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Spatial distributions and eco-partitioning of soil biogeochemical properties in the Everglades National Park

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Abstract Large-scale ecosystem restoration efforts, such as those in the Florida Everglades, can be long-term and resource intensive. To gauge success, restoration efforts must have a means to evaluate positive or negative results of instituted activities. Edaphic properties across the Everglades landscape have been determined to be a valuable metric for such evaluation, and as such, a baseline condition from which to make future comparisons and track ecosystem response is necessary. The objectives of this work were to document this baseline condition in the southern most hydrologic unit of the Everglades, Everglades National Park (ENP), and to determine if significant eco-partitioning of soil attributes exists that would suggest the need to focus monitoring efforts in particular eco-types within the ENP landscape. A total of 342 sites were sampled via soil coring and parameters such as total phosphorus (TP), total nitrogen (TN), total carbon (TC), total calcium, total magnesium, and bulk density were measured at three depth increments in the soil profile (floc, 0–10 cm, and 10–20 cm). Geostatistical analysis and GIS applications were employed to interpolate site-specific biogeochemical properties of soils across the entire extent of the ENP. Spatial patterns and eco-type comparisons suggest TC and TN to be highest in Shark River Slough (SRS) and the mangrove interface (MI), following trends of greatest organic soil accumulation. However, TP patterns suggest greatest storages in MI, SRS, and western marl and wet prairies. Eco-partitioning of soil constituents suggest local drivers of geology and hydrology are significant in determining potential areas to focus monitoring for future change detection.

Keywords Spatial distributions · Eco-partitioning · Soil biogeochemical properties · Everglades National Park

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Introduction

As with many wetland systems worldwide, the Everglades of South Florida, USA, have been greatly impacted due to anthropogenic activities. Alteration of hydrology from the implementation of drainage canals and water control structures, coupled with eutrophication effects from excessive nutrient-laden waters from upstream agricultural activities have resulted in the degradation of large portions of the remaining Everglades ecosystem (SFWMD 1992; Davis and Ogden 1994).

The largest ecosystem restoration effort in history was set in motion when the Water Resources Development Acts of 1992 and 1996 charged the US Army Corps of Engineers (USACE) with the task of researching the Everglades dilemma and developing a plan to restore and protect the remaining Everglades ecosystem while simultaneously providing for other water resource needs in South Florida. This restoration effort is defined under the Comprehensive Everglades Restoration Plan (CERP), the product of a collaborative effort between the USACE, the South Florida Water Management District, and over 100 other agency and university scientists (Scheidt and Kalla 2007). The CERP created the framework from which Everglades restoration efforts are implemented, most appropriately to restore the quality and suitable distribution of water to the Everglades, providing the basis for ecosystem recovery.

Environmental quality, assessed by both soil and water quality, has received much attention in determining factors responsible for the degradation of the unique landscape features, vegetation, and biota of the Florida Everglades (SFWMD 1992; Reddy et al. 1993, 1999; Davis and Ogden 1994; Davis 1994; Newman et al. 1996). The impacts of nutrient enrichment and hydrologic alteration on soil biogeochemical processes have been identified in many studies as the driving forces behind the observed changes in environmental quality and subsequently, ecosystem degradation in the Everglades (Koch and Reddy 1992; Davis 1994; Qualls and Richardson 1995; Amador and Jones 1995; Newman et al. 1998; Miao and Sklar 1998; Noe et al. 2001). Because wetland soils are long-term integrators of environmental conditions such as water quality, hydrology, and dominant vegetation types, they serve as valuable tools to monitor change in the environment (DeBusk et al. 1994; Newman et al. 1997; Reddy et al. 2005; Bruland et al. 2006; Scheidt and Kalla 2007).

In any ecological restoration effort, baseline information is absolutely critical as a metric for future comparisons and assessment of the success or failure of restoration activities. Historically, much work has been done to spatially document soil properties in the northern marshes of the Everglades, namely the Water Conservation Areas (WCAs) (DeBusk et al. 1994; Reddy et al. 1994; Newman et al. 1997). These previous studies have enabled recent comparisons and assessments of restoration efforts (Bruland et al. 2007; Marchant et al. 2009).

