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Characterizing deep soils from an impacted subtropical isolated wetland: implications for phosphorus storage

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Abstract
Purpose Soils within the Lake Okeechobee drainage basin, FL, USA, have been impacted by beef cattle and dairy operations and the landscape ditched and drained to facilitate stocking and grazing pastures. Restoring wetlands located on pastures has been proposed to reduce overland loss of phosphorus (P) by retaining it within the soils. However, soil properties of deeper horizons within impacted wetlands are rarely investigated due to the assumption that most dominant biogeochemical interactions occur at the soil–water interface. In this paper, we investigate soil properties up to 160 cm below the surface from an impacted isolated wetland and its surrounding upland pasture.
Materials and methods Four intact soil cores were collected using the vibracoring technique, sectioned at 2-cm intervals, and analyzed for organic matter content by loss on ignition, total P by acid persulfate digestion, and water-soluble P using 0.01-M KCl solution. Bulk density and digital imaging were conducted using a multisensor core logger. Clay-sized phyllosilicates were identified using a computer-controlled X-ray diffractometer. Saturated hydraulic conductivity was measured using the slug-out technique, and the Hvorslev method was used to evaluate results.
Results and discussion Unobliterated stratification was observed within the wetland in contrast to the pedologically formed A, E, and B horizons within the upland. The presence of clay horizons composed of smectite and kaolinite was dominant below 120 cm, posing potential hydrological and chemical implications, such as low conductivity and higher P sorption capacity. Saturated hydraulic conductivity of the soils was 1.22 m day^{-1} (±0.4). Diagnostic features such as increase in bulk density due to compaction, and the “red-edge effect” were useful in correlating the effect of cattle activity and hydrology on soil profiles. Soil organic matter content (38–48%) and total P (100–600 mg kg^{-1}) concentrations were highest and well-correlated (r^2=0.81) at the surface. However, a significant amount of P was also present in the deeper horizons associated with clay.
Conclusions The deeper clay horizons account for up to 25% of P per hectare of the entire soil profile. These estimates are nontrivial and need to be accounted for while dealing with belowground P budgets, especially because subsurface lateral flows are dominant within the region.

Keywords Impacted soils · Isolated wetlands · Lake Okeechobee · Phosphorus

1 Introduction

1.1 Background and motivation

Over the past 50 years, the drainage basin of Lake Okeechobee, FL, USA has been impacted as a result of ditching and cattle activity from beef and dairy farming. These operations account for only 12% of the land area in the Okeechobee basin yet contribute a disproportionate 35% of phosphorus (P) load to the lake. Isolated wetlands cover nearly 16% of the land within the Okeechobee basin and nearly as much is covered by ditches and canals

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(Hiscock et al. 2003; Gathumbi et al. 2005). Nearly 45% of the wetlands within the basin are drained by these ditches and are surrounded by cow–calf pastures located on active beef or dairy facilities (South Florida Water Management District, Florida Department of Environment Protection, and Florida Department of Agriculture and Consumer Services 2004). Draining the isolated wetlands via ditches and canals was done to provide improved cow–calf grazing pastures but has left the basin hydroscape severely altered. Because wetlands are known to store water and nutrients such as P and exist along the landscape continuum between the upland and the Lake (Braskerud 2002; Hiscock et al. 2003), one of the strategies recently proposed (Lake Okeechobee Protection Plan 2004) to help mitigate P loss from improved pastures and reduce P loads to Lake Okeechobee was to restore the hydroperiod of these isolated wetlands located on beef and dairy farms (Johns and O'Dell 2004). An overall understanding of soil characteristics can help in planning future restoration work and implementing sound management strategies.

Studies of wetland ecosystem functions have shown that soils are the most important long-term P storage compartment compared to litter or plant biomass (Dolan et al. 1981; Graham et al. 2005) and that their properties can influence wetland water quality. Most of the P stored in wetlands is in organic form derived from dead vegetation, typically concentrated in the surface horizons (Graham et al. 2005; Dunne et al. 2007). Under flooded conditions, biogeochemical cycling of P occurs within a few centimeters at or near the soil–water interface (Fisher and Reddy 2001; DeBusk and Reddy 2003); therefore, previous studies have focused primarily on soil properties that relate to P storage capacity of surface soils (Reddy et al. 1998; Pant et al. 2002; Dunne et al. 2007). However, due to the transient hydrologic conditions experienced by these wetlands, there is a need to investigate even the deeper horizons. It is common for the water table to drop more than a meter below the ground surface during the dry season (Perkins 2007), potentially transporting nutrients to the deeper horizons, in addition to introducing temporal variability to the soil redox conditions. An important process controlling P transport in agricultural soils affected by repeated wetting and drying cycles is the mineralization and subsequent mobilization of organic matter (OM; including organic P) near the soil surface (McLatchey and Reddy 1998) and even up to depths of 100 cm within the soil profile (Sigua et al. 2009). Corstanje and Reddy (2004) showed that drawdown events in subtropical marshes resulted in significant stimulation of microbial activities and β-glucosidase activities, concurrent with and affecting the water column P concentrations. High concentrations of OM in the form of manure and decomposed vegetation can drastically increase the availability of labile P within surface soils since organic anions formed by the decomposing OM can compete with P for the same adsorption sites such as clays and iron–aluminum (Fe–Al) minerals (El-Dewiny and El-Aila 2006).

Within soil profiles of subtropical Florida, clays typically accumulate in deeper horizons, below the E and within the B (Bh or Bt) horizons (Harris and Hurt 1999). In addition to the hydrologic impact of reduced hydraulic conductivity of clay horizons, clay particles provide surfaces for mineral and organic interactions, including increased P sorption capacity (Rengasamy et al. 1984; Pant et al. 2002). Capece et al. (2007) reported clay layers below 60 cm near Lake Placid, FL, USA, about 40 km west of our study site. They concluded that the accumulation of P in deep soils from historic fertilization had an overriding influence on P loads in surface runoff. Consequently, net P imports from deeper horizons would also need to be addressed in order to achieve mandated water quality targets in the long term, especially since an important goal of wetland restoration is to increase P retention within the soils.

