RESEARCH ARTICLE

Soil phosphorus stocks and distribution in chemical fractions for long-term sugarcane, pasture, turfgrass, and forest systems in Florida

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Abstract Phosphorus distribution and stability in soils of the Everglades Agricultural Area (EAA) of south Florida is important because of changing land uses. We investigated the effects of land use on P distribution in the soil profile and between chemical fractions for a histosol of the Florida Everglades. Labile, Fe–Al bound, Ca-bound, humic–fulvic acid, and residual P pools in 0–15, 15–30, and 30–45 cm depths were determined for drained soils planted to sugarcane (*Saccharum* sp.) for 50 yr, pasture for 100 yr, turfgrass for 60 yr, and forest for 20 yr. The P concentrations of all chemical fractions decreased with depth in the profile, indicating accumulation in surface soil resulting from oxidation and fertilization. Trends in P distribution between chemical fractions were similar between land uses. Labile P comprised less than 1% of total P. Fe–Al bound P averaged 2.9% of the total P for turfgrass and forest, but 11.4 and 9.6% for sugarcane and pasture. Increasing soil disturbance and long-term fertilization increased P allocation to inorganic fractions, as Ca-bound P contained 49% of total P for sugarcane but 28% for other land uses. Total P stocks in the soil profile (0–45 cm) averaged 1,323, 2,005, 2,294, and 2,317 kg P ha^{-1} for pasture, sugarcane, turfgrass, and forest, respectively. Under current land uses P in organic fractions represents an unstable pool since the soil is prone to oxidation under drained conditions. In contrast, P sequestered in inorganic fractions is more stable under current land uses, thus sugarcane cultivation and incorporation of bedrock $CaCO_3$ into surface soil by tillage will enhance long-term P sequestration.

Keywords Everglades Agricultural Area · Land use · Phosphorus fractionation · Phosphorus sequestration

Introduction

The histosols in the Everglades developed as seasonally-flooded sawgrass prairies, but a major shift in land use in the past century resulted in their conversion to agriculture. The EAA of south Florida primarily consists of drained organic soils subjected to vegetable and sugarcane cropping for 100 years (Shih et al. 1998). The conversion of the seasonally-flooded prairie ecosystem to various land uses under drained conditions altered nutrient cycling and distribution (Snyder 2005). A further result of land use change was subsidence, or oxidation of the soil organic matter, at rates currently approximating 1.5 cm yr^{-1} (Shih et al. 1998; Snyder 2005).

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A result of long-term fertilization and soil oxidation is the export of mineralized nutrients from the EAA through canals into Everglades wetlands, which has been implicated in causing deterioration of water quality and alterations to the natural ecosystem (Childers et al. 2003). However, factors affecting P stability and retention in chemical fractions and distribution in the soil profile may vary between land uses. Phosphorus in organic pools indicates long-term sequestration potential under flooded conditions, but may be unstable under drained conditions due to soil oxidation and organic P mineralization (Sanchez and Porter 1994). Decomposition of organic P, as found in humic and fulvic acids, and lignin-containing residual fractions, depends on heterotrophic microbial activity, thus these pools are more stable under flooded conditions since decomposition rates are lower in the absence of O_2 (Wright and Reddy 2008). Phosphorus sequestered in inorganic fractions is stable under the drained conditions of current land uses in the EAA, but may be unstable upon flooding and stimulate P regeneration from mineral-bound pools (McGrath et al. 2001).

Fractionation schemes have been developed to assess P distribution in chemical fractions related to their degree of recalcitrance (Ivanoff et al. 1998; Reddy et al. 1998; Turner et al. 2005; Castillo and Wright 2008). Soils with a high proportion of P in labile pools indicate greater potential availability to plants but also greater export by leaching or runoff. Phosphorus adsorbed or precipitated with Ca, Fe, and Al is stable when soils are maintained under conditions leading to P fixation, but may be susceptible to dissolution and regeneration upon change in land use or environmental conditions. Of particular concern are land use changes that disturb soil and alter redox reactions, which enhance P regeneration and potential for leaching and runoff (Moore and Reddy 1994).

Future land use changes in the Everglades involve reestablishment of the historic seasonally-flooded prairies on drained, cultivated soil. For these future uses, management practices that increase P retention in inorganic pools may pose a eutrophication hazard (Moore and Reddy 1994; Sanchez and Porter 1994). The distribution of P within chemically-defined pools, such as labile, inorganic, and organic fractions, provides an indication of the potential stability of P in soil which may differ between land uses. The objectives of this study were to determine the soil-profile distribution of P and allocation between chemical fractions for multiple land uses of histosols in the EAA.

