

Phosphorus sequestration in soil aggregates after long-term tillage and cropping

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ABSTRACT

Cultivated soils in the Everglades are being converted to their historic use as pastures or seasonally flooded prairies as parts of restoration efforts, but long-term cultivation may have altered soil P distribution and availability which may pose eutrophication hazards upon change in land use. The objectives of this study were to determine the distribution of P in soil chemical and physical fractions for contrasting long-term land management practices. The distribution of P in labile, Fe–Al bound, Ca bound, humic–fulvic acid, and residual pools in five aggregate-size fractions were measured for fields under sugarcane (*Saccharum* sp.) cropping for 50 years and perennial pasture for 100 years. Both land uses were characterized by a high degree of macroaggregation, as aggregates >0.25 mm contained 76 and 83% of the total soil under cultivation and pasture, respectively. Soils under sugarcane sequestered a total of 77 kg ha⁻¹ more P than pasture at 0–15 cm. The distribution of P in chemical fractions significantly varied between land uses as cultivation increased P sequestration in Ca-bound fractions more for sugarcane (244 kg P ha⁻¹) than pasture (65 kg P ha⁻¹). Pasture sequestered more P in organic pools, as storage in humic–fulvic acid and residual fractions were 26 and 25%, respectively, higher than sugarcane. Labile P was 100% higher for pasture than sugarcane, but Fe–Al bound P storage did not differ between land uses. Aggregation increased P sequestration in humic–fulvic acid and residual fractions, and P storage in organic pools increased with increasing aggregate size. In contrast, cultivation decreased aggregation and increased P accumulation in inorganic fractions. Long-term cultivation altered the distribution of soil P from organic to inorganic pools. The P stored in inorganic pools is stable under current land use, but may be unstable and pose eutrophication hazards upon onset of future land use change to the seasonally flooded prairie ecosystem.

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1. Introduction

The effects of cropping systems and land use changes on soil organic matter dynamics are well-documented due to utilization of soil for sequestration of atmospheric C. Mechanisms to increase soil organic matter levels include diversified cropping systems, residue management, and no tillage regimes, which tend to increase organic matter storage in aggregates (Tisdall and Oades, 1982; Jastrow, 1996). Most studies have shown lower soil organic matter levels for cropping systems that cause disturbance, as tillage enhances the decomposition of plant residues and organic matter and stimulates aggregate turnover (Six et al., 1998; Wright and Hons, 2005). Differentiation of soils by aggregate-size distribution can be used to assess impacts of land use since organic matter can be protected from decomposition within aggregates (Jastrow, 1996; Six et al., 1998). Land management practices that increase aggregation and organic matter levels may

also increase P retention and stability. Effects of aggregation on P sequestration in chemical fractions may illustrate how land use influences P distribution and stability in soil.

The histosols in the Everglades developed under seasonally flooded conditions and were dominated by sawgrass (*Cladium jamaicense*) 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. This region, referred to as the Everglades Agricultural Area (EAA), primarily consists of organic soils cropped for approximately 100 years (Shih et al., 1998). The conversion of this seasonally flooded prairie ecosystem to an annual cropping system altered nutrient cycling and distribution in soil (Snyder, 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 year⁻¹ (Shih et al., 1998; Snyder, 2005).

An emerging interest for the protection of water quality and the unique Everglades ecosystem is the conversion of agricultural lands to their prior use as seasonally flooded prairies. However, the impacts of long-term cropping on P dynamics in these soils may necessitate extensive management or remediation before onset of land use change, especially since these soils developed under

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nutrient-poor conditions. A result of long-term P fertilization and soil subsidence is the export of P from the EAA through canal systems into Everglades wetlands, which has been implicated in causing deterioration of water quality and alterations to the natural ecosystem (Childers et al., 2003). 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). Whereas P sequestered in inorganic P pools is stable under drained conditions, it may be unstable upon flooding and conversion to seasonally flooded prairies since flooding can stimulate the release of mineral-bound P (McGrath et al., 2001). However, P stability may increase with increasing aggregation. Thus, it is important to understand the factors affecting P distribution and aggregation for different land uses to minimize export from soil upon onset of change in land use.

