



## Soil phosphorus pools for Histosols under sugarcane and pasture in the Everglades, USA

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### ABSTRACT

Land use changes in the Everglades Agricultural Area (EAA) in southern Florida may influence the distribution and availability of P. Cultivated soils in the EAA are being converted back to their historic use as seasonally-flooded prairies as part of Everglades restoration projects. The objectives of this study were to determine the distribution of P in soil chemical fractions in relation to long-term land management to predict P cycling and transformations for future land uses. Soil under pasture (100 yr) and planted to sugarcane (*Saccharum* sp.) for 50 yr were amended with P (0, 10, 50, 150 kg P ha<sup>-1</sup>), and its distribution in labile, Fe–Al bound P, Ca-bound P, humic–fulvic acid P, and residual P pools determined for surface soil (0–15 cm). Most P fertilizer entered Fe–Al and Ca-bound fractions. Cultivation contributed to higher pH and increased the Ca content in soil compared to pasture due to incorporation of bedrock limestone into soil by tillage. The land uses were differentiated by P storage in different pools. Subsequently, long-term fertilization increased soil total P for cultivated soil relative to pasture, but plant-available P constituted less than 1% of the total P. Labile P increased with increasing P application rate, ranging from 1.3 to 7.2 mg kg<sup>-1</sup> for cultivated soil and 1.4 to 10.7 mg kg<sup>-1</sup> for pasture. Most of the applied P was recovered in the Fe–Al fraction for pasture and the Ca-bound P fraction for cultivated soil. The Ca-bound P fraction represented the greatest proportion of total P for sugarcane (41%), but only 12% for pasture. The majority of P in the pasture was present in the humic–fulvic acid fraction (45%), compared to only 23% for sugarcane. The higher pH of the cultivated soil (6.8) favored retention in Ca fractions while the lower pH of pasture (5.3) favored P retention in the humic–fulvic acid fraction. The proportion of total P as organic P was greater for pasture (78%) than cultivated soil (52%). Higher P levels in more recalcitrant fractions for cultivated soils indicated that more of the applied fertilizer P was sequestered in stable fractions, which decreased P availability to crops and may subsequently increase P fertilizer requirements necessary to maintain optimal plant-available nutrient levels. Subsequently, continuation of current farming practices and tillage regimes promotes the redistribution of Ca from subsurface to surface soil, which leads to greater P sequestration in the Ca-bound fraction. However, P in inorganic fractions may be released upon onset of changes in land use. Thus, conversion to seasonally-flooded prairies may have a more dramatic effect on P release from cultivated than pasture soils since cultivated soils have more P in inorganic pools.

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### 1. Introduction

The Histosols in the Everglades of south Florida developed under seasonally-flooded conditions under sawgrass (*Cladium jamaicense* Crantz) prairies. A major shift in land use occurred in the past century, as the area south of Lake Okeechobee was drained for conversion to agriculture, mainly for the production of sugarcane and vegetable crops. This region, referred to as the Everglades Agricultural Area (EAA), primarily consists of organic soils subjected to cropping for approximately 100 yr (Stephens and Johnson, 1951; Shih et al., 1998). The

conversion of this seasonally-flooded prairie ecosystem to an annual cropping system altered organic matter and nutrient cycling (Snyder, 1994; Morris and Gilbert, 2005). A further result of this land use change was subsidence, or oxidation of the soil organic matter, at rates currently approximating 1.5 cm yr<sup>-1</sup> (Shih et al., 1998). Subsidence is primarily related to water table depth rather than cropping system (Snyder, 2005). A result of subsidence and crop management practices is an increase in soil Ca levels and pH due to incorporation of bedrock limestone into the surface soil, and closer proximity of shallower soils to bedrock (Morris and Gilbert, 2005).

Soils of the EAA contain approximately 85% organic matter, are high in N, but low in P and many micronutrients (Snyder, 1994). Thus, cropping systems in the EAA require high P inputs, with application rates ranging from 15–150 kg P ha<sup>-1</sup> for sugarcane and vegetable crops

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(Hochmuth et al., 2003; Gilbert and Rice, 2006). A result of long-term P fertilization and soil subsidence is the export of P from the EAA through the canal systems into Everglades wetlands, which has been implicated in causing deterioration of water quality and alterations to the natural ecosystem (Wright and Reddy, 2001; Childers et al., 2003). Thus, it is important to understand the factors affecting P distribution and transformation in these soils to minimize P export upon onset of changes in land use.