Materials and methods

Site description

The EAA (280,000 ha) is characterized by subsiding histosols underlain by limestone bedrock (Snyder 2005). The study sites are located in the northern EAA near Belle Glade, FL (26°39′ N, 80°38′ W). The long-term average annual temperature is 24°C and precipitation 133 cm. The soils are classified as Dania muck (euic, hyperthermic, shallow Lithic Medisaprists) with depth to bedrock of approximately 45 cm. These organic soils developed under seasonal flooding and low nutrient status and supported vegetation adapted to these conditions, primarily sawgrass (*Cladium jamaicense* Crantz). Due to conversion to agricultural use by drainage, the dominant vegetation shifted to annual crops of vegetables and sugarcane (*Saccharum* sp.) in the early 1900s.

The four land uses studied include sites under sugarcane cultivation for approximately 50 years, perennial pasture for 100 years, forest for 20 years, and turfgrass for 60 years. All land uses were under similar water management with soil being drained for most of the year. Soil oxidation generally provides the necessary nutrients for plant growth, so fertilizers were only applied to sugarcane. Management practices for the sampled sites were representative of the respective land uses in the EAA.

The cultivated fields were managed for vegetable production since the early 1900s to the 1950s but predominantly for sugarcane since the 1950s. Typical fertilization for sugarcane is 40 kg P ha^{-1} yr^{-1} (Gilbert and Rice 2006) using a one-time application prior to planting. Sugarcane is planted from August through January and harvested from October through April. Tillage operations include several diskings (to 15 cm depth) after crop harvest, subsoil chiseling (to 30 cm depth) to improve drainage, and frequent in-season tine cultivations (to 4 cm depth) for weed control (Morris et al. 2004). The pasture sites were primarily established by paragrass [*Panicum purpurascens* (L.) Raddi] and bermudagrass [*Cynodon*

dactylon (L.) Pers], received no historic fertilization or tillage, and were mowed with residues returned to soil. The forested sites were planted to bald cypress (*Taxodium distichum*) and pond cypress (*Taxodium ascendens*) around 1988 on soils previously cropped to sugarcane. Spacing between trees was approximately 4 m, and fields received no fertilization since the land use change from sugarcane. The sites were extensively tilled prior to seedling establishment, but no further management occurred. St. Augustinegrass [*Stenotaphrum secundatum (Walt) Kuntze*] turf was established on former cultivated fields in the mid 1940s. Fields were periodically mowed with residues returned to soil, and no fertilizers have been applied since establishment.

Soil sampling and analysis

Triplicate soil cores (5-cm diam.) were taken to bedrock (0–45 cm) and sectioned into 0–15, 15–30, and 30–45 cm depth intervals at four sites for each land use and composited to yield four field replicates for each land use. Soils were sampled in January 2006 prior to sugarcane harvest and analyzed for bulk density (Blake and Hartge 1986) and pH using a 1:3 soil to 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 a factor of 0.51 (Anderson 1976). Total organic N was measured by Kjeldahl digestion followed by NH_4 analysis (Bremner 1996).

The distribution of P in soil was determined using a modified sequential chemical fractionation procedure (Qualls and Richardson 1995; Ivanoff et al. 1998; Reddy et al. 1998). Approximately 1 g soil was extracted with 25 ml water for 1 h, passed through 0.45 μm filters, 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-P*i* (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-P*i* (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 0.1 N NaOH extract with 11 N H_2SO_4 for 4 h at 350°C (NaOH-TP), and subtraction of the NaOH-P*i* from the NaOH-TP. Total P was measured by colorimetric analysis (U.S. EPA method 365.4) after

Kjeldahl digestion (Bremner 1996). The P content of extracts was measured using the ascorbic acid-molybdenum blue method (Kuo 1996) with an AQ2+ discrete analyzer (Seal Analytical Inc., Mequon, WI).

A randomized experimental design was utilized with four land uses, three soil-depth intervals, and four field replications (CoStat Statistics Software 2005). A three-way ANOVA model was used to determine main effects of land use, soil depth interval, and chemical fraction. A one-way ANOVA model was used to determine differences between individual treatments for chemical fractions and soil depth. Significant treatment comparisons were based on Fisher's LSD at $\alpha = 0.05$.