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). Soils with a high proportion of P in labile pools indicate greater potential availability to plants, but also greater potential export by leaching or runoff. Phosphorus in inorganic pools adsorbed or precipitated with Ca, Fe, and Al is stable when soils are maintained in the same condition leading to P fixation, but may be susceptible to dissolution and regeneration upon change in land use (Ivanoff et al., 1998). Of particular concern are land use changes that disturb soil and alter redox potential, which enhance P regeneration from inorganic pools (Moore and Reddy, 1994). Since future land use changes in the Everglades involve creation of wetlands on agricultural lands, management practices that increase P retention in inorganic pools may pose more of an eutrophication hazard than land uses where P is stored in organic pools (Moore and Reddy, 1994; 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, organic pools are commonly more stable under flooding since decomposition rates are lower under anoxic conditions (Wright and Reddy, 2007). 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, and may be different between land uses. The objectives of this study were therefore to determine the distribution of P in aggregates and chemical fractions under different long-term land management practices 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 sawgrass. Due to conversion of these native prairies to agricultural use by drainage, the dominant vegetation shifted to annual crops of vegetables and sugarcane (*Saccharum* sp.) in the early 1900s. Some sites in the EAA were not planted to sugarcane but instead remained as rangeland or pasture, although water management was altered in a similar manner. These areas serve as reference sites for investigating effects of tillage and cropping systems on soil properties.

The study sites are located in the EAA 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 soils are Dania muck (euic, hyperthermic, shallow Lithic Medisaprists) with depth to bedrock of 45 cm. The land uses studied were either

managed for crop production since the early 1900s or were perennial pastures which received no historic fertilization or tillage. The pastures were primarily established by paragrass [*Panicum purpurascens* (L.) Raddi] and bermudagrass [*Cynodon dactylon* (L.) Pers]. Pastures were periodically mowed with residues returned to soil. Typical annual fertilization for sugarcane is 25 kg P ha⁻¹, but perennial pastures have never been fertilized (Gilbert and Rice, 2006).

2.2. Soil sampling and analysis

Triplicate soil cores (5 cm diameter) were taken to the 0–15 cm depth at each of four locations representative of each land use and composited to yield four field replicates for each land use. Soils were sampled in January 2006 just prior to sugarcane harvest. Soils were analyzed for bulk density (Blake and Hartge, 1986), water-holding capacity (Klute, 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 of organic matter content to organic C using a factor of 0.51 (Wright et al., 2008). Extractable NH₄ and NO₃ were determined by extraction (2N KCl) and colorimetric analysis (Bremner, 1996).

Fractionation of soil aggregates was performed using a wet-sieving procedure (Elliott and Cambardella, 1991; Cambardella and Elliott, 1994). Approximately 100 g of air-dried soil were capillary-wetted to field capacity to prevent slaking following immersion. Wetted soil was immersed in water on a nest of sieves (2 mm, 1 mm, 0.25 mm, 0.053 mm) and shaken vertically 3 cm for 50 times during a 2-min period. Soil aggregates retained on sieves were collected, oven-dried at 50 °C for 3 d to remove moisture, and weighed. Material that passed through the 53- μ m sieve was not collected but contents determined by calculation of the difference between whole soil and the sum of the four aggregate-size fractions. Aggregate-size fractions included large macroaggregates (>2 mm and 1–2 mm), small macroaggregates (0.25–1 mm), microaggregates (0.053–0.25 mm), and silt + clay associated particles (<0.053 mm). Whole soil and subsamples of aggregate-size fractions were subjected to chemical P fractionation.