Due to emerging interests for the protection of water quality and the unique Everglades ecosystem, considerable attention has been paid in the past decade to the conversion of agricultural lands to their prior use as seasonally-flooded pastures and wetlands. However, the impacts of long-term cropping on nutrient dynamics in these soils may necessitate extensive management or remediation before reversion to their original state, especially since these pastures historically developed under nutrient-poor conditions.

Phosphorus fractionation schemes have been developed to measure P distribution in chemical fractions related to their degree of recalcitrance (Hedley et al., 1982; Ivanoff et al., 1998; Reddy et al., 1998; Turner et al., 2005). Soils with a high proportion of P in labile fractions indicate availability to plants, but also increased potential leaching or runoff from fields. Phosphorus contained in Ca-bound or Fe–Al bound fractions are often stable under oxic conditions when soils are drained, while organic P is unstable due to potential for oxidation, thus the organic fraction is a source of P export from the EAA for agricultural land use (Ivanoff et al., 1998). Management practices that alter environmental conditions, cause soil disturbance, or disturb hydrologic conditions can initiate P transformations between the various pools. The distribution of P within these fractions provides an indication of the potential turnover in soil, and may be different for various long-term land management practices. The objectives of this study were to determine changes in the distribution of P pools in soils for different long-term land management practices, the fate of applied fertilizer P in soils, and how land use influence P dynamics in Everglades Histosols.

## 2. Materials and methods

### 2.1. Site description

The EAA (280,000 ha) is characterized by subsiding Histosols underlain by limestone bedrock (Snyder, 2005). These organic soils developed under seasonal flooding and low nutrient status and supported vegetation adapted to these conditions, mainly *Cladium*. Due to conversion of these native pastures to agricultural use by drainage, the dominant vegetation shifted to annual crops of winter vegetables and sugarcane (*Saccharum* sp.). In addition to altered vegetation patterns, nutrient inputs into the EAA, particularly N and P, increased with the introduction of row crops (Morris and Gilbert, 2005). However, some remnant fields in the EAA were not planted to sugarcane but instead remained as pasture, although water management was altered in a similar manner to cultivated soil. These pastures serve as reference sites for investigating effects of cropping systems on soil properties. The majority of the current land use in the EAA is for sugarcane and vegetables, with only small scattered remnants in pasture or rangeland. However, large-scale re-establishment of the original prairie ecosystem is being planned on former agricultural lands.

The study site is located at the Everglades Research and Education Center near Belle Glade, FL (26°39' N, 80°38' W). The long-term average annual temperature is 24 °C and precipitation is 133 cm at this location. The soil is classified as a Dania muck (euic, hyperthermic, shallow Lithic Medisaprists), and the depth to bedrock is approximately 45 cm in both fields. Two land uses at this site were utilized for this study. Cultivated fields were managed for vegetable production since the early 1900s to the 1950s, but predominantly for sugarcane since 1960. Pasture fields remained never received fertilization or

tillage, and were populated by paragrass [*Panicum purpurascens* (L.) Raddi] and bermudagrass [*Cynodon dactylon* (L.) Pers]. The cultivated soils under sugarcane and pasture were both approximately 16 ha in size with canals along the periphery for water management.

Typical fertilization for sugarcane is 20–50 kg P ha<sup>-1</sup> yr<sup>-1</sup> (Gilbert and Rice, 2006). Vegetable crops, such as lettuce, corn, and green beans grown periodically between sugarcane crops, receive up to 150 kg P ha<sup>-1</sup>. Nitrogen is typically not needed since organic N mineralization supplies the required N to crops. Fertilizers are applied to sugarcane using a one-time application prior to planting. Sugarcane is planted from August through January and harvested after burning from October through April. Sugarcane is vegetatively propagated by placing stalks into furrows 8–20 cm deep. Tillage operations include several diskings (to 15 cm depth) after crop harvest and subsoil chiseling (to 30 cm depth) to improve drainage (Morris et al., 2004). Frequent in-season tine cultivations (to 4 cm depth) are done for weed control (Gesch et al., 2007).