Results and discussion

Soil characterization

Soil bulk density did not vary between land uses but significantly increased with depth in the profile from 0–15 (0.44 g cm^{-3}) to 30–45 cm (0.53 g cm^{-3}). Total C did not vary with depth or between land uses and averaged 404 g C kg^{-1}. Total N did not vary with depth but was significantly higher for cypress (48 g N kg^{-1}) than other land uses (31 g N kg^{-1}). Soil pH did not vary with depth in the profile except for pasture, which increased from 5.3 at 0–15 cm to 6.8 at 30–45 cm (Fig. 1).

Labile P

The P concentrations of inorganic (Fig. 2) and organic fractions (Fig. 3) varied between land uses. Labile P represents the most biological available form of P, and for this soil had the lowest concentration of all chemical fractions. Labile P was highest at 0–15 cm and decreased with depth in the profile, and was generally highest for turfgrass and cypress (Fig. 2). For all land uses, labile P averaged less than 0.5% of total P (Fig. 4), which was consistent with other studies in the Everglades for canal sediments (Diaz et al. 2006) and wetlands (Reddy et al. 1998). Throughout the soil profile to bedrock (0–45 cm), labile P constituted a total of 11.5 and 7.3 kg P ha^{-1} for cypress and turfgrass, respectively, which was significantly higher than labile P stocks for sugarcane (2.7 kg P ha^{-1}) and pasture (1.6 kg P ha^{-1}) (Fig. 5).
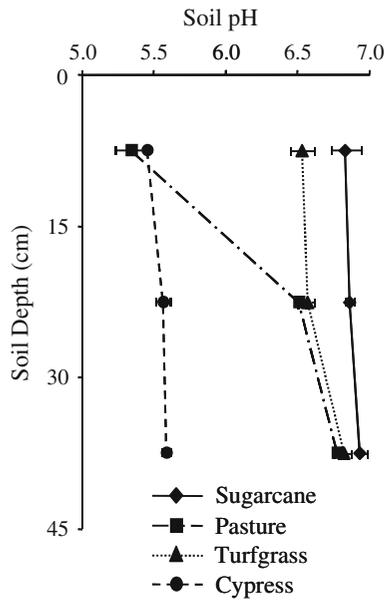
Fig. 1 The soil pH distribution with depth for sugarcane, pasture, turfgrass, and cypress. Bars represent the standard error of the mean

Fe–Al bound P

The Fe–Al bound fraction contains P associated with amorphous oxyhydroxide surfaces and crystalline Fe and Al oxides. The P contained in this fraction may be unstable with fluctuating redox conditions (Moore and Reddy 1994), thus there may be considerable movement of P into and out of this fraction

Fig. 3 Depth distribution of organic P fractions for soil under sugarcane, pasture, turfgrass, and cypress. Bars represent the standard error of the mean

depending on environmental conditions for these soils. For all land uses, this fraction had the second lowest P content of all chemical fractions (Fig. 2). The calcareous nature of this histosol tended to promote the sequestration of P into the Ca-bound rather than the Fe–Al bound fraction. The Fe–Al bound P was significantly higher for sugarcane than other land uses throughout the soil profile. Cypress had higher P in this fraction than turfgrass and pasture from 0–30 cm, whereas no difference