With the exception of Scheidt and Kalla (2007) who report temporally integrated spatial data in the Everglades over a 10-year period, there has been little attention paid to the edaphic properties of Everglades National Park (ENP), the landscape end-member of the Everglades ecosystem. Available information on soil biogeochemical properties in the current literature come from studies that often utilize small numbers of sample sites (Chen et al. 2000; Childers et al. 2003; Daoust and Childers 2004; Chambers and Pederson 2006). Further complicating this lack of information is the exceptional diversity of the ENP in terms of wetland eco-types such as the Shark River Slough, eastern marl prairies, western marl and wet prairies, Taylor Slough, and the mangrove interface. Often, studies reporting soil biogeochemical properties focus on one, or in some cases two, of the five main eco-types found in the ENP.

Because the aforementioned studies are both separated in time and spatial extent of sampling, there exists no definitive data set on soil biogeochemical properties in the ENP from which to evaluate the effectiveness of current and future restoration efforts. Therefore, it is necessary to document the current status of soil biogeochemical properties in the ENP with a spatially appropriate number and distribution of samples within a reasonable time frame. The objective of this research was to characterize and document soil biogeochemical properties across the Everglades National Park and by doing so, provide baseline spatial distributions of these properties for use in future assessment of restoration efforts.

Significant variability in edaphic properties associated with ecological structure is expected, especially in patterned landscapes (Watts et al. 2010), thus it is necessary to take into consideration the local drivers of ecosystem development when using spatial patterns at the landscape scale as metrics of evaluation. Five significant ecotypes, Shark River Slough, Taylor Slough, marl prairies, wet prairies, and the mangrove interface, were expected to accrete soil organic matter and thus soil nutrients at different levels based upon hydrology. Soil phosphorus, a performance measure under CERP and a metric of evaluation of anthropogenic impact, is thought to partition differentially in ENP soils, based upon the proximity to inflows (nutrient-enriched waters) and the duration of inundation (accretion of organic soil material and associated nutrients). For example, Shark River Slough, due to longer duration hydrology and connectivity to inflows, is expected to store more P than marl prairies, which have significantly shorter hydroperiods and exposure to enriched inflow waters. Thus, a second objective was to investigate eco-partitioning of soil nutrients among the very distinct and unique ecotypes found within the ENP to determine which of these ecotypes is most suited as a marker to detect change or evaluate restoration activities.

Methods

Study site

The ENP is located at the southern-most extent of the Greater Everglades Ecosystem (Fig. 1) and receives water from the Water Conservation Areas and Big Cypress National Preserve (BCNP). Water from WCA-3A enters the ENP through a system of controlled flood gates while water from BCNP enters by sheet flow along the northwestern boundary. Due to its location at the end of the freshwater flow path, the ENP has historically been somewhat protected from significantly degraded water quality inputs (Childers et al. 2003); however, the natural hydrology has been altered significantly since the advent of levies and water control structures in the early twentieth century (Davis and Ogden 1994).

