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Abstract We examined interannual variation in soil properties from wetlands occurring in adjacent drainage basins from the southeastern Everglades. Triplicate 10-cm soil cores were collected, homogenized, and analyzed during the wet season 2006-2010 from five freshwater sawgrass wetland marshes and three estuarine mangrove forests. Soil bulk density from the Taylor Slough basin ranged from 0.15 to 0.5 gm-cm^{-3}, was higher than from the Panhandle basin every year, and generally increased throughout the study period. Organic matter as a percent loss on ignition ranged from 7-12% from freshwater marshes and from 13-56% from estuarine mangroves. Extractable iron in soils was similar among drainage basins and wetland types, typically ranging from 0.6 to 2.0 g Fe kg^{-1}. In contrast, inorganic sulfur was on average over four times higher from estuarine soils relative to freshwater, and was positively correlated with soil organic matter. Finally total soil phosphorus (P) was lower in freshwater soils relative to estuarine soils (84 ± 5 versus 326 ± 32 mg P kg^{-1}). Total P from the freshwater marshes in the Panhandle basin rose throughout the study period from 54.7 ± 8.4 to 107 ± 17 mg P kg^{-1}, a possible outcome of differences in water management between drainage basins.

Keywords Bulk Density · Organic Matter · Phosphorus · Sulfur · Southeastern Everglades

Introduction

The comprehensive Everglades restoration plan (CERP) is designed to restore and protect freshwater flows through wetlands of the southern Florida landscape while continuing to meet the water needs of and flood protection for the general public (US Congress 2000). The Florida Coastal Everglades Long-Term Ecological Research program was established in part to monitor and research the wetland responses associated with the proposed, enhanced freshwater flows. To date, however, political and financial hurdles have delayed many wetland restoration projects. Despite these temporal setbacks, coastal Everglades ecosystems still experience spatial and temporal variation in water flows driven by natural phenomena (i.e., hurricanes, El-Niño events, sea level rise) and by ongoing, smaller-scale water management decisions. These changes in water flows—although not part of CERP per se—can be used to examine ecosystem response patterns and to predict the ecological outcome of forthcoming restoration efforts.

Historical flows of freshwater to the Everglades have been reduced drastically. Much of the remaining water flow through the northern Everglades is enriched in phosphorus and other constituents derived from agricultural and urban non-point source runoff (Davis 1994), leading to shifts in plant community dominance from sawgrass (Cladium jamaicense) to cattail (Typha sp.) (Wu et al. 1997; Waters et al. 2012). When water flows are enhanced with restoration, one potential concern is the extent to which increased delivery of water farther south into oligotrophic portions of the Everglades will also carry more phosphorus (Noe et al. 2001). Childers et al. (2006b) documented vegetation changes in response to increased water depth and hydroperiod in a section of the southeastern Everglades with restored water flow. The soil response to hydrologic drivers in the oligohaline Everglades, however, has not been well-studied.

Recent studies of spatial variation in bulk soil properties of the southern Everglades have provided evidence of phosphorus enrichment (Osborne et al. 2011; this volume), but temporal variation in soil properties in this region must be examined in the context of hydrologic change.

Here, we provide a five-year time series documenting interannual variation in bulk soil properties from two adjacent drainage basins in the southeastern coastal Everglades that historically have experienced different water management and flow restoration regimes (Kotun and Renshaw this issue). One of the basins currently receives discharge from water detention areas and from pumping stations; the other basin had freshwater flow enhanced in 1997 by removing canal levees and allowing for more diffuse, overbank flooding. In the absence of any information on soil conditions in downstream wetlands pre-levee removal, we cannot calibrate the basins for a paired watershed experiment (EPA 1993). We can, however, compare the temporal patterns in soil properties and look for evidence of phosphorus enrichment and other potential changes in related, non-conservative soil constituents (bulk density, organic matter, soil sulfur and extractable iron) between basins within the context of recent changes in water management.

