
</tr>
<tr>
<td>Significance</td>
<td>••</td>
<td>*</td>
<td>••</td>
<td>ns</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>20 - 40 cm</td>
<td>percentage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar Cane</td>
<td>0.12c</td>
<td>11.77b</td>
<td>5.44a</td>
<td>34.72</td>
<td>47.94</td>
<td>100</td>
</tr>
<tr>
<td>Coffee</td>
<td>1.03a</td>
<td>23.90a</td>
<td>2.18b</td>
<td>31.88</td>
<td>41.00</td>
<td>100</td>
</tr>
<tr>
<td>Forest</td>
<td>0.48b</td>
<td>18.80a</td>
<td>6.03a</td>
<td>29.88</td>
<td>44.80</td>
<td>100</td>
</tr>
<tr>
<td>Significance</td>
<td>••</td>
<td>••</td>
<td>••</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
</tbody>
</table>

ns not significant at P < 0.05
* Significance at P 0.01 to 0.05
** Significance at P<0.01
Means within the same column followed by the same letter are not significantly different (P<0.05) by LSD test.

Based on data presented in Table 5 and comparing the two depths, the readily and reversibly available P fractions (labile-Pi, NaOH-Pi, and HCl-Pi) were greater in top soil (0-20 cm) whereas the sparingly available P forms (extractable-Po and residual P) were greater in the deep layer (20-40 cm). The sum of P forms was, on average, 200 mg kg⁻¹ higher in top soil than the subsoil (data not presented). These observations are probably related to higher root activity, fertilization practices (in sugar cane and coffee fields), and the low mobility of
P in these high P fixing soils. Richards et al. (1995) point out that subsoil P could be involved in P cycling especially when no P is applied suggesting a possible movement from subsoil to top soil due to plant uptake, mobilization, and deposition on surface. This was not confirmed in this study. No significant differences in trends were found between the two soil depths in terms of P fractions when the spatial analysis was performed (Figures 4 and 5). High or low P content areas in the top soil corresponded to high and low P content areas in the subsoil. Therefore the following discussion will be focused on the top layer (0-20 cm) results.

Table 6. Amounts and relative percentages of P forms obtained by using a modified Hedley et al. (1982) methodology on the top soil (0-20 cm) of a Typic Hapludand, Juan Víñas Costa Rica.

<table>
<thead>
<tr>
<th>P forms</th>
<th>Sugar Cane</th>
<th>Coffee</th>
<th>Forest</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labile-Pi +</td>
<td>Mean</td>
<td>6.1 b</td>
<td>35.7 a</td>
<td>10.3 b</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>0.9 - 13.1</td>
<td>2.4 - 113.4</td>
<td>2.5 - 28.8</td>
</tr>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>4.24</td>
<td>33.96</td>
<td>7.50</td>
</tr>
<tr>
<td>NaOH-Pi</td>
<td>Mean</td>
<td>389 b</td>
<td>443 a</td>
<td>298 b</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>102 - 555</td>
<td>140 - 745</td>
<td>110 - 522</td>
</tr>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>159.17</td>
<td>189.63</td>
<td>147.92</td>
</tr>
<tr>
<td>HCl-Pi</td>
<td>Mean</td>
<td>158 a</td>
<td>53 b</td>
<td>89 b</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>66 - 304</td>
<td>6 - 140</td>
<td>14 - 275</td>
</tr>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>64.18</td>
<td>36.96</td>
<td>75.78</td>
</tr>
<tr>
<td>Extractable-Po +</td>
<td>Mean</td>
<td>555 a</td>
<td>522 a</td>
<td>386 b</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>431 - 757</td>
<td>290 - 738</td>
<td>202 - 630</td>
</tr>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>93.34</td>
<td>133.68</td>
<td>128.99</td>
</tr>
<tr>
<td>Residual-P</td>
<td>Mean</td>
<td>907 a</td>
<td>700 b</td>
<td>636 b</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>729 - 1076</td>
<td>426 - 844</td>
<td>420 - 857</td>
</tr>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>99.32</td>
<td>112.66</td>
<td>146.32</td>
</tr>
<tr>
<td>Total Sum P</td>
<td>Mean</td>
<td>1935 a</td>
<td>1754 a</td>
<td>1419 b</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>1559 - 2516</td>
<td>934 - 2269</td>
<td>993 - 1826</td>
</tr>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>296.53</td>
<td>339.57</td>
<td>271.38</td>
</tr>
</tbody>
</table>

+ ** Proc Mixed was applied instead of GLM
** Significance at P<0.01
Means within the same column followed by the same letter are not significantly different (P<0.05) by LSD test.