Fig. 2 Depth distribution of labile, Fe–Al bound, and Ca-bound P concentrations for soil under sugarcane, pasture, turfgrass, and cypress. Bars represent the standard error of the mean
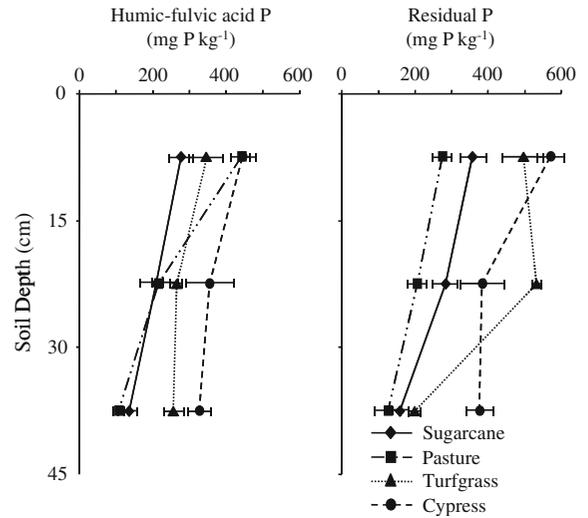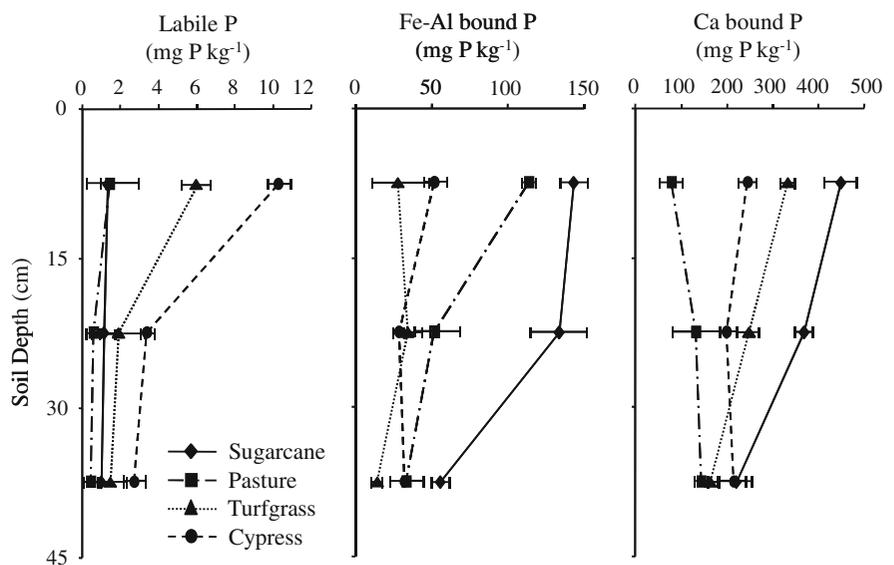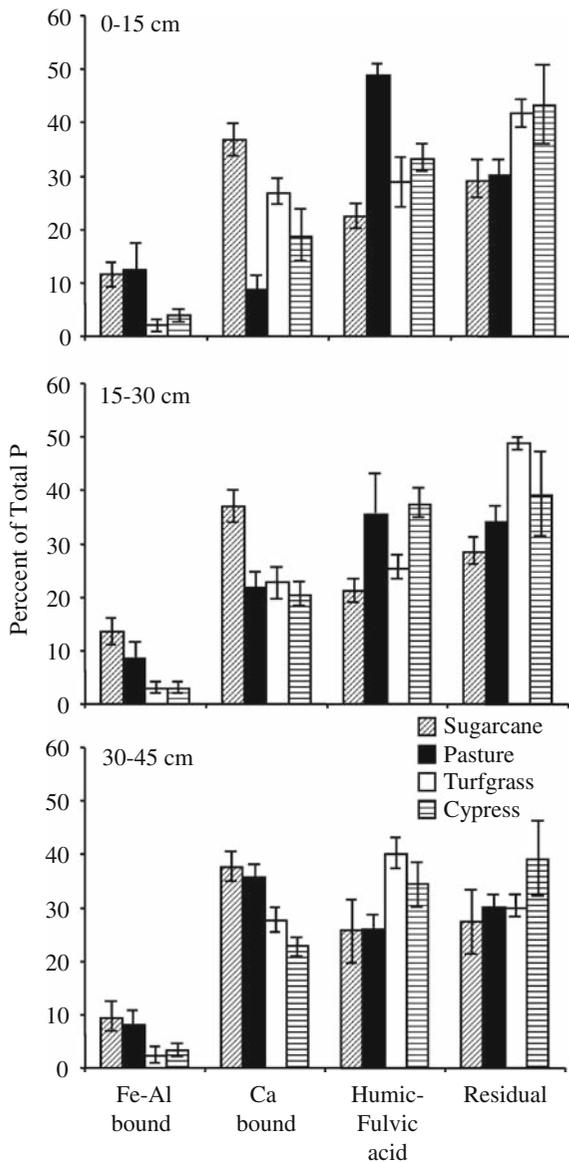
Fig. 4 The contribution of chemical fractions to total P for soil under sugarcane, pasture, turfgrass, and cypress. Bars represent the standard error of the mean
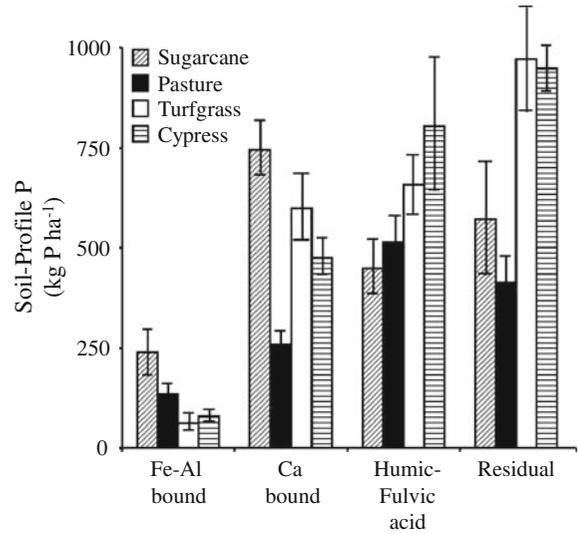