Studies have shown that the P retention capacity of saturated soils that have undergone periodic drawdown diminish on reflooding compared to continually flooded soils (Watts 2000; Klotz and Linn 2001). Bostic and White (2006) evaluated the behavior of periodically saturated marsh soils and found that up to 6% of total P (TP) from the soils was released from a single drawdown and reflooding event. The change in redox conditions affects the iron oxide minerals in the soil and its ability to retain P. For example, De Groot and Van Wijck (1993) showed that when anoxic wetland soils were exposed to air the ferrous sulfide previously present was rapidly oxidized to amorphous ferric oxyhydroxide. These ferric (oxy)hydroxides have both a large surface area and high affinity for orthophosphate, allowing for a stable bond between Fe and orthophosphate. Flooding causes a shift in redox condition from oxic to anoxic which results in the release of Fe-bound P to the water column, potentially increasing the pool of dissolved TP. Episodic flooding and drying cycles are a common occurrence within the Okeechobee basin and reflooding of oxic soils could thus facilitate release of P to the water column. In addition, extended periods of desiccation have been shown to cause significant reduction of the orthophosphate binding capacity with ferric hydroxides in both flooded and drained soils, rendering them nonreactive to concentrations of high P in solution (Sah et al. 1989).

Ditches and canals created to drain the landscape can also have an impact on soil properties. Soil morphology has been used to evaluate ditch effectiveness because morphology has been found to change when the hydrology is altered (Hayes and Vepraskas 2000). For example, Daniels and Gamble (1967) showed that soils (ultisols) along stream-dissected edges of the Middle Coastal Plains (North

Carolina) had redder-colored Bt horizons than soils further from the edge. This "red-edge effect" was believed to have occurred after the Coastal Plain had been incised and drained by streams. Prior to the stream incision, restricted surface and subsurface drainage caused reduced conditions to persist for long periods. Stream incision resulting from lowered water tables and the subsequent oxidation of iron–aluminum minerals produced red- and yellow-colored soil horizons in areas of improved drainage. Such changes in redox conditions can have an overriding effect on P solubility and sorption mechanisms regardless of the soil/sediment mineralogy (Reddy et al. 1998; Hayes and Vepraskas 2000).

With open access to wetlands and ditches, cattle can increase nutrient pollution by depositing manure into surface waters (Bottcher et al. 1999; Alloush et al. 2003) or by stimulating nutrient release from sediments stirred up by cattle activity (Line et al. 1998). Heavy stocking can also lead to the reduction in vegetation cover and an increase in soil erosion (Capece et al. 2007). Cattle trampling can increase soil bulk density (BD) and decrease soil porosity (Tollner et al. 1990; Mulholland and Fullen 1991; Bezkorowajnyj et al. 1993). Mature cattle can exert a static ground pressure of approximately 1.7 kg cm^{-2} of hoof-bearing area, which can affect bulk density up to 100 cm deep within a wet saturated soil profile (Rhoades et al. 1964; Bezkorowajnyj et al. 1993). In addition, cattle activity can also increase the physical breakdown of litter, stimulating enhanced decomposition of OM at the surface (Klemmedson and Tiedemann 1995).

In order to evaluate the effectiveness of wetland restoration, a thorough understanding of prerestoration soil characteristics is important. Soil characteristics of horizons beyond a meter are not routinely investigated from impacted wetlands within the Lake Okeechobee drainage basin, and local soil survey data (US Department of Agriculture (USDA) and Natural Resources Conservation 2007) provide only limited information because the scale of these isolated wetlands is relatively small compared to the resolution of soil mapping units. The objectives of this study were to (1) determine differences in soil characteristics as a function of depth between an impacted isolated wetland and the surrounding upland and (2) determine the P concentrations and net P reserves stored within soil profiles up to 160 cm.

1.2 Site description

The majority of P export to Lake Okeechobee has been identified from four priority sub-basins (Hiscock et al. 2003). The wetland selected for this study is a historically isolated emergent marshland located on an active beef ranch within one of the four priority sub-basins. The wetland is at the head of a ditch that connects to the regional ditch network that ultimately drains into Lake Okeechobee. The system is representative of isolated wetlands within the Okeechobee drainage basin based on size, soil characteristics, vegetation, and transient hydrology. However, particulate and dissolved P concentrations can vary from site to site based on different historical P loading regimes and land use practices (Dunne et al. 2006). The regional gradient is nearly level (<1% slope), and the 1.1-ha wetland is surrounded by cow–calf grazing pastures that are dominated by *Bahia* grass species. The base of the wetland is less than 1 m deep from the surrounding upland and exhibits a somewhat bowl-shaped morphology. This is a remnant of the historic sinkhole collapse features forming in dissolution cavities of the underlying Ocala limestone. The wetland soils are deep, well drained, and rapidly permeable at the surface, formed in reworked sandy marine sediments. The surficial water table fluctuates from as much as 60 cm above the soil surface during the wet season to more than 80 cm below ground surface during the hot dry periods (Perkins 2007). Since 1992, the land surrounding the wetland has been used for cow–calf operation with about 140 cows enclosed within the pasture (yearly average), at a stocking rate of 1.2–2.0 head per hectare at any given time. Based on six sampling events, approximately every other month from July 2005 to March 2006, the concentration of soluble reactive P (SRP) in the wetland water column was 0.93±0.4 mg l^{-1}, while groundwater SRP at a depth of 10 cm was 3.2±0.72 mg l^{-1} (Bhadha 2009). Note that surface water quality data are limited to when the wetland is flooded: on average, approximately 40% of the year (Dunne et al. 2007).

2 Sampling and analytical methods

Four intact soil cores were collected in July 2006 using the vibracoring technique to obtain long intact cores. Vibracoring works on the principle of liquefaction in fine-grained sediments by displacing sediment to allow passage of the pipe and retrieval of long (up to 10 m) continuous sections from unconsolidated saturated sediments (Smith 1984). Vibracoring works best in saturated organic sediments, clays, silty clays, silts, and fine sands but is inefficient in firm clays and medium to coarse sands. Cores 1, 2, and 3 were collected from within the wetland basin, while core 4 was collected from a nearby upland site within 20 m from the ditch (Fig. 1). These cores were 140, 144, 129, and 161 cm long, respectively. The water table was 6 to 10 cm below the ground surface at the time of coring, so the cores were virtually saturated; however, deionized water was added to ensure saturation to the top of the core and to facilitate liquefaction between the core barrel and the soil in