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 hr, passed through 0.45 μ m filters, and analyzed for water-extractable P (labile P). The remaining sample was extracted with 25 mL of 0.1N 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 0.5N HCl for 24 h and analysis of HCl-Pi (Ca-bound P). The remaining sample was digested with 6N 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 0.1N NaOH extract with 11N H₂SO₄ 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 after Kjeldahl digestion (U.S. EPA, 1993; 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 two land uses and four field replications (CoStat Statistical Software, 2005). A three-way ANOVA model was used to determine main effects of land use, aggregate-size fraction, and chemical fraction. A one-way ANOVA model was used to determine differences between individual treatments for each chemical fraction and aggregate-size fraction. Significant treatment comparisons were based on Fisher's LSD at $\alpha = 0.05$.

3. Results and discussion

3.1. Soil characterization

Soil pH was higher for sugarcane than pasture (Table 1) due to inclusion of 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 decreased with cultivation, likely resulting from destruction of soil structure by tillage and disturbance. Bulk density and total C and N content did not differ between land uses, but inorganic N concentrations were significantly higher for pasture. Nitrogen fertilizers are seldom applied for sugarcane production on organic soils of the EAA, so accumulated inorganic N reflects organic N mineralization.

3.2. Soil aggregate-size distribution

Soils under both land uses were characterized by a high degree of macroaggregation comprising 76 and 83% of total soil for sugarcane and pasture, respectively (Fig. 1). The smallest aggregate-size fractions <0.25 mm were unaffected by land use. The pasture had 55% more soil in the 1–2-mm size fraction than sugarcane, indicating that cultivation decreased macroaggregate stability. High macroaggregation in these soils indicates that the organic matter levels promote macroaggregate formation and may thus protect P held within aggregates.

3.3. Phosphorus fractions in whole soil

Soil total P was 13% higher for sugarcane than pasture, which corresponded to a 77 kg P ha^{-1} difference in total P between land uses after 100 years of management (Fig. 2). Characterization of soil P pools by sequential chemical fractionation methods are 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. Labile P was higher for pasture (10 mg P kg^{-1}) than sugarcane (5 mg P kg^{-1}) even though pasture did not receive P fertilizer. The P storage in Fe–Al fraction averaged 45 kg ha^{-1} and was not affected by land use. Tillage influenced soil chemical properties and the distribution of P in labile and recalcitrant fractions. The Ca-bound fraction was the chemical fraction most affected by land use and was significantly greater for sugarcane (244 kg P ha^{-1}) than pasture (65 kg P ha^{-1}). In fact, of all five chemical fractions, sugarcane had higher P than pasture only in the Ca-bound fraction. Sugarcane experienced subsoil tillage (up to 30 cm) which can bring bedrock CaCO_3 in surface soil and frequent shallow cultivations (up to 4 cm) for weed control, which can redistribute Ca into surface soil (Sanchez and Porter, 1994; Snyder, 2005). Elevated Ca levels enhanced precipitation and adsorption of

Table 1

Properties of soils under sugarcane and pasture. Significant differences between land uses were noted by * ($P < 0.05$) and not significant (NS).

Soil Property	Units	Sugarcane	Pasture	$P < 0.05$
pH		6.8	5.3	*
Water-holding capacity	%	142	196	*
Bulk density	g cm^{-3}	0.41	0.44	NS
Total organic C	g kg^{-1}	440	435	NS
Total N	g kg^{-1}	32	30	NS
C/N		14	15	NS
Extractable $\text{NH}_4\text{-N}$	mg kg^{-1}	158	246	*
Extractable $\text{NO}_3\text{-N}$	mg kg^{-1}	54	162	*