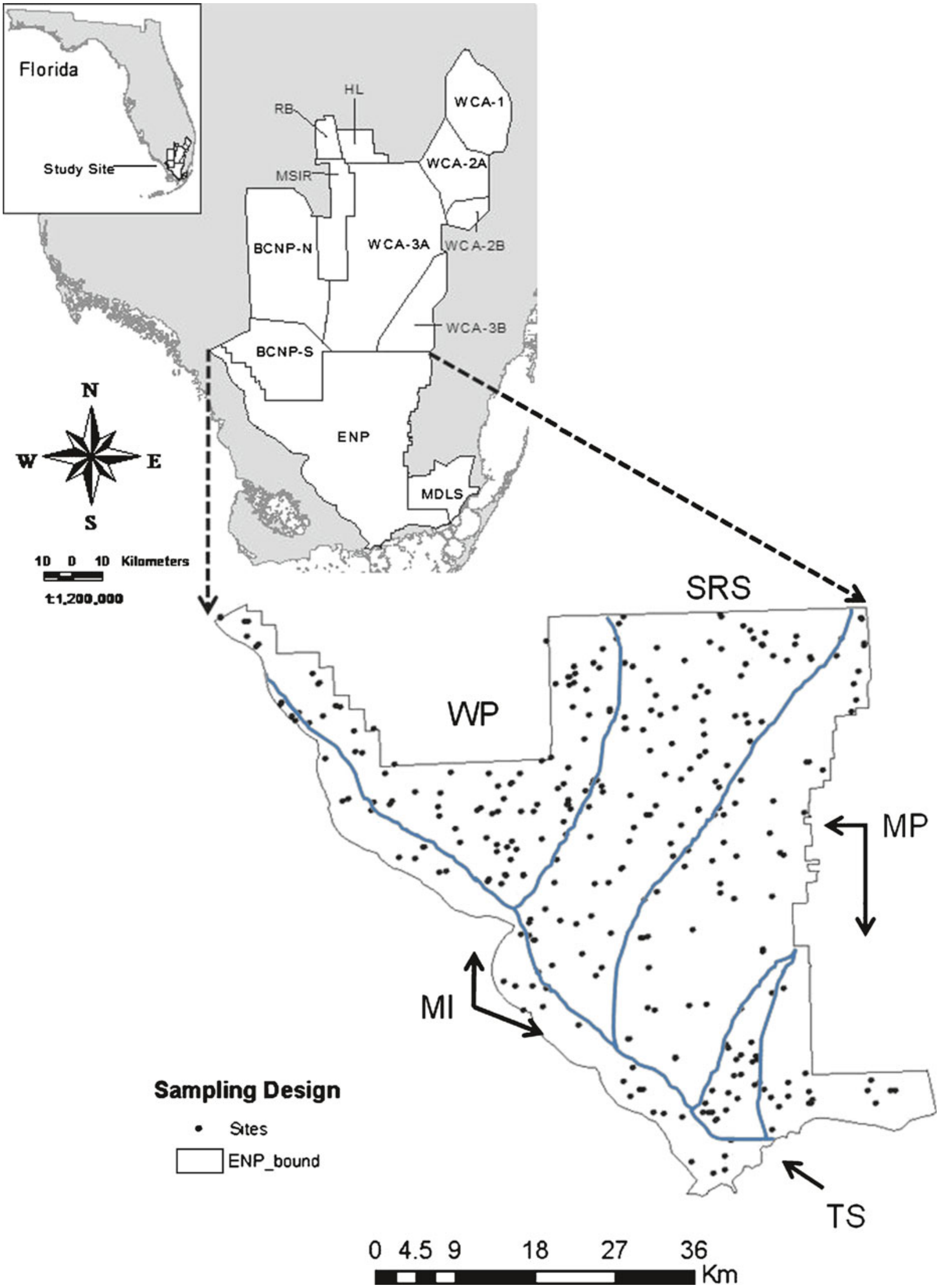
The ENP landscape can be characterized by dominant ecotypes such as the Shark River Slough (SRS), Taylor Slough (TS), eastern marl prairies (MP), western marl and wet prairies (WP), and the mangrove interface (MI; Fig. 1). These ecotypes are designated based on several interrelated factors such as elevational gradients in limestone bedrock, which influence hydroperiod and subsequently drive vegetation community structure (Browder and Ogden 1999) and soil formation processes (Obeysekera et al. 1999).

Ecotype descriptions and delineations

Shark River Slough is a dominant drainage feature on the landscape and extends southward from the park's northern border effectively bisecting the ENP. This slough is a major drainage route for waters entering the park due to its relatively low elevation and maintains a long hydroperiod relative to other ecotypes in this region. It is dominated by *Cladium jamaicense* Crantz. (sawgrass) ridges and open water periphyton and *Nymphea odorata* dominated sloughs (Ogden 2005), but also includes tree islands and sparse wet prairie communities throughout. Soils of the SRS are shallow to deep histosols that are normally inundated or saturated year round. Available hydroperiod data suggest that SRS soils are saturated or inundated 95–100% of the year (USGS 2008), making this ecotype the wettest and therefore the largest net organic soil accreting ecotype in the ENP.

Taylor Slough, similar to SRS, is located in the southeastern portion of the ENP. This slough historically drained the marl prairies and rocky glades to the north and areas that are now the city of Homestead and suburban Miami. Due to higher elevations and shorter hydroperiods, TS did not develop the extensive organic soils found in SRS. Available data suggest that TS is inundated or saturated in its main course for 65–85% of a normal year (USGS 2008). Vegetation is less robust due to the shallow soils that are close to underlying limestone, which results in lower vegetation densities and in some cases shorter stature of vegetation. Dominant vegetation is low-density *C. jamaicense* and *Eleocharis interstincta*. The ridge/slough mosaic of SRS is not a prominent feature of this ecotype, but periphyton is a major contributor to organic matter and marl formation.