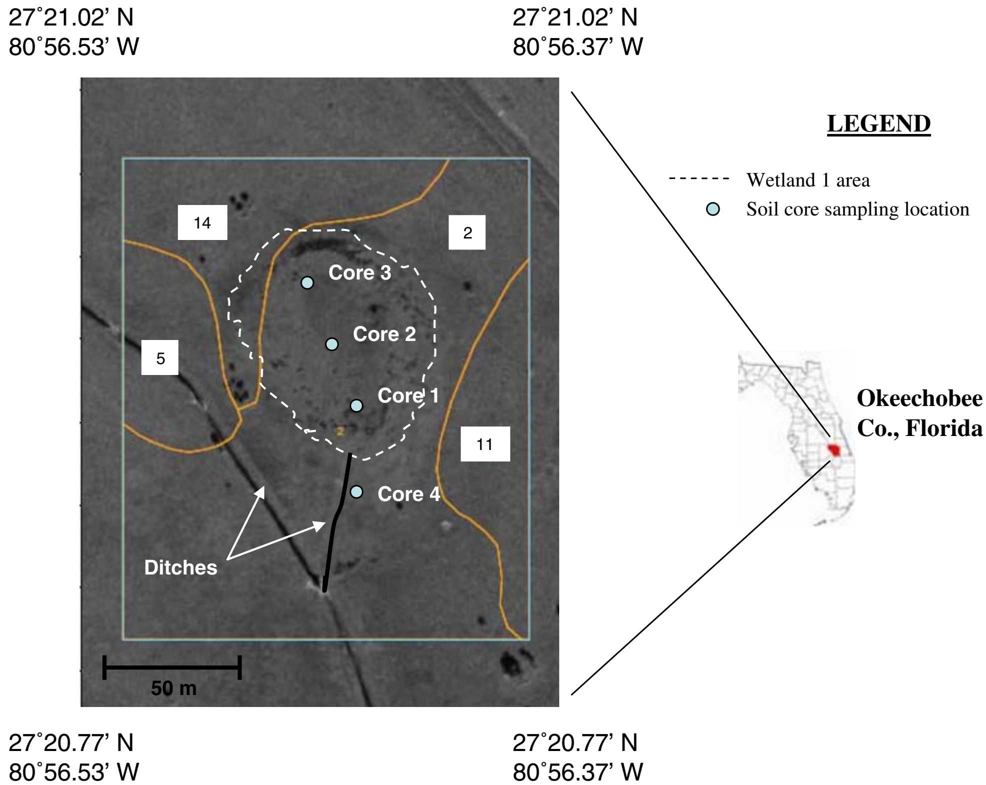


Fig. 1 Location of four soil cores collected from Wetland 1, including the soil survey map units for the area: (*2*) Basinger fine sand; (*5*) Valkaria fine sand; (*11*) Imokalee fine sand; (*14*) Myakka fine sand

contact. There was no compaction or loss of soil during sampling, and 100% of soil was recovered using the vibracoring technique. The cores were transported to the laboratory where they were split lengthwise, described, and photographed. Soil description was conducted on wet soil using USDA and Natural Resources Conservation Service (2006) protocols. The physical properties described included color, texture (based on particle size distribution), bulk density, porosity, and saturated hydraulic conductivity; while chemical analyses included soil OM content, TP, water-soluble P (WSP), and clay mineralogy.

One section of the split core was used to measure soil BD by gamma ray attenuation (Geotek Standard Multi-sensor Core Logger, MSCL-S) at 0.5-cm increments and capture high-resolution digital images (Geoscan II, 40 pixels cm^{-1}) of the entire core lengthwise. The accuracy of the bulk density (r^2>0.99) was determined using a standard aluminum density calibration piece. Particle size distribution (PSD) was measured only on selected soil horizons extracted from core 2 (wetland) and core 4 (upland) based on morphological changes including an evaluation done using “feel and ribbon test” at different horizons on all four cores. The pipette-dispersion method was used to measure PSD (Gee and Bauder 1986). Minerals in the clay fraction were identified by X-ray diffraction (XRD, Nicolet Corporation, Madison, WI, USA) using a computer-controlled X-ray diffractometer equipped with stepping motor and graphite crystal monochromator. Oriented mounts were prepared by sedimentation on unglazed ceramic tiles under suction. Diagnostic cation saturation with $MgCl_2$ and glycerol were performed to aid phyllosilicate identification (Harris and White 2008).

The remaining halves of all four split soil cores were sectioned at 2-cm intervals, weighed, freeze-dried, and reweighed prior to chemical analyses. Freeze-drying the samples was preferred over conventional oven-drying (2 h at 105°C) because the process sublimates the moisture content, with minimal physical or chemical alteration (McClymont et al. 2007). The samples were stored in air-tight containers to prevent any rehydration at this point. Wet and dry soil weights were used to determine water content for each 2-cm section. Soil porosity was calculated using measured BD and a fixed particle density of 2.65 g cm^{-3} (quartz sand).

Soil samples were also analyzed for TP, WSP, and OM content. Soil TP was analyzed colorimetrically (Bran-Luebbe Autoanalyzer) using acid persulfate digestion (Nelson 1987). Water-soluble P was also analyzed colorimetrically, in 0.01-M KCl solution equilibrated for 24 h in a 1:20 soil/solution ratio (Murphy and Riley 1962). Organic matter content was measured by loss on ignition (LOI, Dean 1974) where 2.0 g of dry mass (freeze-dried) sample was oxidized at 550°C in a muffle furnace for 2 h. The preheating and postheating difference in weight represented the OM content of the samples. Note that the LOI method used in this study may overestimate the OM content in clayey material due to dehydroxylation reactions of secondary phyllosilicates in the temperature range of OM combustion. Analytical precision for TP and OM was assessed using duplicates every tenth sample, with relative percent difference of 3.3% for TP, 5.0% for WSP, and 5.2% for OM content.

Saturated hydraulic conductivity was measured using the slug test method (slug-out technique) from five fully penetrating onsite wells extending approximately 1.5 m below the ground, one well located in the wetland and four in the surrounding upland. The Hvorslev method (Fetter 1994) was used to analyze the slug test data for fully penetrating wells with well length more than eight times the well radius.