### 2.2. Soil sampling and analysis

Triplicate soil cores (5-cm diam.) were taken at four sites from each land use and composited to yield eight field replicates. Soil (0–15 cm depth) was sampled in January 2006 just prior to sugarcane harvest, oven-dried, and passed through a 0.5 mm sieve for analysis. Soil subsamples (100 g) were amended with P at rates of 0, 10, 50, and 150 kg P ha<sup>-1</sup>, which encompasses P fertilizer rates typically used for sugarcane and vegetable crops in the EAA. These rates corresponded to 0, 15, 75, and 225 mg P kg<sup>-1</sup> soil. The P source was a mixture of Na<sub>2</sub>HPO<sub>4</sub> and NaH<sub>2</sub>PO<sub>4</sub> in a 1 mg mL<sup>-1</sup> solution adjusted to the pH of the respective soils. Soil samples were then adjusted to 50% of water-holding capacity, thoroughly mixed, and incubated under 21% O<sub>2</sub> at 25 °C for 21 d.

Soil was analyzed to determine background nutrient concentrations and properties before P addition. Soil was also collected after 21 d of incubation and subjected to P fractionation. Soils were analyzed for bulk density (Blake and Hartge, 1986), water-holding capacity (Klute, 1986), and pH using a 1:3 soil:water ratio after equilibration for 30 min. Total organic C was determined by loss-on-ignition at 550 °C for 4 h after conversion to organic C using factor of 0.51. Extractable NH<sub>4</sub> and NO<sub>3</sub> were determined by extraction (2 N KCl) and colorimetric analysis (White and Reddy, 2000).

The distribution of P in soil was determined using a modification of a sequential chemical fractionation procedure (Hedley et al., 1982; Ivanoff et al., 1998; Reddy et al., 1998). Organic soils of the EAA utilize a water extract for determination of plant-available P (Mylavarapu and Kennelley, 2002). Approximately 1 g of soil was extracted with 25 mL water for 1 h, filtered through 0.45 μm, and analyzed for water-extractable P (labile P). The remaining sample was extracted with 25 mL of 0.1 N NaOH for 17 h and analyzed for NaOH-Pi (Fe–Al bound P), followed by the extraction of the remaining sample with 25 mL of 0.5 N HCl for 24 h and analysis of HCl-Pi (Ca-bound P). The remaining sample was digested with 6 N HCl for 1 h at 150 °C and analyzed for residual P. The humic–fulvic acid fraction was determined after digestion of 5 mL of the NaOH extract with 11 N H<sub>2</sub>SO<sub>4</sub> for 4 h at 350 °C (NaOH-TP), and subtraction of the NaOH-Pi from the NaOH-TP. Total P was measured by colorimetric analysis (U.S. EPA method 365.4) after Kjeldahl digestion (Bremner, 1996). The P fractions were measured by the ascorbic acid-molybdenum blue method (Kuo, 1996) using an AQ2+ discrete analyzer (Seal Analytical Inc., Mequon, WI).

A completely randomized experimental design was utilized with two land uses, four P application rates, and four field replications (Costat Statistics Software, 2005). A two-way ANOVA model was used to determine main effects of land use (cultivated and pasture soil) and P application rate (0, 10, 50, and 150 kg P ha<sup>-1</sup>). A one-way ANOVA model was used to determine differences between individual treatments for each P fraction. Linear and quadratic regression equations

were calculated to predict the percentage increase in P fractions after P fertilization. Significant treatment comparisons were based on Fisher's LSD at  $\alpha=0.05$ .

### 3. Results and discussion

#### 3.1. Soil characterization

Cultivation significantly influenced soil physical and chemical properties, as well as P distribution in chemical fractions. Soil pH was higher for cultivated than pasture soil (Table 1) due to inclusion of  $\text{CaCO}_3$  into soil by tillage and the upward flux of dissolved carbonates followed by deposition on the surface after evaporation (Sanchez and Porter, 1994). The water-holding capacity of the organic soils decreased with cultivation, likely resulting from destruction of soil structure by tillage and disturbance. The total C and N contents did not differ between land uses, but extractable N concentrations were highest for pasture. Accumulated inorganic N reflects organic N mineralization since N fertilizers are seldom applied for sugarcane production.