On average labile-Pi was 6.11 mg kg\(^{-1}\) (0.30%) in sugar cane, 35.71 mg kg\(^{-1}\) (1.84%) in coffee, and 10.32 mg kg\(^{-1}\) (0.70%) in forest (Tables 5 and 6). These findings were consistently related to the spatial distribution depicted in Figures 4 and 5. Figure 6 shows a one-dimensional transect across the three management areas; an increase in all the available P forms in coffee field was evident. This result was strongly related to the amount and frequency of P fertilizer that is applied in coffee plantations. Sugar cane had low labile-Pi (Table 6). Labile-Pi is supposed to be held on net-exchange sites, at occluded net-exchange sites, at surface isotopic-exchange sites and within more perfect crystal lattices (Mattingly,
The latter type of labile-Pi is thought to be very slowly mobilized into the soil solution and is related to more stable forms of labile P and also related to the adsorbed P fraction. This is thought to be the labile P form prevalent in the sugar cane field after observing the high residual P fraction in this field.

NaOH-Pi has been suggested by several researchers as a sink for applied P in fertilized soils (Tiessen et al., 1984; Beck and Sanchez, 1994; Zhang and MacKenzie, 1997). Because coffee is managed under high fertilizer application, in both rate and frequency of application during the year, there was a high probability of having higher values in this fraction than the sugar cane and forest areas. The average values of NaOH-Pi were 289 mg kg\(^{-1}\) (14.32\%) in sugar cane, 443 mg kg\(^{-1}\) (24.33\%) in coffee, and 298 mg kg\(^{-1}\) (20.74\%) in forest (Tables 5 and 6). This fact allows differentiation of land use areas based on the soil P status according to fertilization management. The maps representing the spatial P distribution support this finding. It is very likely that desorption/adsorption reactions are acting between NaOH-Pi and labile-Pi fractions. Zheng et al. (2002) mention that the NaOH-Pi fraction acted as a sink for added Pi while at the same time as source of NaHCO\(_3\)-Pi. The question that becomes important is if this rate of desorption is enough for meeting crop demand. In sugar cane the highest values were found in HCl-Pi and other less available P forms like extractable-Po and residual-P whereas the available P forms were low (Table 6). This is also supported spatially in maps presented in Figures 4 and 5.

According to data presented in Tables 5 and 6, the HCl-Pi fraction was 158 mg kg\(^{-1}\) (7.7\%) in sugar cane, 53 mg kg\(^{-1}\) (3.0\%) in coffee, and 89 mg kg\(^{-1}\) (5.9\%) in forest. Magid (1993) suggests that crop areas develop very large pools of easily soluble inorganic P (AEM and NaHCO\(_3\) extractable) compared to non crop areas where the organic pool buildup is more important. The same author mentions that during 20 years a field that is not tilled builds up a considerable amount of organic P (95 mg kg\(^{-1}\)) and concluded that the vegetation seems to be of more importance to the phosphorus fractionation than the parent material on the soils he was studying.
Figure 4. Interpolated maps of soil P forms in top soil (0-20 cm) of three management areas in a Typic Hapludand.
Figure 5. Interpolated maps of soil P forms in subsoil (20-40 cm) of three management areas in a Typic Hapludand.
Extractable-Po was 555 mg kg\textsuperscript{-1} (29.66\%) in sugar cane, 522 mg kg\textsuperscript{-1} (30.14\%) in coffee, and 386 mg kg\textsuperscript{-1} (27.90\%) in forest. Similar results were found by Soto (1998) and Derry (2000) in Andisols from Costa Rica. Clearly, both cropped areas had higher amounts and proportions of extractable-Po which was opposite to results reported by Magid (1993) (Tables 5 and 6). Anderson (1980) mentions that application of inorganic fertilizers can lead to an increase in soil organic matter and its phosphatic components by encouraging vigorous plant growth. Hence, the accumulation of soil organic matter could be much greater in fertilized systems than in soils developing under virgin conditions. Zhen et al., (2002) mention that mineral fertilizer applications tend to transform labile Pi into more stable Po. These authors explain this phenomenon through the relationship between surplus inorganic fertilizer P addition and plant exports. The excess of P was supposed to reduce the phosphorylase activity and consequently the rate of mineralization of organic forms is reduced. Therefore, accumulation of organic forms could be expected under fertilized systems (Zhen et al 2002; Schmidt, 1996).

![Figure 6. Transect representation of available P forms across the three management areas.](image)

Both residual-P and total sum of P were higher in the sugar cane field than the coffee and forest fields (Tables 5 and 6). The residual P was 907 mg kg\textsuperscript{-1} (47.91\%) in sugar cane, 700
mg kg\(^{-1}\) (40.69\%) in coffee, and 636 mg kg\(^{-1}\) (44.74\%) in forest. This significant difference in sugar cane could be related to slow transformation from available forms to more recalcitrant and non available P forms due to the turnover of plant residues at harvesting and the long period of time between fertilizations without N input for organic matter mineralization. According to Parfit (1978) and Espinosa (1992), humus-Al compounds have an important role in adsorbing available P through ligand exchange reactions in Andisols. Under sugar cane the interaction among uptake, input, and time is determining accumulation in this sparingly available P fraction in such a way.

In general, the map representations (Figures 4 and 5) were well related with traditional statistical parameters comparing the areas of study (Table 6). In spite of the fact that the management areas were already defined from previous soil sampling and the subsequent interpolation process, the grid sampling was adequate to separate areas of different management in space. The use of grid soil sampling has been preferred by many researchers because it eliminates personal biases and it seems to be applicable for these type of studies even though it is not always economically feasible in terms of routine soil sampling methodology (Franzen et al., 1998).