3 Results and discussion

3.1 Soil description and characterization

The soil texture in all four cores was sandy up to a depth of 100 cm (Fig. 2). The top of the upland core 4 showed a distinct Ap horizon with high OM, underlain by an eluvial E horizon (10–40 cm depth), a Bt horizon (40–80 cm), a sandy loam Btg1 horizon (80–140 cm), and a sandy clay Btg2 horizon (140–161 cm). While the upland core comprised horizons Ap, E, Bt, and Btg formed by pedogenesis, all three wetland cores showed stratified C horizons. Deposition of surface sediments eroded from surrounding uplands may have given rise to the stratified morphology observed in all three of the wetland cores. Below 100 cm were observed finer-textured horizons (sandy loam and sandy clay), in which fine stratification was not as prominent as the overlying horizons. In the upland core 4 was observed what may be a result of the "red-edge effect" within the Bt horizon where a well-defined yellow to red coloration (high chroma) was visible between 75 and 83 cm. Being in close proximity to the ditch, it is possible that following ditch incision the subsequent lowering of the water table due to surface and subsurface drainage may have resulted in oxidizing conditions, conducive for iron oxides to form in that horizon.

The upland soil was classified as an Alfisol, while the wetland soils were classified as Entisols by virtue of having >50 cm of recent material (stratification). The genesis of Alfisols involves the translocation of clay from the upper to lower soil zones, ultimately forming thick argillic horizons. Such horizons also have the ability to sorb P, similar to the spodic-Bh horizons seen in Spodosols, commonly reported in this area (Harris and Hurt 1999). Dissolved P moving vertically downwards from the A and O horizon through

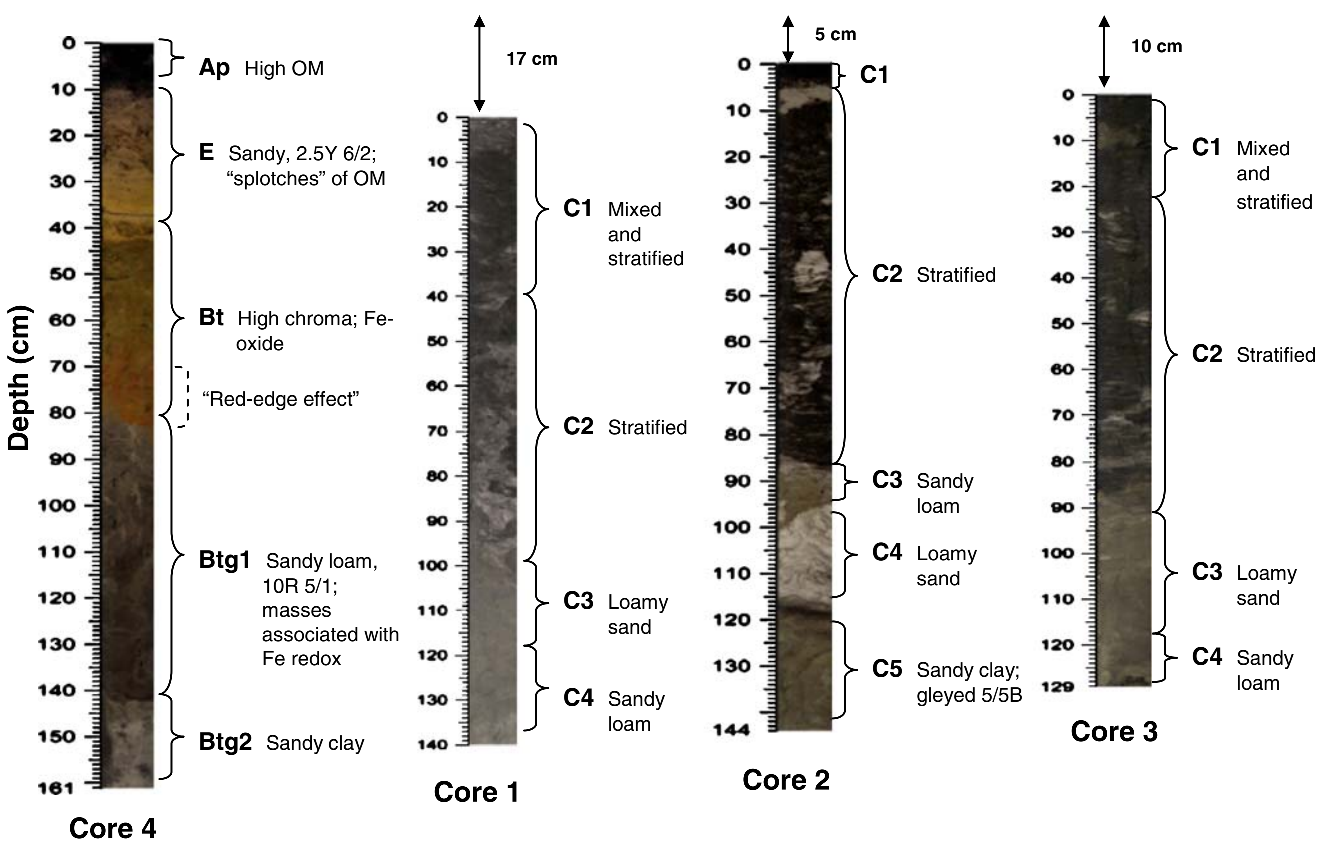


Fig. 2 Soil description. Cores 1, 2, and 3 were collected from the wetland, while core 4 was collected from the upland <20 m from the ditch. Relative difference in elevation from the upland shown on the *top*

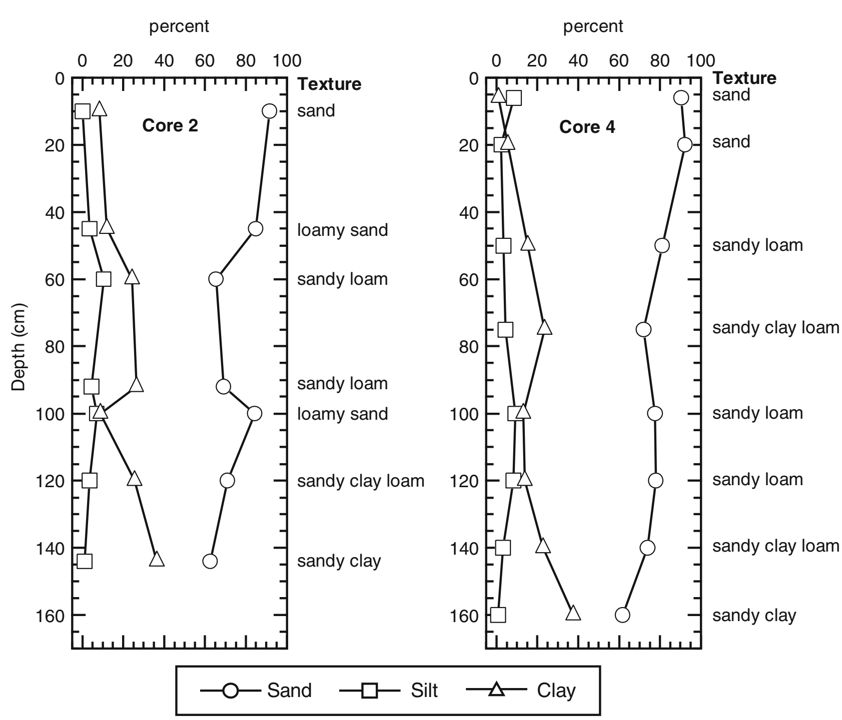
the E generally accumulates in the B horizon. However, the presence of clay within the B horizon can impede the movement of water, thus promoting transport of P via surface runoff and lateral seepage to the ditches through A and E horizons; a process previously addressed by (Allen 1987). Under such condition, groundwater could be short-circuited rapidly along preferential flow paths and emerge as surface water (Kadlec and Wallace 2008).