Marl prairies are the dominant ecotype on the eastern side of SRS and have the shortest hydroperiod in the ENP completely drying in winter/spring months. These areas are very shallow


Florida
Study Site
HL
RB
WCA-1
WCA-2A
MSIR
BCNP-N
WCA-3A
WCA-2B
WCA-3B
BCNP-S
ENP
MDLS
N
W
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S
10 0 10 Kilometers
1:1,200,000
SRS
WP
MP
MI
TS
Sampling Design
Sites
ENP_bound
0 4.5 9 18 27 36
Km

Fig. 1 Map of Greater Everglades Ecosystem delineating the Everglades National Park boundary, sampling locations, and the five major ecotypes. Shark River Slough is denoted by (*SRS*), Taylor Slough (*TS*), eastern marl prairies (*MP*), western marl and wet prairies (*WP*), and the mangrove interface (*MI*)

to limestone and do not accrete organic soils like the other eco-types due to excessive drying. The limestone bedrock grades slowly from the rocky pinelands to the SRS, and along this gradient, periods of inundation may span from only >10–60% of the year. Along this gradient, soils are characterized as shallow (often less than 10 cm) marl derived from calcareous periphyton and limestone parent material (Gleason 1972; Chen et al. 2000) with little contribution from vegetation detrital material. Sparse, but very diverse vegetation is present in the MP, such as short stature *C. jamaicense*, *Muhlenbergia fillips* Curtis, *Schizachyrium rhizomatum* Gould, and a variety of grasses, sedges, and rushes, which are mostly limited to growth in dissolution pockets of the limestone bedrock (Olmstead and Loope 1984; Davis et al. 2005a, b)

Western marl and wet prairies are an intermediate ecotype, which has a shorter hydroperiod than the SRS and MI, yet unlike the eastern marl prairies, the gradient from marl-dominated soils to peat soils is much less dramatic. This area is characterized by alternating patches of marl prairie located along the western edge of SRS which transitions to more peat accreting wet prairies below the southern boundary of Big Cypress National Preserve. Marl prairies on the western edge of SRS are slightly lower in elevation than the corresponding marl prairies bordering the eastern edge. Intermediate hydroperiods make soil accretion possible in limited areas dominated by marl and gradually become peat accreting towards the west. Vegetation is similar to that of the eastern MP; however, vegetation densities are greater. Shallow organic soils, often less than 20 cm in depth, are accreted from vegetation such as *C. jamaicense*, large expanses of *E. interstincta*, and an assortment of grasses, sedges, and calcareous periphyton.

The mangrove interface represents the transition zone from fresh to brackish waters in the southern and western reaches of ENP. This ecotype is characterized by a mixture of emergent marsh, wet prairie, and sparse mangroves. *Rhizophora mangle* encroaches northward along tidally influenced creeks into areas of wet prairie subjected to occasional brackish water flooding. Dominant vegetation consists of mixed grasses, sedges, and rushes punctuated by mangroves. Soils are characterized by shallow to deep organic soils with noticeable influence of calcareous periphyton.

Ecotypes depicted in this research were delineated using guidance from previous studies (Flora and Rosendahl 1982; Noe et al. 2001), conceptual ecological models (Ogden 2005; Davis et al. 2005a, b), and visual determinations of the landscape while in the field. Delineations were created prior to grouping data or conducting data analyses.

Soil sampling

A stratified random sampling design was employed to determine field sampling sites prior to field collection. Strata were derived using available information such as historic soil and hydrologic and vegetation data. Official boundaries of the ENP were used in establishing the sampling scheme for this study, however, the mangrove interface was determined to be the southernmost extent of sampling, as areas south of this line are more brackish or estuarine in nature and therefore not useful for our objectives. A total of 342 sites in the ENP were sampled by helicopter in December, 2003. Concomitant with soil sampling, water depth, dominant ecotype, and a visual assessment of vegetation coverage was recorded at each site.

Samples were retrieved utilizing a 10-cm diameter stainless steel coring device following the methods described in Reddy et al. (2005) and Bruland et al. (2006). Cores were sectioned into floc, 0–10 cm, and 10–20 cm increments in the field, placed in zip closure plastic bags, and stored in coolers with ice until returned to the Wetland Biogeochemistry Laboratory at the University of Florida (UF) for analysis. In many places, shallow to limestone soils were encountered that did not extend to 20 cm depth. Likewise, a floc sample was not present at every site due to environmental or vegetative characteristics.