#### 3.2. Phosphorus distribution in unamended soil

Soil total P was higher in cultivated soil (Table 1) as a result of past P fertilization, averaging  $40 \text{ kg P ha}^{-1} \text{ yr}^{-1}$  for the past 50 yr. In addition, Histosols in the EAA can mineralize  $17\text{--}39 \text{ kg ha}^{-1}$  of plant-available P annually (Diaz et al., 1993). Even though total P levels were  $268 \text{ mg kg}^{-1}$  higher for cultivated than pasture soil, P transformations and cycling are likely more dynamic in cultivated soils due to fertilization, removal by crop harvest, and tillage, which affects P placement in the soil profile.

Rainfall is the primary P input for pasture, thus concentrations and distribution among chemical fractions should be more stable than cultivated soil. Characterization of soil P pools by sequential chemical fractionation methods is somewhat operationally-defined, but in general order of increasing recalcitrance are labile P, Fe–Al bound P, humic–fulvic acid P, Ca-bound P, and residual P pools (Reddy et al., 1998; Turner et al., 2005). Labile P represented water-extractable P, which is the standard test procedure for determining plant-available P for Histosols in the EAA. Both labile P and Fe–Al P concentrations did not differ between land uses (Table 1). The humic–fulvic acid fraction was higher for pasture, but the Ca and residual P fraction were highest for cultivated soil. Soil pH may have influenced P retention in the Ca and humic–fulvic acid fractions, as the higher pH of the cultivated soil (6.8) favored P retention in Ca fractions while the lower pH of pasture (5.3) favored P retention in the humic–fulvic acid fraction. Because of increases in soil Ca levels due to tillage (Sanchez and Porter, 1994; Snyder, 1994), P retention was enhanced in the Ca-bound P fraction of cultivated soils. The pasture soils had higher levels of humic and fulvic

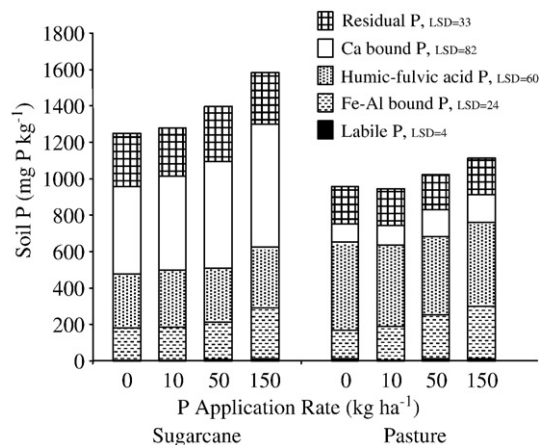


Fig. 1. Phosphorus concentrations of various chemical fractions for soils under sugarcane and pasture receiving different P fertilizer rates 21 d after application.

acids as reflected by the lower pH than cultivated soil, hence greater P retention in this organic fraction.

Long-term sugarcane cropping and fertilization significantly increased P levels in cultivated more than pasture soil, but fertilizer inputs were to a large degree offset by P removal in harvested biomass, hence the  $317 \text{ mg P kg}^{-1}$  difference in total P between land uses after 50 yr of cropping to sugarcane. Most of the P in pasture soil was in the organic fraction (78%), compared to only 52% for cultivated soil. In contrast, total P in inorganic forms averaged  $594 \text{ mg kg}^{-1}$  for cultivated soil but only  $194 \text{ mg kg}^{-1}$  for pasture. The differences in the P contents of inorganic fractions between land uses likely reflect P inputs by fertilization (Sanchez and Porter, 1994), and greater organic matter turnover rates for cultivated soil (Gesch et al., 2007). However, organic P averaged  $633 \text{ mg kg}^{-1}$  for cultivated soil and  $717 \text{ mg kg}^{-1}$  for pasture. Other studies in Histosols showed that natural areas had a greater proportion of total P in organic forms, while soils that changed land use had more P in inorganic pools (Graham et al., 2005). The greater P retention in organic fractions for pasture soil suggests that P cycling is dependent on the decomposition of organic matter, which is primarily affected by water management in the EAA (Snyder, 2005).