The texture of the wetland soils below the stratified horizon was loamier, gradually transitioning to clay at the core bottom. Particle size distribution analysis of cores 2 and 4 both showed that the sand fraction (0.05–2.0 mm) gradually decreased with depth, while the clay fraction (<0.002 mm) increased with depth to 36% in core 2 and 38% in core 4 (Fig. 3), representing a significant ($p<0.05$) change in clay content between the surface (0–10 cm) and the deepest horizons. The sandy clay layer observed in all four cores will subsequently be referred to as "clay horizons." The top of the clay horizon was encountered at approximately 120 cm in all three wetland cores. The thickness is unknown but extended all the way to the bottom of the soil cores. A similar 15-cm clayey horizon was observed between 85 and 100 cm in core 2. Such clay horizons could promote perched water tables, separating the hydrologic unit from underlying aquifers, and reduce the loss of P through leaching. The presence of clay also increases P sorption capacity due to the greater surface area-to-volume ratio.

In all four cores, the porosity was highest (0.49±0.05) within the top 20 cm (Fig. 4). This is probably due to the presence of the loosely bound OM associated with plant roots within the top 20 cm (Justin and Armstrong 1987). Below 20 cm, the porosity gradually decreased to less than 0.45 in the wetland cores. The small range in porosity (±0.006) between 50 and 160 cm in upland core 4 reflects uniform grain size. Bulk density increased with depth in all four cores: in the wetland soils from 1.33±0.15 g cm^{-3} in the top 20 cm to 1.56±0.03 g cm^{-3} in the bottom 20 cm and in the upland soil from 1.39±0.11 g cm^{-3} in the top 20 cm to 1.70±0.01 g cm^{-3} in the bottom 20 cm (see Fig. 4). Cattle poaching, which is the penetration of the soil surface by the hooves of grazing animals (Mulholland and Fullen 1991), may be responsible for the increase in BD observed at 10-cm depth observed in the wetland cores. The sharp increase in BD from 1.45 to 1.70 g cm^{-3} in the upland core 4 at the E-Bt horizon interface is because of the change in soil texture due to pores being filled during illuviation.

Saturated hydraulic conductivity of the soils based on slug test measurements was 1.22 m day^{-1} (±0.4). These values are comparatively lower than those reported by (USDA and Natural Resources Conservation 2007) for the Basinger and Valkaria fine sands of this region (3.7 to 12.2 m day^{-1}). The discrepancy in values may be because the 1.5-m-long screened wells intercept the clay horizons that lowered the integrated conductivity for the soil unit up to the well depth.

Fig. 3 Particle size distribution and soil texture based on the soil texture triangle for core 2 (wetland) and core 4 (upland)



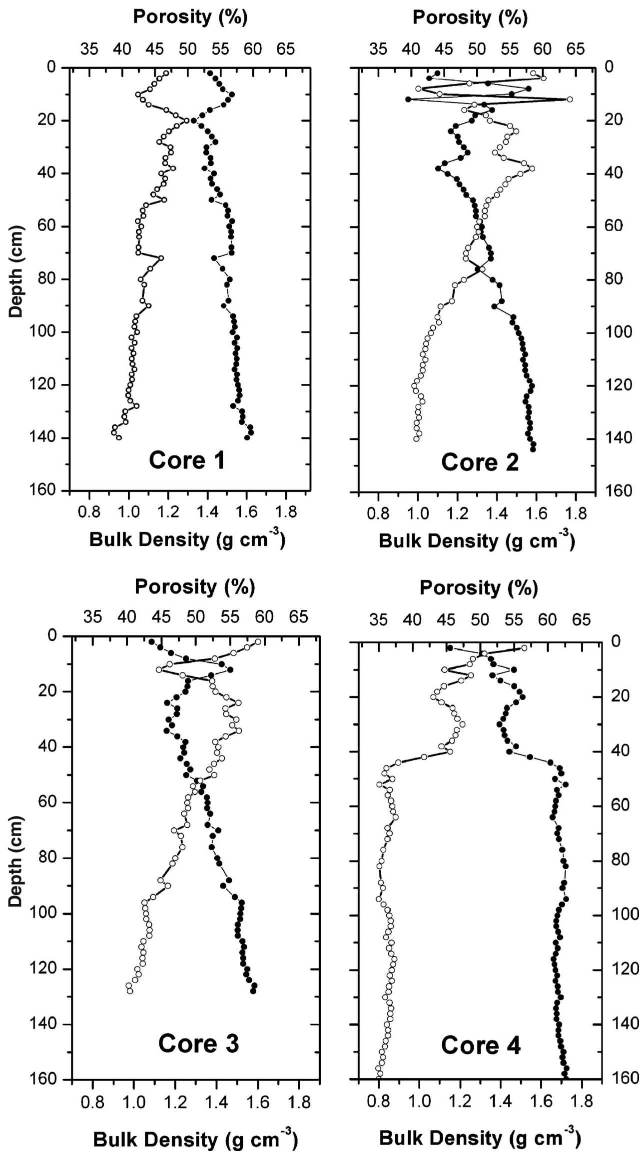


Fig. 4 Changes in soil bulk density (*solid circles*) and porosity (*empty circles*) with depth

The XRD analyses on four selected soil horizons from core 2 showed that smectite was the dominant mineral in the clay-size fraction and that smectite enrichment generally increased with depth, as evidenced by the smectite-to-kaolinite ratio (based on peak areas) of 1.16, 1.38, 3.07, 2.23 from samples collected at 45-, 60-, 92-, and 144- cm depth, respectively (Fig. 5). Smectite is an expansible secondary phyllosilicate, with a relatively high density of permanent negative charge. Hence, it imparts a high cation exchange capacity than kaolinite, in addition to its lower edge to face ratio than kaolinite which would not favor retention of anionic species such as orthophosphate (Pant et al. 2002). A more weathered mineral suite, consisting of minerals such as metal oxides and kaolinite, would tend to impart higher P retention capacity per gram of clay than would smectite.