Fig. 5 The total soil-profile P storage in each chemical fraction for soil under sugarcane, pasture, turfgrass, and cypress. Labile P storage averaged 2.7, 1.6, 7.3, and 11.5 kg P ha^{-1} for sugarcane, pasture, turfgrass, and cypress, respectively. Bars represent the standard error of the mean

The contribution of Fe–Al bound P to total P was significantly lower than organic fractions and the Ca-bound fraction. The proportion of total P as Fe–Al bound P decreased with depth in the profile for pasture and sugarcane, but not for other land uses.

Similar to labile P, Fe–Al bound P tended to accumulate in surface soil. Since Fe–Al bound and labile fractions represent the least recalcitrant pools, P in these pools likely represents recent inputs from fertilizer, rainfall, or P mineralized from organic matter, which explains accumulation at the 0–15 cm depth. The total P stocks in the Fe–Al bound fraction were significantly higher than labile P but lower than the Ca-bound and organic P fractions, and were highest for sugarcane and lowest for turfgrass and cypress (Fig. 5).

Ca-bound P

The Ca-bound fraction contained more P than other inorganic fractions as a result of high Ca levels throughout the soil profile (Ivanoff et al. 1998). Phosphorus adsorption and precipitation with Ca represents a more stable pool than labile and Fe–Al bound fractions (Diaz et al. 2006), thus P held in Ca-bound fraction poses less of an eutrophication hazard. In fact, excess P fertilizer is often sequestered

between turfgrass and pasture were observed at any depth interval. In contrast, P concentrations decreased with depth for sugarcane and cypress. The P concentration in this fraction averaged less than 3.5% of the total P for turfgrass and cypress, but 11.4 and 9.6% of the total P for sugarcane and pasture, respectively (Fig. 4). In canal sediments that collected runoff from the EAA, the Fe–Al fraction contained up to 27% of the total P (Diaz et al. 2006).

in inorganic fractions, as P concentrations in the Ca-bound fraction were higher for sugarcane than other land uses not receiving fertilizer (Fig. 2). Sugarcane was the most intensively managed land use with multiple tillage operations and annual P fertilization, thus the higher contribution of Ca-bound P to total P for sugarcane than other land uses (Fig. 4). A similar trend was observed for Everglades canal sediments (Diaz et al. 2006). The Ca-bound fraction typically had a lower proportion of P than organic fractions for turfgrass and cypress. Total soil-profile P stocks in the Ca-bound fraction were significantly highest for sugarcane (745 kg P ha^{-1}) and lowest for pasture (259 kg P ha^{-1}), which corresponded with management intensity (Fig. 5). The pasture had the lowest Ca-bound P concentrations because it was the least disturbed land use, and the percentage of total P as Ca-bound P significantly increased with depth (Fig. 4). This result for pasture was in contrast to the other three land uses.

Changes in Ca-bound P concentrations with depth indicate upward flux or translocation of Ca from subsurface to surface soils (Sanchez and Porter 1994) and sequestration of P, thus the decrease with depth in Ca-bound P for sugarcane. Tillage redistributes Ca from subsurface to surface soils (Snyder 2005), thereby increasing potential P sequestration in Ca-bound fractions. Increasing Ca contents of this histosol and effects on P sequestration into pools unavailable to plants may result in higher fertilization rates necessary to maintain labile P at concentrations sufficient to crops.