Future land use changes may include conversion of drained cultivated soils and pastures to the historic seasonally-flooded prairie ecosystem. Flooding of the pasture soil would have the effect of organic matter accretion (Moore and Reddy, 1994), thereby increasing P retention and stabilizing P held in organic pools. Thus, soils that have a higher proportion of their total P in organic forms would be less prone to release P, which would minimize P enrichment of proximal aquatic systems. In contrast, soils under cultivation had 48% of their total P in inorganic fractions, such as labile P, Fe–Al P, and Ca-bound P. Whereas flooding increases the stability of organic P, it has the opposite effect for mineral-associated P (Sanchez and Porter, 1994). The dissolution of P in inorganic pools is stimulated by the flooding of soil (Graham et al., 2005), thus these cultivated soils would likely be sources of labile P when converted back to historic seasonally-flooded prairies and may cause eutrophication of surface water and alteration of the structure and function of vegetation and microbial communities (Wright and Reddy, 2001; Childers et al., 2003).

#### 3.3. Soil phosphorus pools after fertilizer application

##### 3.3.1. Labile P

The short-term response of soil to added P can be used to assess the fate of P fertilizer in different chemical fractions and potential availability to crops. Labile P increased with P application, up from  $1.3$  to  $7.2 \text{ mg P kg}^{-1}$  for cultivated soils, and from  $1.4$  to  $10.7 \text{ mg P kg}^{-1}$  for pasture (Fig. 1). However, the proportion of total P as labile P increased from an average of 0.1% before P application to 0.5 and 1.1% of total P

Table 1  
Background properties of cultivated soil planted to sugarcane and pasture soil

Soil property	Units	Cultivated	Pasture	$P < 0.05$
pH		6.8	5.3	*
Water-holding capacity	%	142	196	*
Bulk density	$\text{g cm}^{-3}$	0.41	0.44	NS
Total organic C	$\text{g kg}^{-1}$	440	435	NS
Total N	$\text{g kg}^{-1}$	32	30	NS
C/N		14	15	NS
Extractable $\text{NH}_4\text{-N}$	$\text{mg kg}^{-1}$	158	246	*
Extractable $\text{NO}_3\text{-N}$	$\text{mg kg}^{-1}$	54	162	*
Total P	$\text{mg kg}^{-1}$	1227	959	*
Labile P	$\text{mg kg}^{-1}$	1.3	1.4	NS
Fe–Al bound P	$\text{mg kg}^{-1}$	143	113	NS
Humic–fulvic acid P	$\text{mg kg}^{-1}$	277	442	*
Ca-bound P	$\text{mg kg}^{-1}$	450	79	*
Residual P	$\text{mg kg}^{-1}$	356	275	*

Significant differences between mean values were noted by \* ( $P < 0.05$ ) and not significant (NS).

for cultivated and pasture soil, respectively (Fig. 2). Similar small contributions of labile P to total P were observed in other studies (Ivanoff et al., 1998; McGrath et al., 2001). Farming practices decreased the proportion of applied P recovered in plant-available forms (Fig. 3), as more of the applied P was held in non-labile pools. The percentage of applied P recovered in the labile pool decreased with increasing P application rate, and was higher for pasture than cultivated soil. These results have important implications for continuation of cultivation practices, or conversion of pasture to crop production, as cultivation decreased fertilizer P recovery in plant-available forms, necessitating greater fertilizer P requirements with increased farming intensity. Relationships between soil test P concentrations and crop response likely differ as a result of farming intensity, so that relationships developed for historic land uses may not be applicable for future soil conditions due to projected increases in soil Ca levels resulting from subsidence, which enhances P retention in pools not considered plant-available. Linear regression equations for predicted changes in soil P concentrations after fertilizer application differed between land uses (Table 2). A linear model best fit the data for cultivated soil, but the response of soil P concentrations to application rate best fit quadratic equations for pasture.