**Soil P forms correlation**

Although correlation analysis does not necessarily establish a cause and effect between two variables, it can be used to make important validations. Differences in correlation coefficients were obtained when the whole set of data were analyzed as three separate populations according to areas of management (Table 7a, b, c, and d). The correlation coefficients suggest that the relationships among the soil P forms should be differentially treated according to the management areas instead of using a pooled set of the entire area (Table 7). The latter statement is represented graphically in Figure 7 in which it is possible to observe the behavior after separating the three different populations of data. A correlation of 0.82 (\(R^2=0.68^{**}\)) was found between NaOH-Pi and labile-Pi in coffee whereas a coefficient of 0.64 (\(R^2=0.38^{*}\)) and a non significant 0.41 (\(R^2=0.18\) ns) were found for sugar cane and forest, respectively. These same results were obtained for other correlations (Table 7)
Table 7. Pearson's correlation coefficients for P forms extracted by a modified Hedley scheme (only coefficients significant at $P < 0.05$ are shown).

a) Overall relationships ($n=38$)

<table>
<thead>
<tr>
<th>Extractant</th>
<th>Labile-Pi</th>
<th>AEM-P</th>
<th>NaHCO$_3$-Pi</th>
<th>NaOH-Pi</th>
<th>HCl-Pi</th>
<th>Extrac-Po</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Olsen</td>
<td>0.93</td>
<td>0.89</td>
<td>0.94</td>
<td>0.78</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Labile-Pi</td>
<td>*</td>
<td>-§</td>
<td>-</td>
<td>0.71</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>AEM-P</td>
<td>*</td>
<td>0.93</td>
<td>0.65</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>NaHCO$_3$-Pi</td>
<td></td>
<td>*</td>
<td>0.75</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>NaOH-Pi</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCl-Pi</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
<td>0.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extrac-Po</td>
<td>*</td>
<td></td>
<td></td>
<td>0.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

b) Sugar Cane field ($n=11$)

<table>
<thead>
<tr>
<th>Extractant</th>
<th>Labile-Pi</th>
<th>AEM-P</th>
<th>NaHCO$_3$-Pi</th>
<th>NaOH-Pi</th>
<th>HCl-Pi</th>
<th>Extrac-Po</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Olsen</td>
<td>0.67</td>
<td>0.61</td>
<td>0.68</td>
<td>0.71</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Labile-Pi</td>
<td>*</td>
<td>-§</td>
<td>-</td>
<td>0.64</td>
<td>ns</td>
<td>0.62</td>
<td>ns</td>
</tr>
<tr>
<td>AEM-P</td>
<td>*</td>
<td>0.85</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>NaHCO$_3$-Pi</td>
<td></td>
<td>*</td>
<td>0.69</td>
<td>ns</td>
<td>0.62</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>NaOH-Pi</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCl-Pi</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
<td>0.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extrac-Po</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>ns</td>
<td></td>
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<tr>
<td>Residual</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

c) Coffee field ($n=14$)

<table>
<thead>
<tr>
<th>Extractant</th>
<th>Labile-Pi</th>
<th>AEM-P</th>
<th>NaHCO$_3$-Pi</th>
<th>NaOH-Pi</th>
<th>HCl-Pi</th>
<th>Extrac-Po</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Olsen</td>
<td>0.96</td>
<td>0.93</td>
<td>0.97</td>
<td>0.89</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Labile-Pi</td>
<td>*</td>
<td>-§</td>
<td>-</td>
<td>0.82</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>AEM-P</td>
<td>*</td>
<td>0.94</td>
<td>0.79</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>NaHCO$_3$-Pi</td>
<td></td>
<td>*</td>
<td>0.84</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>NaOH-Pi</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCl-Pi</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extrac-Po</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>ns</td>
<td></td>
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</tr>
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d) Forest field ($n=13$)

<table>
<thead>
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<th>Extractant</th>
<th>Labile-Pi</th>
<th>AEM-P</th>
<th>NaHCO$_3$-Pi</th>
<th>NaOH-Pi</th>
<th>HCl-Pi</th>
<th>Extrac-Po</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Olsen</td>
<td>0.89</td>
<td>0.79</td>
<td>0.81</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Labile-Pi</td>
<td>*</td>
<td>-§</td>
<td>-</td>
<td>ns</td>
<td>0.69</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>AEM-P</td>
<td>*</td>
<td>0.63</td>
<td>ns</td>
<td>0.60</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>NaHCO$_3$-Pi</td>
<td></td>
<td>*</td>
<td>0.58</td>
<td>0.68</td>
<td>ns</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>NaOH-Pi</td>
<td>*</td>
<td>0.51</td>
<td>-0.62</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCl-Pi</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extrac-Po</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Sum of resin-Pi and NaHCO$_3$-Pi
‡ Sum of NaHCO$_3$-Po and NaOH-Po
§ Correlation not performed
This suggests the importance of the NaOH-Pi fraction as sink or reservoir (temporal or not) under intensive P fertilizer application systems (in amount and time) which is the case for the coffee field. Hence, in this study, the overall correlations values (Table 7a) neither represented the possible relationships established for each crop area nor explain the behavior occurring in each P fraction based on fertilization and crop management.