3.2 Soil organic matter content and total phosphorus

Characterizing P storage in wetland soils is often accompanied by OM characterization, as the TP pool within wetland ecosystems is often dominated by organic P, which can comprise >50% of soil TP (Reddy et al. 1998). High concentrations of OM in the form of manure and decomposed vegetation can drastically increase the availability of P within surface soils since organic anions formed by the decomposing OM can compete with P for the same adsorption sites such as clays and iron–aluminum minerals (El-Dewiny and El-Aila 2006). Except for core 1, OM concentrations were found to be greatest within the top 2 cm in the remaining three cores (Fig. 6). The OM content within the top 6 cm was 38% (±14%) and 48% (±2%) for the wetland and upland soils, respectively. The high OM content at the surface is believed to be associated with decomposing vegetation and manure deposited by cattle. Below 6 cm, the OM concentrations steadily dropped to <2% up to the top of the clay horizon. An irregular decrease in OM with depth was consistent with the observed fine stratification within the wetland soils.

Similar to OM, clays can also influence the P storage capacity with depth because of the ability to sorb P. Except for core 1, soil TP concentrations were also highest within the top 2 cm of the soil profile (Fig. 7). In the wetland soils, these concentrations gradually decreased with depth to about 100 cm but then increased again as the clay content increased. In comparison, the upland core showed a sharper increase in TP concentrations below 120 cm. This increase in TP concentrations below 1 m in the soil profile is also associated with the clay fraction within and below the Btg1 horizon at those depths. Depth-averaged soil TP concentrations between 0 and 20 cm were 62.8±28, 182.6±241, 166.1±104, and 124.2±172 mg kg^{-1} for cores 1, 2, 3, and 4, respectively. The high variability is primarily because of the high concentration on TP within the top 2 cm of the soil profile. The increase in P concentration between 40 and 60 cm seen in core 4 corresponds to the affinity of P for iron-bearing minerals present within the Bt horizon in the upland. The pool of organic P was not measured as part of this study; however, Dunne et al. (2006) reported that in the same study wetland with 81±7.1% of TP was composed of organic P within 0–20 cm from the wetland soils. They concluded that inorganic P as a fraction of TP increased with depth. Here, WSP was used as a proxy for labile, readily available form of P. The concentration of WSP was significantly lower ($p<0.005$) than TP in all four cores, and the ratio of WSP/TP varied as a function of depth. In the surface horizon (0–10 cm), WSP/TP was higher (0.10±

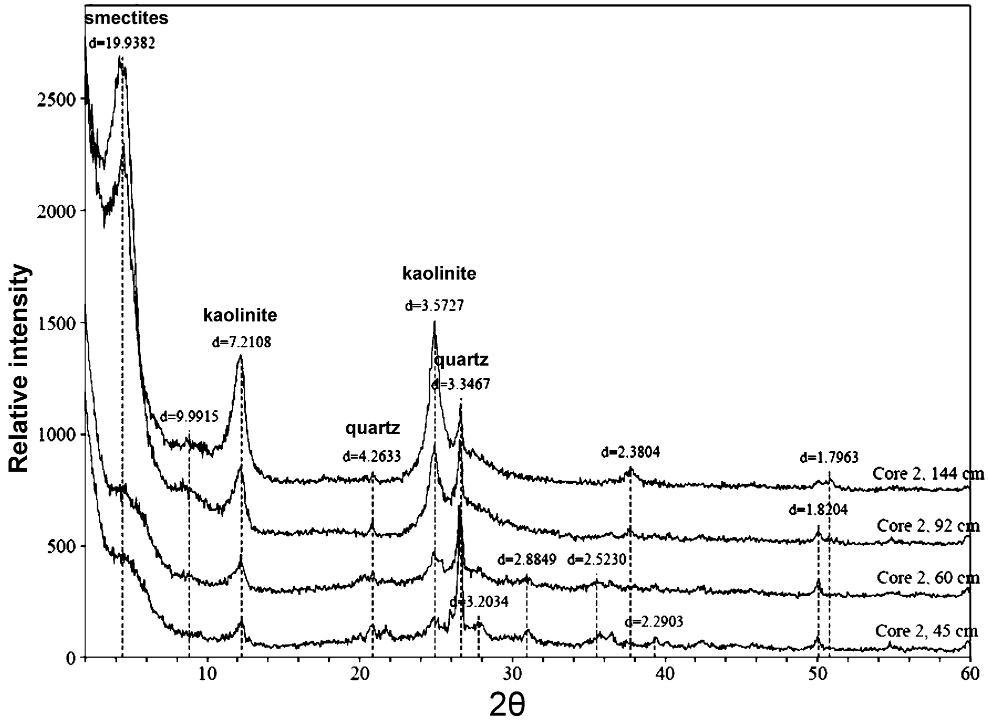


Fig. 5 Sequences of X-ray diffraction patterns for soil clays from core 2 at four different depth intervals and scanned at 25°C after cation saturation of MgCl and glycerol

0.08) compared to the deeper horizons ($7.9\times10^{-4}\pm5.7\times10^{-4}$). The relative depletion of WSP in the deeper layers is indicative of the high retention potential of these horizons. The high TP concentrations in the deeper clayey horizons are likely a result of interception of P transported from the surface through the sandy horizons.