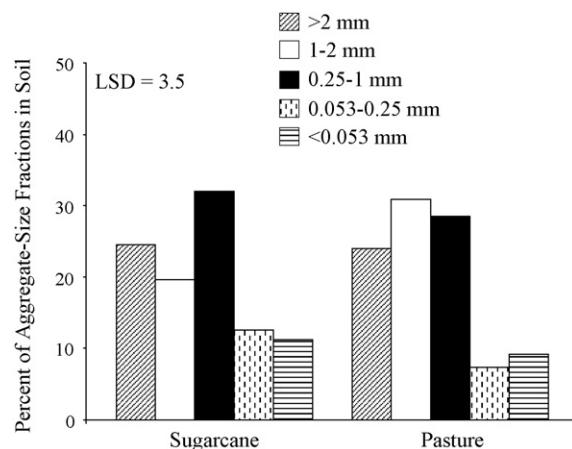


Fig. 1. The proportion of five aggregate-size fractions to total soil for sugarcane and pasture. The LSD was determined at $\alpha = 0.05$.

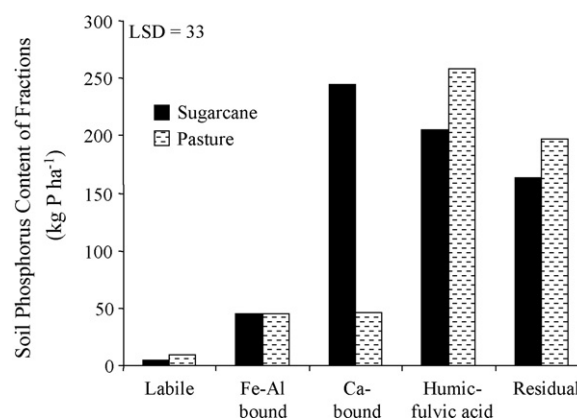


Fig. 2. The P storage in the 0–15 cm depth interval for sugarcane and pasture soil for five different chemical fractions. Total P averaged 675 kg P ha^{-1} for sugarcane and 598 kg P ha^{-1} for pasture.

P from fertilizer or mineralized from organic matter, resulting in higher P in Ca-bound fractions for sugarcane than pasture.

Pasture sequestered 26 and 25% more P in humic–fulvic acid and residual fractions, respectively than sugarcane (Fig. 2). Soil pH may have influenced P retention in the humic–fulvic acid fraction, as the higher pH of sugarcane (6.8) favored retention in Ca fractions while the lower pH of pasture (5.3) favored P retention in the humic–fulvic acid fraction. Total P storage in organic pools was significantly lower for sugarcane (381 kg P ha^{-1}) than pasture (478 kg P ha^{-1}) due to enhanced organic matter decomposition under cultivation. Organic P constituted 86% of total P for pasture but only 57% of total P for sugarcane.

Total P in inorganic forms averaged 294 kg P ha^{-1} for sugarcane but only 120 kg P ha^{-1} for pasture. The differences in P content of inorganic fractions between land uses likely reflects P inputs by fertilization and higher organic matter turnover rates for sugarcane cropping (Castillo and Wright, 2008). 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). Future land use changes may include conversion of sugarcane and pasture soils to seasonally flooded prairies. Flooding of the pasture soil would have the effect of organic matter accretion (Moore and Reddy, 1994), thereby increasing P retention and stability in organic pools (Qualls and Richardson, 1995). Thus, soils that have a higher proportion of their total P in organic forms would be less

prone to release P which would minimize eutrophication of proximal aquatic systems. Flooding has the opposite effect for mineral-associated P (Sanchez and Porter, 1994), as dissolution from inorganic pools can increase after flooding (Graham et al., 2005). Thus, soils under sugarcane may be sources of P if converted to seasonally flooded prairies ecosystems.

3.4. Soil P fractions within aggregate-size classes

3.4.1. Labile P

For both land uses, labile P comprised less than 2% of total P. Pasture had higher labile P than sugarcane for all aggregate-size fractions (Fig. 3), and most of the labile P for sugarcane was contained in the smallest aggregate-size fraction (<0.053 mm). The proportion of total P as plant-available P increased with decreasing aggregate and increasing particle surface area for both land uses (Fig. 4). The smallest aggregates contained the most plant-available P, indicating that P in larger aggregates was more protected from decomposition and more stable. Phosphorus within aggregates may also be protected from reactions with minerals which can decrease P availability (Linquist et al., 1997).