Figure 7. Overall and particular linear relation for labile-Pi and NaOH-Pi in three management zones.

For the sugar cane area, NaHCO$_3$-P and labile-Pi were related to both NaOH-Pi and extractable-Po (Table 7b). Despite the fact that the sugar cane field had higher organic matter content (Table 2) this variable was poorly correlated with extractable-Po (data not shown). A similar observation was reported by Soto (1998). It is possible that the processes involved in organic matter accumulation are acting through different pathways to those related to the
extractable-Po fraction. On the other hand, in the coffee area all available P forms (P Olsen, labile-Pi and AEM-P) were highly related to the NaOH-Pi fraction, supporting the idea of this fraction as a sink of P applied as fertilizer in intensively fertilized systems. In contrast with some general statements made by different authors about fertilized crop production systems (Ball-Coello et al., 1993; Neufeldt et al., 2000; Buehler et al., 2002), it could be more appropriate in terms of this study, to indicate the differences occurring between these two examples of cropped areas and relate them to the method of fertilization in each system. The sugar cane plantation receives fertilization approximately each year and a half for each growing period whereas coffee is fertilized two or three times a year. This fact provides an explanation of the differences in soil P status on these fields and it is strongly supported by the spatial distribution of soil the P fraction at both sampling depths (Figure 3 and 4).

In the forest area labile-Pi and AEM-P fractions were more correlated with HCl-Pi, suggesting major participation of Ca phosphates and other primary minerals in P availability (Table 7c). This behavior is graphically depicted in Figure 4. No correlation was found between extractable-Po and P availability for the forest suggesting an apparent stable system under stabilized organic matter and the low requirement of P by plants. The unique negative correlation found in this study was in the forest area between extractable-Po and NaOH-Pi that may have been due to complexation of the organic matter on Fe and Al compounds that are related to NaOH-Pi extraction (Table 7c).

The results shown so far underscore the importance of evaluating the amount of other soil P forms and not solely the routine soil test levels to develop fertilization management strategies.

**Conclusion**

Spatial distribution of soil P forms and other selected soil properties at the study site were related to soil and crop management areas. However, it is our opinion that the generalization of changes in soil P forms in both fertilized and non fertilized systems may be done only under comparable soil and crop management systems. Crops fertilized differently not only in amount but also in frequency will have a different distribution of soil P forms. This approach
could allow discerning the possible pathways for fertilization for each type of crop in relation to time and intensity of application.

Acknowledgements

The authors acknowledge Dr. Jose Espinosa and the economic support given by the Potash and Phosphate Institute (Northern Latin American-INPOFOS). We also wish to mention the valuable cooperation of the staff and workers from Hacienda Juan Viñas and the Laboratory of Soil and Plant Analysis in Centro de Investigaciones Agronomicas at the Universidad de Costa Rica. Special thanks to Freddy Sancho, Gloria Melendez, Luis Garcia, Pablo Lopez, Danilo Alpizar, and Ivania Cartin.

References


CHAPTER 4
SOIL P FORMS AND P UPTAKE UNDER INTENSIVE PLANT GROWTH IN AN ANDISOL WITH DIFFERENT LAND USE

Carlos Henriquez and Randy Killorn

Abstract

The concentration of available soil phosphorus (P) is a function of the equilibrium established among different soil P forms through numerous and different reactions in soil. This equilibrium is affected mainly by fertilizer application and plant uptake, but microbial activity is also involved. Depletion of available P causes changes and transformations in the unavailable soil P forms. The objective of this study was to examine the changes in P forms and P supply under exhaustive extraction conditions in soils from three 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 Hapludand in Costa Rica. One field was a coffee plantation (Coffea arabica var Catuai), one was a sugar cane plantation (Saccharum spp. var H611721), and the third field was a secondary forest. Sorghum (Sorghum bicolor var Glazer 41) was planted in 1L pots and harvested four times consecutively. The treatments were no P and P application (100 mg kg$^{-1}$) for each of the different land-use soil samples. The pots were arranged in a randomized complete block design with five replications. Soil samples were taken before and after each of the four plant growth cycles. Shoot and root dry matter and total P uptake were determined. Soil samples were 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. Ca, Mg, K, NaHCO$_3$-P, pH (H$_2$O), and acidity were also determined. Additionally P desorption was measured to estimate the supply of P over time in the three soils. Sugar cane soil had the lowest fertility values followed by forest and coffee. 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 act as a temporary pool of applied P. A significant and negative trend was observed in the sugar cane soil relating the residual-P with labile-Pi and NaOH-Pi whereas non significant negative trends were found in coffee and
forest. The results suggest the possible participation of residual-P in replenishment of labile-P and NaOH-Pi. The amount of plant P uptake and P desorbed by soil were closely related to the initial amount of labile-Pi and were higher in coffee than forest and sugar cane soils. The labile-P was depleted by plant uptake. The initial amount of labile-Pi was not observed again during the experiment due to intensive plant withdrawal. Rapid changes in reversibly available soil P forms (NaOH-Pi and HCl-Pi) were observed during the experiment. Slight changes in time were also found in reversible and sparingly available forms suggesting intensive and rapid soil P cycling. 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 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 phases; it is thought the opposite reactions occur in soils as well (Sample et al., 1980). Hence, this so called soil labile P consists 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 the soil solution, depleting P from the surrounding 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 available. 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.