Methods

Study Site

The study was completed in the southeastern portion of the Everglades as part of the Florida Coastal Everglades Long-Term Ecological Research program. Two drainage basins underlain by limestone bedrock comprise this portion of the Everglades, including Taylor Slough (TS) and an adjacent region called the Panhandle (Ph) (Fig. 1). Ecosystem structure of coastal Everglades wetlands is influenced strongly by hydrologic factors including water volume, source, and residence time (e.g., Ross et al., 2003). Freshwater runoff through canals, natural channels, and sheetflow drains into the coastal region where saltwater mixing from Florida Bay creates an estuarine environment. Whereas water delivery to the TS basin since 2000 has been dominated by directed flow through pump structures and associated detention areas to increase marsh hydroperiod (Kotun and Renshaw this issue), levee removal at the headwaters of the Ph basin (C-111 canal) in 1997 (Parker 2000) combined with lower elevation has led to more diffuse water delivery and a greater hydroperiod downstream relative to the TS basin (Childers et al. 2006b). In the TS basin, we sampled from three freshwater marshes dominated by sawgrass (*Cladium jamaicense*) and spikerush (*Eleocharis* sp.) and two estuarine mangrove forests dominated by scrub red mangrove (*Rhizophora mangle*). In the Ph basin, we sampled from two freshwater marshes and one estuarine mangrove forest dominated by the same species as in the TS basin. Relative to southwestern Everglades wetlands in the Shark River Slough basin, soils from the TS and Ph basins are more shallow and tend to have less peat and more marl deposits (Childers et al., 2003; Chambers and Pederson 2006).

Soil Collection and Analysis

Because of field logistics, soil collections were completed in the wet season at the beginning of August for each of the five years of the study, at locations within the wetland vegetation, i.e., at least 50 m away from stream or canal channels. Between years, samples at each site were collected within 20 m of each other. From each of the eight sampling sites, surface periphyton and floc were cleared and three 60-ml syringe barrels were pushed into the soil to a depth a 10 cm while holding the plunger at the soil surface to minimize compaction. The syringe barrels were capped with butyl rubber stoppers and stored on ice for transport to the laboratory, where cores were refrigerated prior to analysis.

Soils were extruded and homogenized, then sub-sampled. Samples for bulk density, % organic matter, total phosphorus (P) and extractable iron (Fe) analyses were placed in tared vials, dried at 80°C and weighed to determine bulk density, then ashed at 450°C for four hours to determine weight loss on ignition. The ashed soils were then resuspended in 1N HCl to hydrolyze phosphate for total P analysis (Chambers and Fourqurean 1991) and to determine extractable iron using the ferrozine method (Stookey, 1970). Although the largest P pool in south Florida wetland soils is associated with calcium carbonate (Koch et al. 2001), recent studies suggest iron oxide coatings play a critical role in P exchange between sediment and water in calcareous systems (Huang and Zhang 2010).

Soil samples for total sulfide extraction were first suspended in 1N zinc acetate to precipitate any free sulfide in solution. Then, the samples were boiled for one hour in a concentrated HCl and 1M reduced chromium solution to liberate sulfur gas as H_2S that was sequestered in a 1M NaOH trap. The trapped sulfide was fixed using Cline's reagent and analyzed colorimetrically (Cline 1969). Total sulfide includes free sulfide, iron monosulfide (FeS), polysulfides, and pyrite (FeS_2) (Chambers and Pederson 2006) and is used here as a proxy for the relative amount of sulfate exposure in reduced wetland soils.

Soil measurement averages ± standard errors were calculated by wetland type, by basin and by year. Data were summarized using factor analysis, and interannual variation in soil characteristics were examined graphically. Relationships between bulk density, organic matter and the concentration of non-conservative species (P, Fe, S) were investigated using multiple regression.

Results

Factor analysis of all soil parameters across years yielded three significant principal components accounting for 78% of the cumulative variation. The first principal component (PC1) had highest loadings for wetland type (freshwater marsh or mangrove forest), organic matter, and soil sulfide. PC2 had highest loadings for total P, extractable iron, and bulk density. Finally, PC3 had the highest loading for basin. We view these groupings as a separation by wetland type for PC1, with the primary difference in freshwater and mangrove soils characterized by relative amounts of organic matter and inorganic sulfide. For PC2, the grouping reflects soil differences characterized by P abundance that is influenced by amounts of extractable iron and calcium carbonate (both components of bulk density). For PC3, the separation of basin as a single factor indicates differences in soil parameters between TS and Ph basins. Differences between basins, wetland types, and among sampling years are summarized below.