### 3.3.2. Fe–Al bound P

The size of the Fe–Al fraction increased with increasing P application rate for both land uses, but no significant difference between land uses was observed (Fig. 1). The size of the Fe–Al fraction increased linearly with increasing P rate from 166 mg P kg<sup>-1</sup> for unamended soil to 281 mg P kg<sup>-1</sup> at 150 kg P ha<sup>-1</sup>. The proportion of P in this fraction averaged 14% from 0 to 50 kg P ha<sup>-1</sup>, but significantly increased to 18% at 150 kg P ha<sup>-1</sup> for cultivated soil (Fig. 2). In contrast, the P content in the Fe–Al fraction increased with each incremental increase in application rate for pasture from 0 kg P ha<sup>-1</sup> (16 mg P kg<sup>-1</sup>) to 150 kg P ha<sup>-1</sup> (26 mg P kg<sup>-1</sup>), and the rate of increase was greater for pasture than cultivated soil. Soil from the pasture had significantly higher total Fe (15.6 g kg<sup>-1</sup>) than cultivated soil (3.2 g kg<sup>-1</sup>) (Ivanoff et al., 1998), likely because of crop uptake and removal of Fe from cultivated fields. In acidic soils, P precipitation by Fe and Al comprises the primary P retention mechanism (Sanchez and Porter, 1994). Thus, the higher Fe content for pasture contributed to a greater P retention capability. Soil subsidence has been shown to increase the exposure of Fe and Al minerals to P liberated from organic matter decomposition (Graham et al., 2005), which would explain the accumulation of P

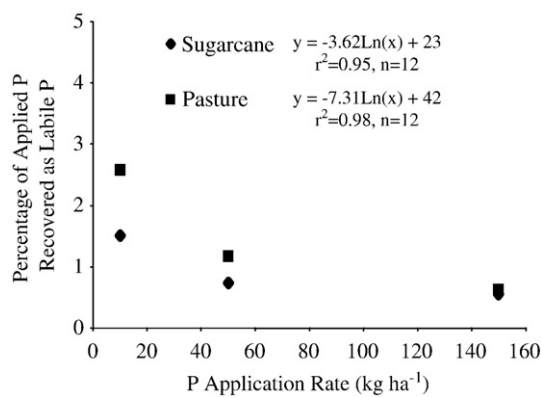


Fig. 3. The percentage of applied P fertilizer recovered in the labile pool 21 d after application as a function of the application rate.

fertilizer in the Fe–Al bound fraction in this study. The pasture soil developed a greater proportion of P in this fraction than cultivated soils when P application rates ranged from 10 to 150 kg P ha<sup>-1</sup>. Thus, less P retention in the Fe–Al fraction occurred in cultivated soils presumably as a result of low Fe concentrations and high Ca levels. Less P held in this fraction for cultivated soils indicated that most of applied P is sequestered in other inorganic pools, such as the Ca-bound P fraction. Accumulation of P in this fraction in pasture may pose problems as P is unstable when associated with Fe and Al under fluctuating redox conditions (Sanchez and Porter, 1994). The flooding of soil tends to lead to dissolution of Fe and Al phosphates and increased labile P availability, thus establishment of the traditional seasonally-flooded wet prairie ecosystem may actually lead to P release from pasture soils currently managed under drained conditions. However, under current land use, the P bound to Fe and Al oxides is largely considered unavailable to plants (McGrath et al., 2001).

### 3.3.3. Ca-bound P

The major difference in P distribution between land uses occurred with the Ca–P bound fraction. The P content in this fraction increased 40% from 0 to 150 kg P ha<sup>-1</sup> for cultivated soil, but 56% for pasture soil for this P application rate range (Fig. 1). For cultivated soil, P increased 38, 105, and 194 mg kg<sup>-1</sup> soil after addition of 10, 50, and 150 kg P ha<sup>-1</sup>, respectively. For pasture soil, P increased 12, 55, and 55 mg P kg<sup>-1</sup> for these P application rates. Farming practices thus increased the amount