3.4.2. Fe–Al bound P

The distribution of Fe–Al bound P among aggregate-size fractions followed similar patterns as labile P (Fig. 3). In contrast to labile P, there was no difference in Fe–Al bound P storage between land uses. For both land uses, the Fe–Al bound fraction contributed an average of 7% of the total P, but approximately 71% of the total P in this fraction was contained in macroaggregates >0.25 mm. The 0.053–0.25 mm fraction had the lowest P for both land uses, but no other differences occurred for sugarcane. For pasture, most of the P was contained in macroaggregates >0.25 mm, suggesting that the lack of tillage enhanced macro-aggregate P relative to sugarcane since tillage distributed Fe–Al bound P throughout all aggregate-size fractions for sugarcane. Phosphorus storage in the Fe–Al fraction increased with decreasing aggregate size, especially for the <0.053 μm fraction (Fig. 4). Phosphorus sorption generally increases with decreasing aggregate size due to increases in surface area and reactivity (Linquist et al., 1997).

Accumulation of P in the Fe–Al bound fraction may pose problems since it is unstable when associated with Fe and Al under fluctuating redox conditions (Sanchez and Porter, 1994; Diaz et al., 2006). The flooding of soil tends to lead to dissolution of Fe–Al bound P which increases its availability (Moore and Reddy, 1994). Thus, establishment of seasonally flooded wet prairies may lead to P regeneration from pasture and sugarcane soils currently managed under drained conditions.

3.4.3. Ca-bound P

Soils under sugarcane had significantly higher Ca-bound P than pasture for all aggregate-size fractions (Fig. 3). The proportion of the Ca-bound P to total P was consistent across aggregate sizes for both land uses. Macroaggregates contained 72% of P in the Ca-bound fraction compared to 81% for pasture. Of the 663 kg ha^{-1} total P in soil under sugarcane, 244 kg P ha^{-1} was contained in the Ca-bound P fraction, which was a significantly greater contribution than other chemical fractions. In contrast, pasture soil only had 12% of its total P in the Ca-bound fraction. Farming practices increased P sequestration in the Ca-bound fraction under sugarcane relative to pasture soil, possibly due to higher Ca levels (Sanchez and Porter, 1994; Snyder, 2005). The lower pH of pastures soils may have retarded P association with Ca and decreased retention in this pool relative to sugarcane. Since P retained in the Ca-bound fraction is considered relatively stable under current land management, higher P fertilizer rates for sugarcane may be