It is thought that precipitation-dissolution, adsorption-desorption, and immobilization-mineralization are the processes that define the capacity factor (intensity-quantity relationship) (Frossard et al., 2000). 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 it is possible to simulate strong and rapid changes in soil P forms and measure 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 (Hedley et al., 1982; Hedley et al., 1994; Buehler et al., 2002).

Anionic exchangeable membrane-P (AEM-P) is considered the freely available P and it is thought to represent P in the soil solution (Tiessen and Moire, 1993). Inorganic P extracted by bicarbonate (NaHCO₃-Pi) is loosely adsorbed to the surfaces of clays, sesquioxides and carbonates. The HCO₃⁻ 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 NaHCO₃-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) is thought to act as a sink of fertilizer P and also as a source of P to labile-Pi (Beck and Sanchez, 1994). Calcium phosphates extracted by HCl (HCl-Pi) may be plant-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.

In spite of the information mentioned so far, the importance of soil P forms and the different reactions related to P transformations under different land use systems still remains largely unstudied in Andisols of the tropics. 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 three different but adjacent land-use areas. One area had 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 were located in Juan Viñas, Costa Rica.
(9°55'N and 83°44'W). The soil was a sandy loam to loam, well drained, Typic Hapludand derived from andesitic volcanic ash (USDA, 1994; Bertsch et al., 2000). The soil samples were taken from the surface 20 cm and were a composite of 20 subsamples collected randomly at different points from each of the fields. The soils samples were air dried and sieved to pass a 2 mm screen.

**Greenhouse experiment and treatments**

Two treatments, no P and 100 mg P L\(^{-1}\) (−P and +P treatments respectively) were applied. Five separate subsamples of 1 L from each type of land use were placed in plastic bags. The +P treatments were applied to the soil, mixed, and incubated for two 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 1L plastic pots. The experiment was arranged in a randomized complete block design (RCBD) with five replications. The pots were placed on hollow wooden pans located over plastic containers filled with water in order to maintain a 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\(^{-1}\) as NH\(_4\)NO\(_3\)) and potassium (78 mg L\(^{-1}\) as KCl) which was repeated at the beginning of each of the four 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 seven 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\(^{0}\)C. Dry matter production was determined. A sample of 0.5 g of dry and ground tissue was digested by a wet nitric-perchloric acid digestion (5:1 nitric acid and perchloric acid). Inorganic P was determined by colorimetric absorption spectrophotometry (Diaz-Romeu and Hunter, 1978). Phosphorus 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 four 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 NaHCO₃ extraction (1:10 soil:solution). Ca, Mg and K were determined by atomic absorption spectrophotometry and P by colorimetric absorption spectrophotometry (Diaz-Romeu and Hunter, 1978). 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 using 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 not determined. The methodology makes use of different steps of extraction, water + anion exchange membrane (AEM), 0.5M NaHCO₃, 0.1M NaOH, and 1M HCl) and digestion (a mixture of concentrated H₂SO₄ and H₂O₂) applied in sequence to a single soil sample (Fixen and Grove, 1990). Samples of 0.5 g of soil were 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 NaHCO₃ extracts another portion of the 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 NaHCO₃ 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 NaHCO₃ and NaOH extracts and the P in the digest is an estimate of the extractable organic P. The sum of these determinations was called extractable-Po. The 1M HCl is thought to extract Ca phosphates of different nature and source in soil (apatites, monocalcium, dicalcium and other phosphates etc.). The remaining soil was digested with concentrated H₂SO₄ and H₂O₂ for 8 hours at 270°C. The P determined after this digestion was called residual-P and is 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 spectrophotometry.

Desorption P curves

A modification of the soil desorption procedure of Soto (1998) was used to determine soil P desorption curves for each soil. Three g of dried and sieved (<2 mm) soil samples from each land use type (sugar cane, coffee, and forest) were weighed into 50-ml screw-cap centrifuge tubes. Thirty ml of deionised water and 3 drops of chloroform were added. 1.5x1.5 cm strips of AEM were used to extract the labile-soluble P. The tubes were set on end-over-end shaking for different times of extraction (0.5, 1.5, 3.5, 7.5, 12.5, 24.5, 48, 96, 144, and 192 hours). At each appropriate time the AEM was removed and replaced by a new NaHCO₃ regenerated AEM (Tiessen and Moire, 1993). The P on the AEM was recovered with 20 ml of 0.5 M HCl and determined by the molybdate-ascorbic acid procedure of Murphy and Riley (1962). Analyses were performed in triplicate.