Bulk Density

From the freshwater marsh sites, average bulk density each year was higher from the TS basin relative to the Ph basin and generally rose between 2006 and 2009 (Fig. 2A). Likewise, average bulk density from the estuarine mangrove sites rose between 2006 and 2009, then dropped in

2010. The range in bulk density was from a low of 0.119 g cm^{-3} from the Ph estuarine site in 2006 to a high of 0.521 g cm^{-3} from the TS freshwater sites in 2009.

Organic Matter

From freshwater marsh sites, average soil organic matter (OM) ranged between 7.4 and 12.1% and each year was higher from the TS basin relative to the Ph basin (Fig. 2B). In contrast, average OM was lower from the TS estuarine mangrove sties and exhibited a much broader interannual range (between 12.6 and 55.6%). Whereas OM from the two freshwater sites from the TS basin rose slightly between 2006 and 2009, OM from both TS and Ph estuarine sites tended to fall over that same time frame. OM was 2-3 times higher from estuarine sites relative to freshwater sites.

Total Phosphorus

Total P levels were comparably low from the five freshwater marsh sites in both TS and Ph basins (Fig 3), averaging less than 100 mg kg^{-1} over the five years sampled. Some interannual variation was noted in that total P from the two Ph marsh sites on average increased over the five years from 54.7 ± 8.4 mg kg^{-1} in 2006 to 107 ± 17 mg kg^{-1} in 2010. Total P levels were larger, more variable and exhibited no interannual pattern from the estuarine mangrove sites, although each year average total P was higher from the Ph site (410 ± 21 mg kg^{-1}) relative to the TS sites (240 ± 27 mg kg^{-1}) (Fig. 3). Stepwise, multiple regression of total P as a function of wetland type, bulk density, extractable iron and year yielded a significant correlation accounting for 48% of the variation in soil P ($p < 0.001$).

Extractable Iron

Average extractable Fe varied between 0.62 and 1.27 g kg^{-1} from freshwater marsh sites and between 0.82 and 9.05 g kg^{-1} from estuarine sites (Fig. 4A). Wetland soils from the Ph basin were typically higher in extractable Fe, relative to wetland soils from the TS basin (excluding one outlier from the Ph basin in 2006, 1.4 ± 0.1 versus 1.0 ± 0.1 g kg^{-1}). No interannual trends of increasing or decreasing Fe concentration were obvious. Stepwise, multiple regression of extractable iron as a function of total P, soil S, basin, and wetland type yielded a weak but significant correlation accounting for 23% of the variation in extractable iron ($p < 0.001$).

Total Sulfide

Reduced sulfur concentration was on average less than 1 mg kg^{-1} from freshwater marsh soils (0.36 ± 0.08 g kg^{-1}) and for most years greater than 1 from estuarine mangrove soils (2.41 ± 0.93 mg kg^{-1}) (Fig. 4B). Similar to the pattern observed for extractable Fe, in most years sulfur was higher in soils from the Ph basin relative to the TS basin. Multiple regression of soil S as a function of wetland type, percent organic matter, extractable iron, total P, and basin yielded a significant correlation accounting for 65% of the variation in soil S ($p < 0.001$).

Discussion

Soil characteristics are the integrated expression of a suite of physical and biogeochemical processes that take place over different spatial and temporal scales. For the coastal Everglades, the timing, volume, and quality of water flows through the landscape are principal factors influencing plant community structure (Ross 2003) and soil structure as well (Childers et al. 2003). Since large-scale restoration plans proposed for the Everglades will include increases in water flow, changes in soil properties may be expected. Here we present the results from adjacent drainage basins subjected to small-scale differences in water management, as a potential model system for determining the Everglades response to large-scale restoration. Superimposed upon water management differences between basins are potential differences in topography and other drivers of water movement, including sea level rise, acute storms and other meteorological phenomena that occur on regional scales. The two basins in the current study, however, are sufficiently close—similar to paired watersheds—that water management may account for the largest difference in water movements between basins.