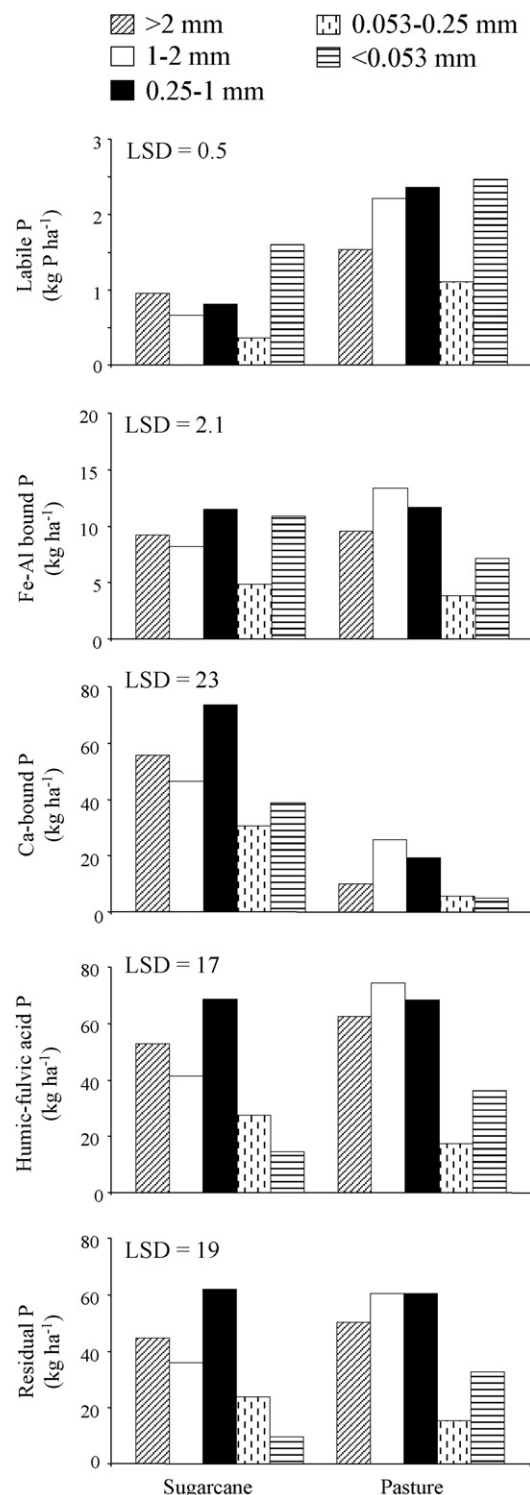


Fig. 3. The P storage in aggregate-size fractions for different chemical fractions.

necessary for projected increased soil Ca levels in the future resulting from tillage and subsidence. The higher P retention for sugarcane may have an advantage of minimizing potential for runoff or leaching as long as the soils remain drained.

3.4.4. Humic–fulvic acid P

The P sequestered in the humic–fulvic acid fraction was significantly higher for pasture than sugarcane for the 1–2 mm and <0.053 mm fractions (Fig. 3). Pasture averaged 26% more P