Based on BD and average TP for a given thickness of soil horizon, the net P reserve within wetland and upland soil horizons was estimated (Fig. 8). While the majority of the P is accumulated in the upper 10 cm (46–49%), up to 25% is also present in the deeper argillic horizons of the upland, and 17% in the deep, finer-textured layers of the wetland. The increasing trend of TP observed at the bottom of cores 2 and 4 indicates that there may still be more P in horizons deeper than the core bottom; this would further decrease the relative proportion of net TP reserves

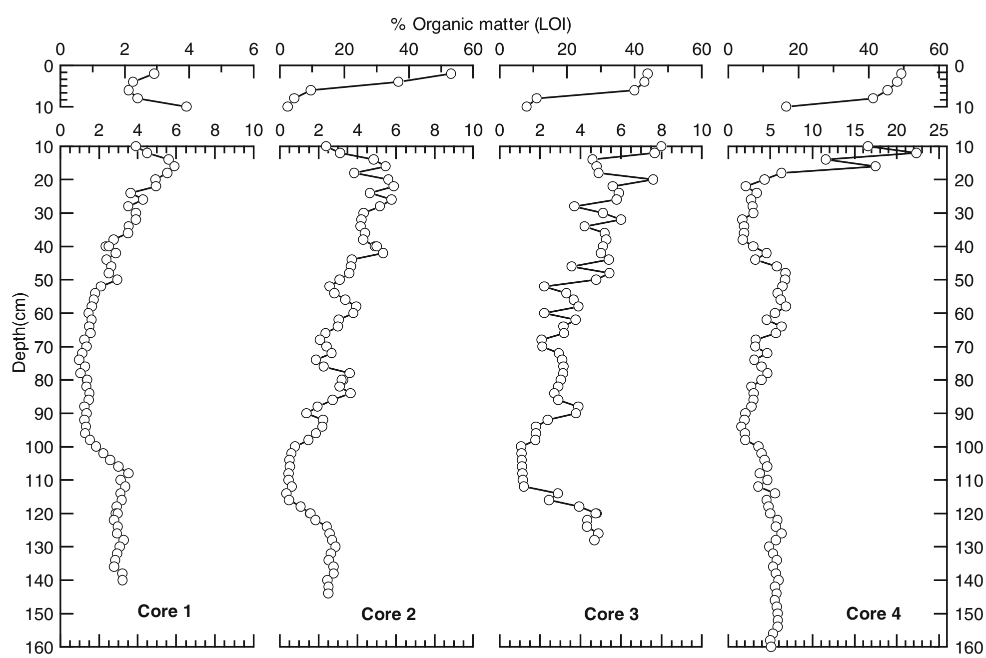
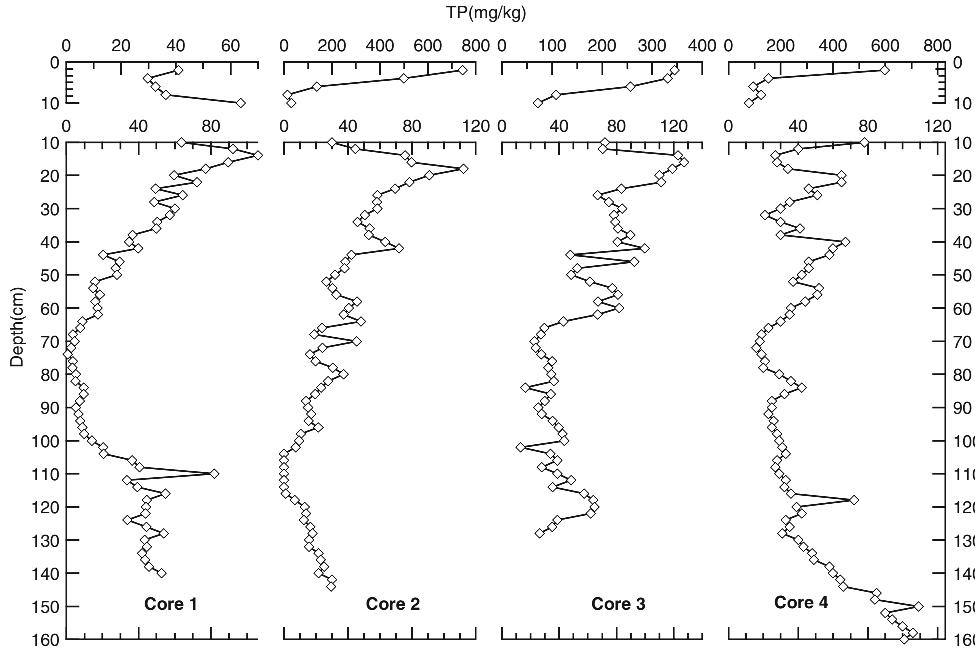


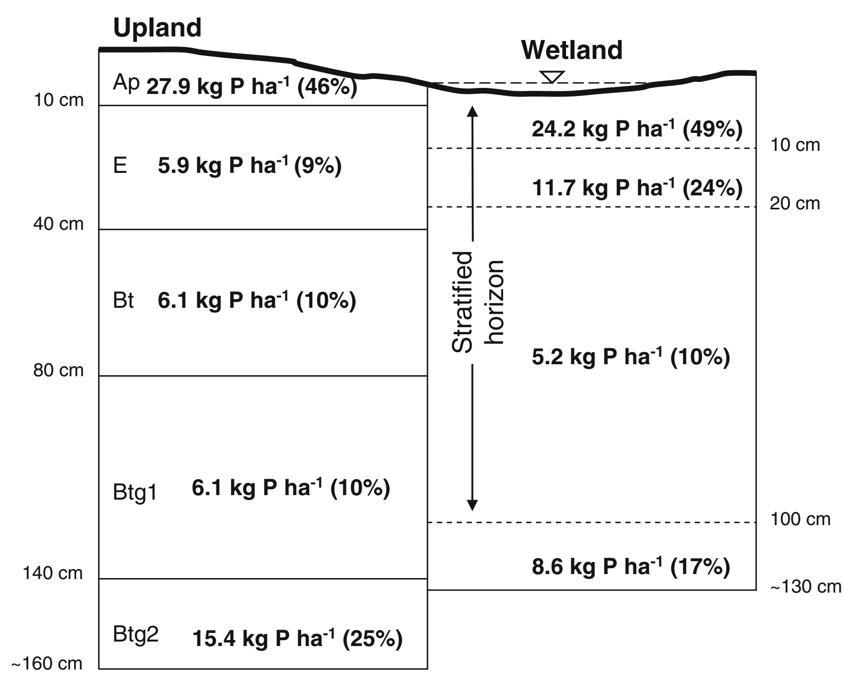
Fig. 6 Changes in soil organic matter concentration with depth