Over the five-year time series of soil measurement, we observed no systematic changes in soil organic matter in either freshwater or estuarine wetland locations. Although percent organic matter was higher in estuarine mangrove forest soils relative to freshwater marsh soils, the patterns between basins were similar throughout the study, i.e., relative to the TS basin, organic matter from the Ph basin was lower every year in the freshwater marsh sites and higher in the estuarine forest sites from 2006-2010. Organic matter and bulk density typically are inversely related, but the small measured increase in organic matter (from 10% to 13%) when bulk density was also increasing (Fig. 2) could occur, for example, if organic density increased but inorganic density did not. A prior study reported values for organic matter averaged across all TS and Ph sites for 2003 that were higher for both freshwater and estuarine wetlands (14.4% and 35.8%, respectively) (Chambers and Pederson 2006). Given the range in organic matter from estuarine sites (Fig. 2A), we conclude that small-scale spatial variability of mangrove soils may limit our ability to detect interannual changes in OM associated with changes in water flow.

Soil bulk density differences among years were rather large, but consistent between basins and between wetland types. For both freshwater and estuarine soils, the average bulk density was always lower in the Ph basin relative to the TS basin, and all soils exhibited an average increase in bulk density 2006-2009, followed by a drop in 2010. All soils in the TS/Ph region are high in inorganic marl deposits (Childers et al. 2006a), although Osborne et al. (2011) found lower bulk density in the marl prairies typical of our Ph sites, relative to their TS sites. Rather than a response to water management, these discrepancies suggest that spatial variation among sites within a particular basin may be larger than temporal variation at the same site. This conclusion is consistent with the results of factor analysis that identified “basin” as a principal component (PC3) of variation among the data.

We measured substantial interannual variation in total soil phosphorus from estuarine mangrove sites (Fig. 3). Estuarine Everglades soils have more organic matter and thus store more P, as has been observed in prior studies (Koch and Reddy 1992; Childers et al. 2003; Chambers and Pederson 2006; Osborne et al. 2011). Soil P from the freshwater sites, in contrast, was less variable from year-to-year in our study, and low relative to prior years. Childers et al. (2003) collected soil in 1999 from the same three TS locations as our study and measured 142 mg P kg^{-1}, and Chambers and Pederson (2006) measured 220 mg kg^{-1} in 2003, roughly double what we found in 2006. Although the use of water retention areas in the TS basin in 2000 Sullivan et al. this issue) and removal of canal levees in the Ph basin in 1997 changed water flows farther upstream (Kotun and Renshaw this issue), we view these soil differences as a reflection of spatial variation within sampling sites or the result of other factors besides water management, such as hurricane-driven storm deposition (e.g., Castañeda-Moya et al. 2010), or interannual variation in rainfall patterns (Childers et al 2006a).

Total P from the freshwater marsh sites of the Ph basin, however, increased throughout the study period 2006-2010 (Fig. 3), unlike the pattern observed for any other soil property. Although a majority of soil P is organic (Scinto 1997), a significant fraction of Everglades soil P is carbonate-bound (Osborne et al. 2011), so soil P potentially could increase along with soil bulk density. Marsh soils from the Ph basin did exhibit increases in bulk density 2006-2009, but decreased in 2010. Further, increases in bulk density in the TS marsh soils were not matched by increases in total P, so we do not think the rise in soil P from the Ph marsh sites is due solely to increased P deposition with marl, the most common mode of P accumulation in Everglades soils (Noe and Childers 2007). Factor analysis identified a principal component (PC2) along an axis defined by variation in total P, extractable iron, and bulk density, suggesting an influence from iron oxides and perhaps other soil components in addition to carbonates.

Childers et al. (2006b) found that restoration of water flows in the Ph basin led to a decrease in primary production by sawgrass and a concomitant increase in spikerush (*Eleocharis* sp.) stem density. Shifts in plant community structure or algal production in the Ph marshes in response to increased water flow since 1997 could potentially shift the distribution and abundance of P in the soil, reflected in the observed increase in soil P 2006-2010 (Fig. 3). Plant root production and decomposition dynamics could change with the altered hydrology in the Ph basin. Alternately, the increased soil P could be a consequence of increased delivery of P along with the water (Rudnick et al. 1999), although Noe et al. (2002) found that experimental enrichment of Everglades water with P did not lead to increases in soil P after six months. More recently, Noe et al. (2003) used a radiotracer study to show that 27% of P added to the Everglades water column could be incorporated into soil within 18 days, so perhaps the time frame for rapid soil processing of P (weeks) is much shorter than the time frame needed for detection of long-term P accumulation used in the current study (years).