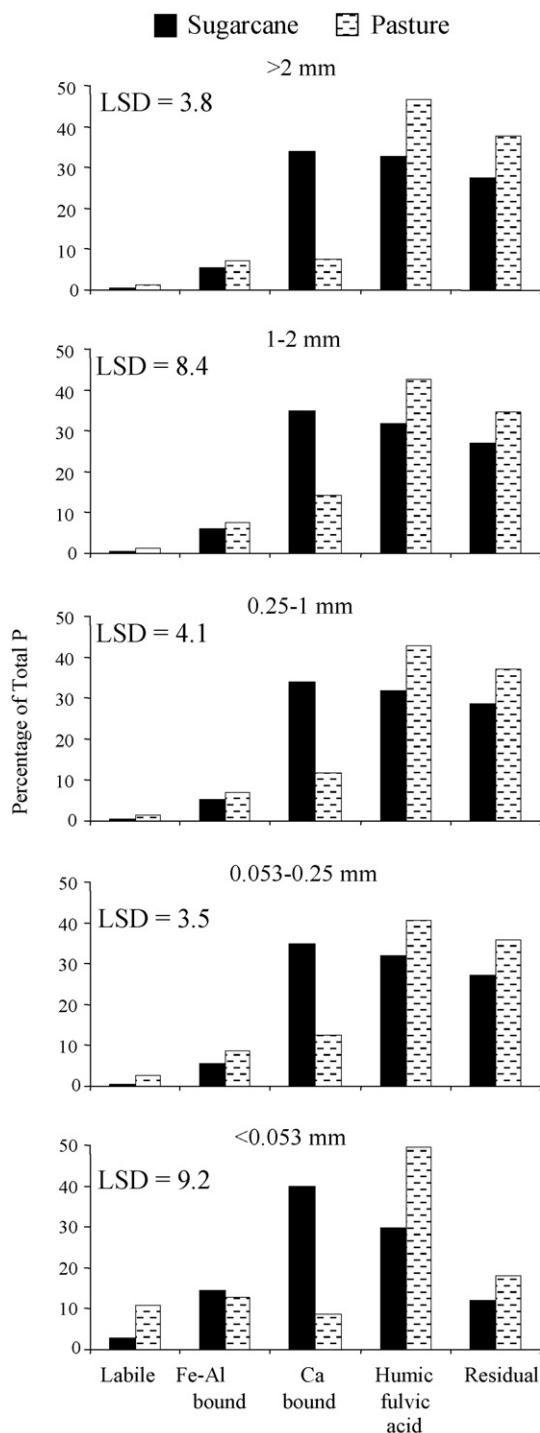


Fig. 4. The percentage of the total P contained in each aggregate-size fraction for five different chemical fractions in soils under sugarcane and pasture.

than sugarcane. Similar to the Ca-bound fraction, the majority of P storage in this fraction occurred in macroaggregates (80%). The humic–fulvic acid fraction comprised 31% of the total P for sugarcane and 47% for pasture. Humic–fulvic acid P constituted as greater proportion of total P for all aggregate sizes for pasture compared to sugarcane (Fig. 4). Farming practices likely enhanced organic matter decomposition relative to pasture due to greater soil disturbance by tillage which decreased levels of humic–fulvic acids and decreased P storage in this chemical fraction.

3.4.5. Residual P

The residual P pool is characterized by stable lignin and organo-metallic complexes (Ivanoff et al., 1998). The P distribution in the residual fraction followed similar patterns as the humic–fulvic acid fraction (Fig. 3). Phosphorus storage in macroaggregates averaged 81 and 78% of the total P in this fraction for sugarcane and pasture, respectively. Pasture soils had higher P storage in the residual fraction for aggregate sizes from 1 mm to 2 mm and <0.053 mm than other size-fractions. Pasture soil had more residual P than sugarcane, as this chemical fraction averaged 39% of the total P for pasture but 27% for sugarcane. The contribution of residual P to total P decreased with decreasing aggregate size, as residual P for the <0.053 mm fraction had the lowest percentage of total P of all aggregate size-fractions (Fig. 4). Residual P contributed 17% of total P in the <0.053 mm fraction compared to an average of 32% for the larger aggregate-size fractions. The pasture was characterized by the majority of its P in humic–fulvic acid and residual fractions, while sugarcane had less of its total P in the residual fraction. Lower P storage in organic fractions of sugarcane soil indicated enhancement of organic matter decomposition by cultivation, which increased organic P mineralization and sequestration in inorganic pools, primarily the Ca-bound fraction.

4. Conclusions

Mineral-associated and labile P increased with decreasing aggregate size, suggesting that P sequestered in aggregates afforded some degree of protection to organic P. This soil was characterized by high macroaggregation with most P sequestered in large aggregates. Pasture soils tended to have a higher proportion of macroaggregates than sugarcane which contributed to greater P storage in organic than inorganic pools. The distribution of P among soil chemical fractions differed between land uses, with the highest storage in the Ca-bound fraction for sugarcane but in the humic–fulvic acid and residual fractions for pasture. Tillage and cultivation decreased organic P, and the incorporation of CaCO₃ into soils by tillage enhanced P sequestration in the Ca-bound fraction. Continuation of conventional crop management practices will likely further increase soil pH and Ca levels, leading to greater recovery of P fertilizer in the Ca-bound fraction and lower P availability to plants. Sequestration of P in stable, inorganic pools under current land uses would necessitate higher fertilizer rates in the future to offset P retention and to maintain plant-available concentrations sufficient for crop production. Phosphorus accumulation in inorganic pools may be unstable and ultimately result in regeneration of P upon onset of flooded conditions that occur during high rainfall events or conversion to the seasonally flooded prairie ecosystem. Since most of the P in pasture soil was in organic pools, flooding of these soils would decrease organic matter decomposition and increase P stability. Thus, the conversion of current land uses to seasonally flooded prairies may have a more dramatic effect on P release from sugarcane than pasture soils since soils under sugarcane have more P in inorganic pools.

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