The accumulated desorbed P and rate of desorption were graphed. A simple mathematical model was used to relate the log of time with the log of accumulated of P (mg kg⁻¹) desorbed during the time. The data were fitted using a linear model \( y = bx + a \). The slope \( b \) represented the rate of P desorption in time whereas the intercept \( a \) was the initial P desorbed that was related to the initial status of availability. Both constants were substituted into the equation \( q = at^b \) that represents the real behavior of the desorption process. In this
equation, \( q \) is the amount of P desorbed at time \( t \). The constant \( b \) is the rate of desorption in time whereas \( a \) allowed us to estimate the initial P desorbed and was related to initial labile-Pi content in the soil. Desorption curves were calculated for each soil.

**Data analysis**

Data were analyzed using an analysis of variance (ANOVA) (SAS Institute, 1996). The experiment was analyzed as a factorial (3 soils x 2 treatments). Correlation coefficients were determined among the variables. Separation of means was performed by least significant difference (LSD). 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 three soils that varied in their soil 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 be discussed 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.

**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 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 (neither set of data is shown).

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

<table>
<thead>
<tr>
<th>Areas</th>
<th>P Olsen</th>
<th>pH H2O</th>
<th>Ca</th>
<th>Mg</th>
<th>K</th>
<th>Acidity</th>
<th>O.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg kg$^{-1}$</td>
<td>cmol(+) kg$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>g kg$^{-1}$</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>7.0</td>
<td>5.2</td>
<td>1.5</td>
<td>0.4</td>
<td>0.24</td>
<td>0.15</td>
<td>124</td>
</tr>
<tr>
<td>Coffee</td>
<td>7.6</td>
<td>5.4</td>
<td>6.8</td>
<td>1.2</td>
<td>0.26</td>
<td>0.20</td>
<td>132</td>
</tr>
<tr>
<td>Forest</td>
<td>5.9</td>
<td>5.3</td>
<td>6.4</td>
<td>2.0</td>
<td>0.27</td>
<td>0.17</td>
<td>141</td>
</tr>
<tr>
<td>Critical level</td>
<td>10.0</td>
<td>5.5</td>
<td>4.0</td>
<td>1.0</td>
<td>0.20</td>
<td>&lt;0.50</td>
<td>-</td>
</tr>
</tbody>
</table>

The higher values of these two soil P forms observed in the coffee soil were related to a higher intensity of fertilization that this crop received during the years as compared with the sugar cane plantation. This same trend has been found by Beauchemin and Simmard (2000) and Zheng et al. (2002) for fertilized systems. Sugar cane had lower values compared with forest. Because of variations inherent in the fractionation methodology, also reported by Paniagua et al. (1995), soil P form changes in time will be discussed below as percentages instead of absolute values (Table 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. This trend was obvious during the entire 164 days of the experiment. This finding suggests that those three soil P forms were affected by P fertilization in the very short term. Knowing the nature of the NaOH-Pi and HCl-Pi forms could be possible to suggest the participation of these two P forms a sink for applied P (Zheng et al. 2002).
Table 2. Changes of percentages of labile-Pi, NaOH-Pi, and HCl-Pi forms in top soil (0-20 cm) from three different land use areas in a Typic Hapludand during five sampling times (Roman numerals).

<table>
<thead>
<tr>
<th>P forms</th>
<th>%Labile-Pi</th>
<th>%NaOH-Pi</th>
<th>%HCl-Pi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>S.C.</td>
<td>0.48b</td>
<td>0.76b</td>
<td>0.27b</td>
</tr>
<tr>
<td>C.</td>
<td>0.97a</td>
<td>1.06a</td>
<td>0.47a</td>
</tr>
<tr>
<td>F.</td>
<td>0.96a</td>
<td>1.05a</td>
<td>0.53a</td>
</tr>
<tr>
<td></td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
</tbody>
</table>

**Significance**

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

not significant at $P<0.05$

* Significance at $P=0.01$ to 0.05

** Significance at $P=0.01$

Means within the same column followed by the same letter are not significantly different ($P<0.05$) by LSD test.

Sharpley (1985) and Neufeldt et al. (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 (or AEM-P in this study), NaHCO$_3$-Pi, and NaOH-Pi increased with P fertilization (the first two 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).

Figure 1. Effect of P application on soil P forms in a Typic Hapludand during five samplings times.
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 amorphous 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 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).