Humic–fulvic acid P

The organic pools are characterized by humic and fulvic acids and the more recalcitrant residual pools, primarily comprised of lignin (Reddy et al. 1998; Turner et al. 2005). In contrast to inorganic pools where concentrations were highest for sugarcane, P concentrations in organic pools were generally lower for sugarcane than other land uses (Fig. 3). Cypress and turfgrass had the highest humic–fulvic acid P concentrations throughout the soil profile. Concentrations decreased with depth for all land uses, with the greatest rate of decrease occurring for pasture. Humic–fulvic acid P was higher than Ca-bound P concentrations for pasture and cypress, were the same for turfgrass, but lower for sugarcane. The percentage

of humic–fulvic acid P to total P decreased with depth for pasture but not for other land uses (Fig. 4). Pasture soil had more of its total P in this fraction than other land uses at 0–15 cm, indicating a more decomposed organic material. Other studies in histosols showed that natural areas had a greater proportion of total P in organic forms, while disturbed soils that changed land use had more P in inorganic pools (Graham et al. 2005). For turfgrass and cypress, more P was contained in the humic–fulvic acid fraction than the Ca-bound fraction. The total P stocks in this fraction for significantly lower for pasture (481 kg P ha^{-1}) than turfgrass and cypress (Fig. 5).

Residual P

The residual fraction is generally considered to be a stable and recalcitrant chemical fraction (Turner et al. 2005), but under current land uses in the EAA represents an unstable P pool due to organic matter oxidation. Residual P concentrations were lowest for pasture and sugarcane and highest for cypress and turfgrass, and generally decreased with depth in the profile (Fig. 3). For all land uses except pasture, the residual fraction had higher P concentrations than the humic-acid fraction. Pasture soils were characterized by higher levels of oxidation due to higher soil temperatures resulting from low canopy cover (Shih et al. 1982), which increased microbial activity, P regeneration, and potential for P export from fields as sediment-bound or soluble reactive P (Daroub et al. 2003). These results were reflected in the lower residual P content for pasture than other land uses, which upon decomposition increases the size of the humic–fulvic acid P fraction. In contrast to other chemical fractions, the percentage of residual P to total P did not vary with depth for any land use (Fig. 4). Total P stocks in the residual fraction were higher for turfgrass (970 kg P ha^{-1}) and cypress (947 kg P ha^{-1}) than sugarcane and pasture (Fig. 5).

Comparison of P distribution between land uses

Soil total P stocks in the entire soil profile of 0–45 cm averaged 2,005, 1,323, 2,294, and 2,317 kg P ha^{-1} for sugarcane, pasture, turfgrass, and cypress, respectively. The 0–15 cm depth retained more P than lower depth intervals (Fig. 6). In addition to total P
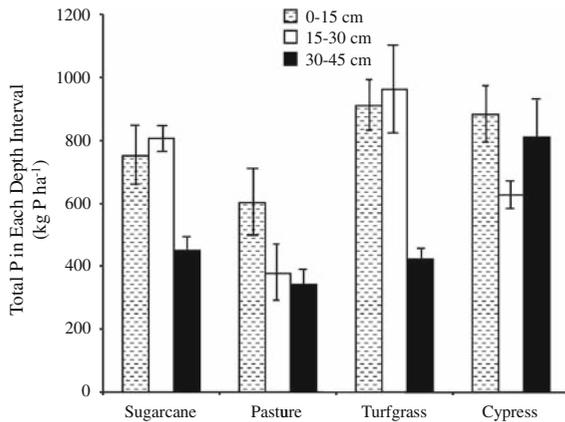
Fig. 6 Total P stocks for each soil depth interval for soil under sugarcane, pasture, turfgrass, and cypress. Bars represent the standard error of the mean

storage differences between land uses, the distribution of P with depth and between chemical fractions (Figs. 2 and 3) varied between land uses. Sugarcane had a greater percentage of its total P in inorganic fractions (49%) compared to other land uses (28%). Thus, intensive fertilization and management increased P sequestration in inorganic fractions. Other studies have also shown that cultivation increases P retention in mineral-associated pools (McGrath et al. 2001). The increasing calcification of soil by tillage and distribution of underlying limestone throughout the soil profile by cultivation encouraged P retention in the Ca-bound fraction, which represents a stable long-term pool (Reddy et al. 1998) under current land use. Land uses with minimal management and no fertilization, such as turfgrass and forest, sequestered more P in organic pools. However, under current land use and environmental conditions conducive to soil oxidation, organic P is not considered a stable pool and may eventually be lost from fields.