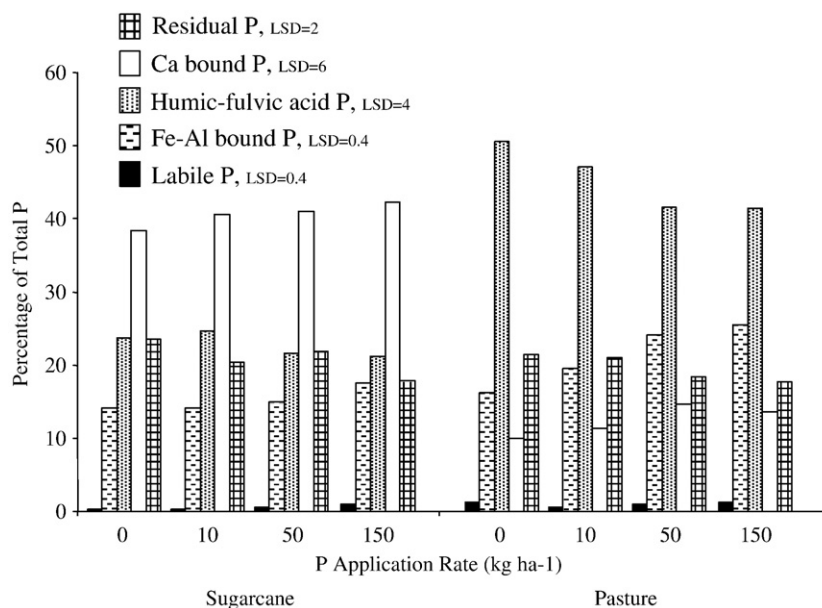


Fig. 2. The percentage of each chemical fraction of total P for cultivated soil cropped to sugarcane and pasture soil.

**Table 2**  
Equations predicting the percentage increase in concentrations of different soil fractions after P fertilizer addition

Land use	Equation	r <sup>2</sup>
<i>Cultivated soil</i>		
Labile P	$y = 6.63x + 166$	0.999
Fe–Al bound P	$y = 0.47x + 22$	0.997
Humic–fulvic acid P	$y = 0.073x + 10$	0.662
Ca-bound P	$y = 0.27x + 12$	0.949
Residual P	$Y = 0.01x - 20$	0.016
<i>Pasture soil</i>		
Labile P	$y = 0.029x^2 - 1.70x + 708$	0.460
Fe–Al bound P	$y = -0.0083x^2 + 2.02x + 44$	0.998
Humic–fulvic acid P	$y = 0.0024x^2 - 0.39x + 8$	0.819
Ca-bound P	$y = -0.0096x^2 + 1.92x + 20$	0.997
Residual P	$y = -0.0011x^2 - 0.19x - 24$	0.984

$y$  = percentage increase in P concentration,  $x$  = application rate (kg P ha<sup>-1</sup>),  $n$  = 16.

of P held in the Ca-bound fraction relative to pasture soil, possibly due to a higher pH which facilitated P retention by Ca (Perrot, 1992; Sanchez and Porter, 1994; Ivanoff et al., 1998) with increasing application rate. The lower pH of pastures soils may have retarded P association with Ca and decreased P retention in this pool relative to cultivated soil. The greatest differences between land uses occurred in the background P concentration in the Ca-bound fraction, which was 470% greater for cultivated than pasture soil (Table 1). The proportion of P in the Ca fraction to total P increased to 41% for cultivated soil and 12% for pasture soil after P application. Since P retained by the Ca-bound fraction is considered relatively unavailable under current land management conditions, and since more of the applied P was sequestered in this fraction for cultivated than pasture soil, higher P fertilizer rates will be necessary for projected increased soil Ca levels in the future resulting from subsidence. However, the higher P retention in cultivated soils may have an advantage of minimizing potential for runoff or leaching as long as the soils remain drained. However, conversion of cultivated land to wet prairies and the onset of flooded conditions may increase P regeneration from inorganic fractions (Sanchez and Porter, 1994; Graham et al., 2005).

### 3.3.4. Humic–fulvic acid P

The humic–fulvic acid fraction represents P associated with organic matter or as part of decomposed plant material. This generally represents a stable fraction since these organic soils developed under flooded conditions which accumulated organic matter. However, for the past 100 yr, these organic soils were drained for agricultural use, thus subsequent soil subsidence has resulted in shallower soils and enhanced organic matter decomposition rates (Morris and Gilbert, 2005; Snyder, 2005). Thus, in current cultivated and pasture systems, organic matter decomposition exceeds the rate of organic matter deposition, so there likely is a large turnover of humic–fulvic acid P for both land uses.