Extractable iron as a proxy for reactive iron is a fraction of total soil iron that in Everglades soils averages roughly 10 g kg^{-1} (Osborne et al. 2011). Because iron occurs in these biogenic carbonate soils in low concentration relative to terrigenous soils, the extent of various biogeochemical processes involving iron is diminished (Chambers et al. 2001). Soil phosphorus, for example, can sorb to reactive iron oxides, but prior studies have shown this is a minor fraction of the total P pool in carbonate sediment (Koch et al. 2001; Zhang et al. 2004). Reactive iron may be reduced under anaerobic conditions during the wet season in Everglades marsh soils, but during the dry season and water drawdown the iron may be re-oxidized. Thus, a seasonal sorption and release of P from iron still is plausible in carbonate soils (e.g., Huang and Zhang 2010). In mangrove soils, extractable iron content is slightly higher than marsh soils, and some "reacted" iron has precipitated largely as iron sulfide in this estuarine environment. The source of most of the iron in the south Florida landscape is atmospheric deposition from African dust (Prospero et al. 2010), and deposition rates were fairly uniform spatially and not dramatically different over the five years of our study (J.M. Prospero, pers. comm.). Thus, the very high level of extractable iron in the Panhandle mangrove soil in 2008 cannot be the result of localized deposition of atmospheric iron, but may instead be a localized concentrated source of iron.

The distribution of total reduced sulfur (Fig 4B) and the results of factor analysis identifying a principal component (PC1) along an axis of variation defined by wetland type, soil organic matter and inorganic sulfide demonstrate how anaerobic sulfate reduction is driven by the availability of both organic matter as an energy source and sulfate as a terminal electron acceptor. The estuarine soils are higher in organic matter and seawater-derived sulfate; the mangrove forests also experience more prolonged flooding than the freshwater marshes. As a result, reduced sulfur compounds accumulate more extensively in the mangrove soils in both the TS and the Ph basins. Interestingly, sulfur content is higher in Ph marsh soils relative to TS, even though organic content is slightly lower (Fig 2A). To the extent that freshwater canals may operate to deliver elevated levels of sulfate derived from agriculture to the northern Everglades (EPA 2000; Gilmour et al. 2007), increased flows of water derived from canal discharge originating in agricultural and urbanized areas could be a source of sulfate that will increase sulfide deposition in southeastern Everglades marshes. We did not observe an increase in soil sulfide deposition in the Ph basin over the same time interval that soil P was increasing, however, suggesting either that S inputs were relatively constant or had equilibrated more rapidly, or that the availability of reactive iron limited sulfide deposition. Finally, Price et al. (2006) found evidence of greater saltwater intrusion of groundwater into the Ph freshwater basin relative to TS, so the elevated sulfide signature in Ph soils could be from seawater sulfate and not from freshwater canal discharge.

The ongoing objective of Everglades restoration initiatives is the enhancement and re-distribution of freshwater flows through the south Florida landscape (Perry 2004). As paired drainage areas, the TS and Ph basins currently differ with respect to freshwater management.

Since basin soils were not characterized prior to the recent "treatment" of increased water flow into the Ph basin in 1997 and inclusion of water detention areas in the TS basin in 2000, however, the possible causes of the differences in soil properties (rising levels of soil P; higher levels of reduced sulfur) are speculative. It is entirely possible that—in the absence of a calibration phase prior to 1997—soils in the two basins were different before the recent changes in flow. Nevertheless, our five-year time series provides a baseline against which future, post-restoration measurements can be compared.

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Figure Legends

Fig. 1 Site map of the eastern coastal Everglades, where water flows through freshwater marshes and estuarine mangrove forests before discharging to Florida Bay. Soils were collected from eight locations within the Taylor Slough (TS) and Panhandle (Ph) drainage basins

Fig. 2 A Soil bulk density 2006-2010 from freshwater marsh and estuarine mangrove locations. B Percent organic matter as weight loss on ignition (LOI)

Fig. 3 Soil total phosphorus 2006-2010 from freshwater marsh and estuarine mangrove locations. Freshwater P scale is one-fourth the estuarine P scale.

Fig. 4 A Soil extractable iron from freshwater marsh and estuarine mangrove locations. B Total inorganic sulfide