Oxidation has been occurring since these soils were drained for agricultural use in the early 1900s (Snyder 1994). The current rate of soil oxidation is approximately 1.5 cm yr^{-1}, with soil loss primarily attributed to oxidation of organic matter (Shih et al. 1998; Snyder 2005). Soil oxidation rates were reported to be more dependent on water table depth than land use (Snyder 2005). Soil loss by organic matter oxidation primarily affects the surface depths because the water table often inundates the subsurface, creating anaerobic conditions and lowering

organic matter decomposition rates (Snyder 1994). At the current rate of soil oxidation, approximately 60–90 kg P ha^{-1} is generated, which is similar to prior projections of 87 kg P ha^{-1} yr^{-1} made in 1975 (Morris 1975). The amount of P generated by soil oxidation is greater than typical P fertilization rates to sugarcane of 40 kg P ha^{-1} (Gilbert and Rice 2006) and P removed as harvested biomass (23 kg P ha^{-1}) (Coale et al. 1993). Plant biomass is not harvested for other land uses, so P inputs accumulate in soil but with potential losses occurring as runoff or leaching (Daroub et al. 2003). These soils were indeed sources of P to proximal aquatic systems as runoff in solution and as sediment-bound (Daroub et al. 2003), which caused eutrophication of downgradient wetlands (Childers et al. 2003). Phosphorus runoff from cultivated soil can range up to 8.9 kg P ha^{-1} yr^{-1} (Rice et al. 2002), which is similar to leaching losses of 8.2 kg P ha^{-1} yr^{-1} (Sanchez and Porter 1994). Since fertilized soil under sugarcane had the same total P stocks as unfertilized soil under turfgrass and cypress, long-term fertilization did not appear to enhance total P storage, although it did alter the distribution between chemical fractions.

Phosphorus concentrations of chemical fractions generally decreased with depth in the profile. Higher P levels at 0–15 cm reflect the accumulation of P inputs from organic P mineralization and soil oxidation. Lower total P stocks for the low pH pasture soil indicated poor P retention in Ca-bound fractions. The lower pH of pasture indicates less effect of soil disturbance and calcification, and thus lower potential for P sequestration. Moreover, the lower P levels for pasture compared to other land uses may result from higher rates of soil oxidation (Shih et al. 1982) and subsequent runoff of mineralized P. A dense canopy cover, as occurred for sugarcane and cypress, decreased soil temperature, microbial activity, and soil oxidation rates by 16% compared to pasture (Shih et al. 1982). The lower soil temperature under canopy also decreased soil organic P mineralization and potential for loss of P as runoff or leaching. Less vegetative coverage of soil and the greater exposed areas of pasture sites compared to other land uses were responsible for higher temperatures and soil oxidation (Shih et al. 1982), which likely resulted in greater runoff of mineralized P and subsequently lower P stocks (Fig. 6). Thus, land uses that have good canopy cover, including forest systems,

sugarcane cropping, and turfgrass, promoted higher total P stocks and lower soil oxidation rates.

Conclusions

Soil total P storage varied with depth in the profile and between land uses, with the major factors affecting P stocks and distribution being fertilization and soil oxidation. Effects of soil oxidation include mineralization of organic P following by accumulation in mineral-associated fractions. Soil P concentrations for both inorganic and organic fractions decreased with depth, even for unfertilized soils. These results indicate that soil oxidation led to P accumulation in surface soils regardless of land management or fertilization history. Labile and Fe–Al associated P fractions comprised a relatively small percentage of the total soil P. Cultivation to sugarcane and long-term fertilization increased P retention in mineral-associated fractions, particularly the Ca-bound fraction. The higher inorganic P stocks for sugarcane indicates a more stable pool under current land uses since Ca-bound fraction is not affected by soil oxidation. In fact, tillage increased soil Ca levels and enhanced the potential for long-term P sequestration for sugarcane cropping. The P retained in organic fractions may not be stable and in fact may pose a long-term eutrophication hazard due to runoff of the P generated by oxidation. With the exception of pasture, total P stocks were similar between land uses, although differences in distribution among chemical fractions were observed. Higher rates of oxidation of pasture soil and resulting lower P stocks appeared related to its low canopy cover which increased soil temperature and oxidation, followed by P loss from fields.

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