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

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.C. +P</td>
<td>37.6</td>
<td>30.3</td>
<td>30.9</td>
<td>30.8</td>
<td>30.7</td>
<td>54.9</td>
<td>50.4</td>
<td>50.5</td>
<td>49.7</td>
<td>50.7</td>
</tr>
<tr>
<td>S.C. -P</td>
<td>28.2</td>
<td>30.7</td>
<td>30.8</td>
<td>30.9</td>
<td>31.5</td>
<td>31.4</td>
<td>31.4</td>
<td>31.4</td>
<td>31.4</td>
<td>31.4</td>
</tr>
<tr>
<td>C. +P</td>
<td>28.4</td>
<td>30.3</td>
<td>30.8</td>
<td>30.8</td>
<td>30.9</td>
<td>47.2</td>
<td>47.2</td>
<td>47.2</td>
<td>47.2</td>
<td>47.2</td>
</tr>
<tr>
<td>C. -P</td>
<td>32.0</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
<td>55.9</td>
<td>55.9</td>
<td>55.9</td>
<td>55.9</td>
<td>55.9</td>
</tr>
<tr>
<td>F. +P</td>
<td>36.1</td>
<td>37.3</td>
<td>37.3</td>
<td>37.3</td>
<td>37.3</td>
<td>47.1</td>
<td>47.1</td>
<td>47.1</td>
<td>47.1</td>
<td>47.1</td>
</tr>
<tr>
<td>F. -P</td>
<td>38.8</td>
<td>37.3</td>
<td>38.5</td>
<td>38.5</td>
<td>38.5</td>
<td>43.9</td>
<td>43.9</td>
<td>43.9</td>
<td>43.9</td>
<td>43.9</td>
</tr>
</tbody>
</table>

A particular and unique increase occurred in labile-Pi at the second sampling time just after the first harvest (Figures 1 and 2). The increase was observed in the NaOH-Pi form too. This trend was also observed in absolute values (data not presented). 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 reversibly 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 five samplings the initial level of labile-P was not reached again, maybe due to high plant uptake.

Figure 2. Changes in soil P forms in three different land use areas in a Typic Hapludand during five sampling times.

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 three soils. Similar results are reported by Dobermann et 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.

![Figure 3. General trends of soil P forms in soils from three different land use areas in a Typic Hapludand.](image)

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, NaHCO₃-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 very good relationship between total dry matter (g pot⁻¹) and plant P uptake (mg P kg⁻¹). Therefore, and based on the assumption that under our conditions both variables behave in similar way, P uptake will be used in discussing plant response variables in the following discussion.

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 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 three 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 to 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 two soils (Table 1).

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

<table>
<thead>
<tr>
<th>Variable</th>
<th>P uptake mg kg⁻¹</th>
<th>Shoot weight g per pot</th>
<th>Root weight g per pot</th>
<th>Total dry matter g per pot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest  I</td>
<td>II</td>
<td>III</td>
<td>IV</td>
<td>Harvest  I</td>
</tr>
<tr>
<td>S.C.</td>
<td>0.83b</td>
<td>0.42b</td>
<td>0.39c</td>
<td>0.47b</td>
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<tr>
<td>C.</td>
<td>0.80b</td>
<td>1.80a</td>
<td>1.49a</td>
<td>1.00a</td>
</tr>
<tr>
<td>F.</td>
<td>0.99b</td>
<td>1.74a</td>
<td>1.04b</td>
<td>0.82a</td>
</tr>
<tr>
<td>Significance</td>
<td>**</td>
<td>*</td>
<td>ns</td>
<td>**</td>
</tr>
<tr>
<td>S.C. +P</td>
<td>1.10a</td>
<td>1.82a</td>
<td>1.09a</td>
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</tr>
<tr>
<td>S.C. -P</td>
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<td>0.81b</td>
<td>0.85b</td>
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<tr>
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<td>0.43</td>
<td>0.52</td>
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<tr>
<td>C. -P</td>
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<td>0.38c</td>
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<tr>
<td>F. +P</td>
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<td>2.72a</td>
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<tr>
<td>F. -P</td>
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<td>0.78</td>
<td>0.55</td>
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<tr>
<td>Significance</td>
<td>**</td>
<td>*</td>
<td>ns</td>
<td>**</td>
</tr>
</tbody>
</table>

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

ns not significant at P < 0.05

* Significance at P < 0.01 to 0.05

** Significance at P < 0.01

Means within the same column followed by the same letter are not significantly different (P < 0.05) by LSD test.
Figure 4. Relationship between total dry matter and P uptake in sorghum (*Sorghum bicolor*) in a Typic Hapludand under three land use.

Figure 5. Accumulated P uptake by sorghum (*Sorghum bicolor*) during four sampling times in soils from three land use areas.
The response to P by plants growing in the forest soil was probably due to the favorable chemical characteristics of this soil 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 was different from the trend observed in plants growing in the sugar cane soil (Figure 7). The rate of response in Figure 7 agrees with that 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 7). This is 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)
Figure 7. Total dry matter accumulation in sorghum during four harvest evaluations in three different land use areas in a Typic Hapludand.

P desorption curves

Ion exchange membranes used to develop the desorption curves are a sink for solution Pi and thereby extract water soluble or "free exchangeable" P. This analysis has been well correlated with crop yield and it has been used to categorize the status of P supply over time as well (Olsen and Khasawneh, 1980; Soto, 1998).