Fertilizer P was not entering the humic–fulvic acid pool. Soil P concentrations in the humic–fulvic acid fraction were not affected by P application rate, but were significantly higher for pasture than cultivated soils (Fig. 1). Farming practices likely enhanced organic matter decomposition relative to pasture due to greater soil disturbance by tillage, which physically destructed soil organic matter and improved aeration, and incorporated crop residues into soil. However, organic acids may accumulate in pasture soil as evidenced by lower pH and higher humic–fulvic acid P, thus P turnover in this pool would theoretically be less than cultivated soil. The percentage of the humic–fulvic acid pool of total P was not affected by the P application rate for cultivated soil, but significantly decreased with increasing application rate for pasture (Fig. 2). Because of no prior fertilization for pasture, heterotrophic microorganisms may have been limited by P, thus fertilization may stimulate organic matter decomposition and P miner-

alization (Wright and Reddy, 2001), resulting in lower concentrations in humic–fulvic acid fractions and higher concentrations in Fe–Al and labile fractions. These results are supported by our data showing increases in labile P and Fe–Al bound P with increasing P rate to a greater extent for pasture than cultivated soils.

### 3.3.5. Residual P

Residual P is the fraction remaining after the sequential chemical extraction of soil, and is defined as non-labile or the most resistant P fraction (Turner et al., 2005). The residual P pool is characterized by stable lignin and organo-metallic complexes (Ivanoff et al., 1998), and averaged 20% of the total P (Fig. 1). The P concentration did not vary with application rate for either land use, but was significantly higher for cultivated than pasture soil due to higher levels in unamended soil. However, the proportion of residual P of total P decreased with increasing P application rate (Fig. 2) as a result of more of the applied P being sequestered in inorganic fractions, mainly the Fe–Al fraction for pasture and Ca-bound fraction for cultivated soil. Because residual P contains approximately 20% of the total P, small changes in the size of this pool could significantly influence P concentrations in the much smaller labile fraction, which comprises only 1% of the total P. In fact, tillage and sugarcane cropping systems enhanced oxidation of organic soils and promoted subsidence (Morris et al., 2004; Gesch et al., 2007), which likely enhanced organic P mineralization from the humic–fulvic acid to inorganic pools.

## 4. Conclusions

The distribution of P among soil chemical fractions differed between land uses, with greater levels observed in Ca-bound P fractions for cultivated soil and in humic–fulvic acid fractions for pasture soil. Continuation of conventional crop management practices will likely further increase soil pH and Ca levels, leading to greater recovery of applied P fertilizer in the Ca-bound P fraction and a decrease in the proportion of applied P recovered in the labile fraction. Soil pH appeared to influence P distribution among chemical fractions by increasing concentrations in Ca-bound fractions for high pH cultivated soils, while increasing concentrations in humic–fulvic acid fractions for the low pH pasture soil. Likewise, concentrations of mineral elements influenced P distribution, as soil Ca of cultivated soils enhanced P retention, while higher Fe levels stimulated P retention in Fe–Al fractions for pasture. Sequestration of P in stable, inorganic pools under current land uses would necessitate higher fertilizer P rates in the future to offset retention in plant-unavailable pools and to maintain plant-available P at concentrations sufficient for crop production. Phosphorus fertilizer distribution differed between land uses, as most of the applied P was recovered in the Fe–Al fraction for pasture and the Ca-bound fraction for sugarcane. Phosphorus addition and accumulation in inorganic pools may be unstable and ultimately result in dissolution of P upon onset of flooded conditions that may occur during high rainfall events or conversion back to the original wet prairie ecosystem. Since most of the P in pasture soil was in organic fractions, flooding of these soils would decrease organic matter decomposition, thus most P would be stable. In contrast, about half of the P in cultivated soils was present in inorganic pools, thus stability would depend more on redox chemistry since flooding increases the regeneration of P retained in inorganic pools. Thus, the conversion of current land uses to wet prairies may have a more dramatic effect on P regeneration from cultivated than pasture soil since cultivated soil has more P in unstable, inorganic pools.

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