Fig. 7 Changes in soil total phosphorus with depth



estimated in the upper 10 cm of the wetland and upland soils. The TP concentrations within the soil profiles followed OM trends in all four cores (Fig. 9). The regression was strongest in the surface horizon (r^2=0.81), and correlations in other horizons were all much weaker probably due to the dynamic behavior of OM and P within different horizons. For example, root zone (10–20 cm) r^2= 0.31, mixed zone (20–100) r^2=0.42, and finer-textured zone (>100 cm) r^2=0.47. The strong OM to P correlation within the top 10 cm likely corresponds to P in cattle manure and decaying vegetation deposited at the soil surface. The slope of the regression for surface soils (0–10 cm) corresponded to an increase of 10.3 mg kg^{-1} of TP for every 1% increase in OM. In comparison, Dunne et al. (2007) estimated an increase of 4.2 mg kg^{-1} of TP for every 1% increase in OM (r^2=0.86) similar to 0–10-cm surface soils from adjoining wetlands including this one located on the same pasture land. Below 10 cm, an increase of 6.6 mg kg^{-1} of TP was estimated for every 1% increase in OM (r^2=0.34). An inverse correlation between OM and P was

Fig. 8 Amount of TP (kg ha^{-1}) estimated within various soil horizons in the upland and wetland



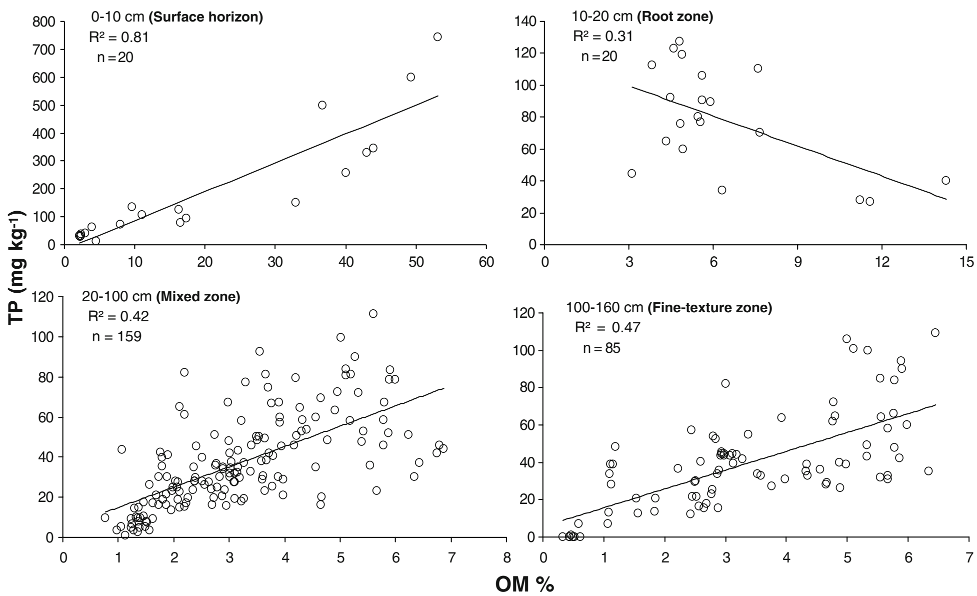


Fig. 9 Correlation between soil TP (mg kg^{-1}) versus OM percent compared at four separate depth horizons using a total of 284 samples from all four cores. Every 1% increase in OM corresponds to a 10.3-mg kg^{-1} increase in TP within surface soils (0–10 cm)

observed between 10 and 20 cm within the root zone (rhizosphere). This is not unusual because at this depth C/P ratios are typically elevated, as virtually all the P sequestered within the rooted macrophytes is delivered to the plant from those depths, resulting in a decrease in soil P concentrations (Davis 1991). The P within the clay horizons is primarily associated with the increase in clay content and its ability to retain P onto reaction sites. This deep pool of TP could be critical for understanding soil P retention dynamics associated with clayey horizons, especially if the water table intercepts those depths during the dry periods.

4 Conclusions

Based on our investigation, the soils recovered from the wetland are classified as Entisols by virtue of unobliterated stratification seen throughout the entire soil profile, possibly resulting from upland soil erosion. In contrast, the soil recovered from the upland was composed of pedologically formed horizons and was classified as Alfisols because of a distinct argillic horizon, and the Bh consisted of <5% diffused OM which does not meet the taxonomic criteria for a spodic diagnostic horizon. Because only one upland core was analyzed, caution is warranted in extending the upland characterization to other areas. However, the analyses conducted on the four long intact cores collected here were sufficient to provide a detailed perspective on the deeper horizons in wetlands and nearby upland soils up to 160 cm.

All four soil cores recovered from the site included fine-textured clayey material below 120 cm. The two dominant phyllosilicate minerals present within the wetland soils were smectite and kaolinite. The presence of both of these minerals can lower hydraulic conductivity as observed by the slug test measurements and increase P sorption capacity in zones where fine-textured material are dominant. A low WSP/TP ratio seen in the deeper horizons (below 120 cm) indicated higher retention capacity compared to surface horizons. The high chroma reddish-yellow horizon within the Bt horizon was indicative of oxidized Fe and Al mineral phases in the upland soil, which may have resulted from the altered hydrology as a result of ditching (the “red-edge effect”). The effect of cattle trampling was evident within the top 10 cm of the wetland soils, causing an increase in soil BD, as seen between 0 and 20 cm in all four cores.

Organic matter and P within the top few centimeters of the soil profile were highest compared to the rest of the soil profile; both were at least partially derived from manure inputs. Significant amounts of P were also found within the deeper Btg1 and Btg2 horizons (upland) and in the clay horizons (below 100 cm in the wetland). The vertical translocation of P due to infiltration may result in further accumulation of P at those depths. Net TP reserves within the deeper horizons are nontrivial and cannot be ignored while computing P budgets. We estimate that the clay horizon accounts for nearly 25% of TP per hectare of the measured soil profile in the upland and 17% of TP per hectare of the measured soil profile in the wetland. Note that evaluation of additional wetlands is suggested before results from this study are extended to the larger Lake Okeechobee drainage basin. Based on these findings, further investigation of soil characteristics in the deeper horizons on neighboring wetlands, under both oxic and anoxic conditions, is encouraged to improve our understanding of belowground soil P dynamics and in delineating soil properties below a meter that is rarely measured.

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