Based on the equations in Figure 8, the estimated initial P desorbed (constant a) was 1.24 mg P kg$^{-1}$ in sugar cane soil, 2.15 mg P kg$^{-1}$ in coffee soil, and 1.28 mg P kg$^{-1}$ in forest soil. These values are proportionally comparable with the labile-Pi content in the soils as discussed above. The estimated total accumulated amounts of P desorbed after 200 minutes of study were 20, 32, and 40 mg P kg$^{-1}$ for sugar cane soil, coffee soil and forest soil respectively. Even though the forest soil was initially lower in Pi than the coffee soil, it desorbed more P than the other two soils.

This is supported by data shown in Figure 9 where the rate constant (represented here by the slope of the linear trend) in the forest soil was different from those of the other soils. The cropped areas had similar rate constants suggesting that sugar cane and coffee soils share the same rate of P desorption. Despite this approach, Ball-Coelho et al. (1993) suggest that
similarly to a forest system, the presence of roots in the decomposing litter layer in sugar cane, provides a mechanism whereby P could be recycled efficiently.

Figure 8. Accumulated P desorbed in soils from three different land use areas in a Typic Hapludand.

Figure 9. Relationship between the log of accumulated P desorbed and log of time in soils from three different land use areas in a Typic Hapludand.
The amounts of P desorbed after 200 minutes exceeded the amount of labile-Pi suggesting the replenishment from other soil P forms. Although it is thought that the real amounts of P desorbed by this method come from a forced mechanistic model, it is still a useful tool to estimate the P supply among soils from different management or treatments. This finding confirms the existence of a continuum of mobility between the Pi found in soil solution and Pi sorbed onto the solid phase (Frossard et al., 2000). The same authors pointed out that it is arbitrary to distinguish available and unavailable Pi fractions. In our case we suggest that the soil P fractionation methodology categorized soil P forms in a defined and particular time but the changes in time should be explained upon another approach. This idea is supported by Selles et al. (1995).

In summary, the sugar cane soil had the lowest P desorption capacity through 200 minutes whereas the forest soil was low at the beginning but increased until it reach a higher level than the coffee soil (Figure 9). The projection of the desorption curve for the forest soil showed higher amounts of P desorbed over time. A good relationship was found between the initial labile-Pi and NaOH-Pi and desorption of P by soils.

![Graph showing the rate of P desorption in soils from three land use areas in a Typic Hapludand.](image)

**Figure 10.** Rate of P desorption in soils from three land use areas in a Typic Hapludand.
These findings are supported by the Figure 10 which shows the capacity of Pi replenishment in the three areas. As shown in Figure 9, the two cropped areas have a similar trend. The difference is due to the initial P value that was higher for coffee soil. The slope for sugar cane and coffee was 0.53 and 0.52, respectively whereas forest soil had a higher slope of 0.63 that was correlated with a higher P desorption capacity compared with cropped areas. The drop in sugar cane soil was evidently faster than occurred in coffee and forest soils.

**Conclusion**

Phosphorus fertilization impacted labile-Pi, NaOH-Pi, and HCl-Pi supporting the readily and reversible available nature of these soil P forms. 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 of replenishment may not meet the plant requirements over time. Plant P uptake was related to the amount of 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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References


CHAPTER 5
GENERAL CONCLUSIONS

The primary objective of this research was to characterize soil phosphorus (P) forms as affected by different land use. Different crop management practices seem to have a differential and direct impact on all P forms in the soil.

The P forms accumulated based on the manner of fertilization and intensity of P uptake by crops. The changes observed over time in soil P forms suggest that P cycling is rapid and intensive in response to applied P and plant uptake. The increase in labile-Pi, NaOH-Pi, and HCl-Pi after P application suggested that these forms are related in the short term to P supply to plants supporting the readily and reversibly available nature of these soil P forms. NaOH-Pi and HCl-Pi seem to act as sinks of applied P in the short term whereas extractable-Po and residual-P would act as sinks in the long term. Because labile-Pi is not able to store high amounts of applied P, NaOH-Pi and HCl-Pi become the alternative and short-term sink for fertilizer P. It seems that residual-P may replenish depleted available P forms under certain conditions, i.e. low amounts of labile-Pi, even though the rate or replenishment may not meet plant requirements over time.

Plant P uptake was related to the amount of labile-Pi and NaOH-Pi. The initial amount and rate of P desorption seem to be initially related to labile-Pi. Over time P desorbed could come from NaOH-Pi and HCl-Pi. Coffee soil had higher initial P desorbed, the forest soil had a higher rate of P desorption as compared with coffee and sugar cane soils. The relationship between the spatial distribution of soil P forms and other selected soil properties with the three crop management areas support the idea that management practices affect the differential accumulation of soil P forms. Crops fertilized differently not only in amount but also in frequency, had a different distribution of soil P forms. This approach could allow discerning possible methods for fertilization for each type of crop in relation to time and intensity of application.

It is concluded that under a sustainable crop production framework the adequate input of not only P but also other essential nutrients is necessary in order to maintain the nutrient supply over time. Crop production without added fertilizer will, in the long term, deplete all
P forms in the soil. It is our opinion that generalization of criteria about the changes in soil P forms in both fertilized and non fertilized systems may be done only under comparable soil and crop management systems.
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