Samples were analyzed for total carbon (TC), total nitrogen (TN) total phosphorus (TP), total inorganic phosphorus (TPi), total calcium (TCa), total magnesium (TMg), total iron (TFe), total aluminum (TAl), loss on ignition (LOI), and bulk density (BD), among other properties, by standard analytical methods utilizing National Environmental Laboratory Accreditation Conference quality assurance and quality control protocols. Briefly, BD was determined by dividing oven dried weight of sample by the core sample volume. Total carbon and TN were measured using a Carlo-Erba NA 1500 CNS analyzer (Haak-Buchler Instruments, Saddlebrook, NJ, USA). Measurement of TP was made by following the ashing procedure of Anderson (1976) while TPi was determined by 1.0 M HCl extraction. Both TP and TPi were measured by automated colorimetric determination (Method 365.1, USEPA 1993a). The solutions from TP ashing procedure were also analyzed for TCa, TMg, TFe, and TAl by inductively coupled argon plasma spectrometry (Method 200.7, USEPA 1993b).

Geostatistical analysis

Maps of spatial distributions were created using Geostatistical Analyst extension of ArcGIS v9.1 (Environmental System Research Institute, Redlands, CA, USA) at the GIS Research Laboratory (UF). Inspection of the semivariograms indicated the appropriate range for modeling each analyte. Modeling the data required several iterations employing different geostatistical models such as ordinary kriging, universal kriging, and spline models. To evaluate the best fit of the data, the root mean square error (RMSE) was compared among the models for TP, as this parameter was considered the most important based upon our study objectives. Universal kriging and ordinary kriging RMSE values for TP were found to be 121.5 and 99.9, respectively. The RMSE for the spline model was found to be 89.6, the most accurate of the models tested, and was thus chosen as the model to utilize for final interpolations. A secondary reason for choosing the spline model was the lack of spatial averaging in the mathematical equation. While this method produces less visually aesthetic models, the need to detect change in the future requires the use of the most accurate model. In the case of TCa, the RMSE of the spline model (60,560) was higher than that of ordinary kriging (52,455), but was chosen to maintain consistency of present and future analyses.

Results and discussion

Comparison of soil properties by depth

Mean observed values of soil parameters measured in this study indicate differences in storages among soil depths across the ENP landscape (Table 1). As expected, soil BD tended to increase with depth, as did LOI and TC, suggesting that across the system, organic matter is more highly decomposed as depth increases. Bulk density and LOI trends are in agreement with similar studies of other hydrologic units (HUs) in the Everglades. Similarly, increasing TC with depth is not a new finding with respect to organic soils in the Everglades (Corstanje et al. 2006; Rivero et al. 2007); however, Bruland et al. (2006) reported decreasing TC with depth in WCA-3, just north of ENP.

More relevant is the wide range of values found in ENP versus the other HUs to the north. For example, ENP soils ranged in BD from 0.01 to 1.39 g cm^{-1}, a large range when compared to WCA-1 (0.001–0.40 g cm^{-1}; Corstanje et al. 2006) or WCA-2 (0.005–0.325 g cm^{-1}; Rivero et al. 2007). Similarly, LOI of ENP soils range from 4.1% to 94.6% as compared with 39–99% for the WCAs. These comparisons suggest that the variability in the soil physical properties is very high in ENP in contrast to other portions of the Everglades to the north. This finding is recurrent when making comparisons of the bulk soil properties of this study to similar data sets from other areas of the Everglades.

Total nitrogen tended to increase with soil depth as did TC, with TC/TN being consistently 15–17 for all soil depths, suggesting higher storage of TC and TN in lower strata of ENP soils. Again, this was not unexpected, however, it does contrast with the directional trends reported for WCA-3A (Bruland et al. 2006).

Of significant interest with respect to Everglades restoration, TP and TPi in ENP soils

Table 1 Mean observed values for all soil depths sampled in ENP

Parameter	Units	Floc $n = 142$	0–10 cm soil $n = 310$	10–20 cm soil $n = 226$
BD	g cm^{-3}	0.12 (0.01–0.6)	0.25 (0.06–0.87)	0.30 (0.06–1.39)
LOI	%	35.9 (10.4–87.8)	47.7 (7.1–94.6)	50.7 (4.1–93.6)
TP	mg kg^{-1}	143 (25–685)	312 (38–1317)	260 (30–853)
TPi	mg kg^{-1}	40 (8–220)	70 (2–516)	52 (6–370)
TN	g kg^{-1}	13.5 (5.5–37.0)	18.6 (3.0–43.1)	18.9 (1.4–42.5)
TC	g kg^{-1}	230 (146–431)	273 (29–495)	289 (26–501)
TCa	g kg^{-1}	241 (19–365)	162 (8–374)	137 (2–371)
TMg	g kg^{-1}	2.25 (0.7–9.0)	2.6 (0.6–11.0)	3.2 (0.5–13.3)
TFe	g kg^{-1}	5.87 (0.35–38.2)	10.2 (0.6–99.5)	10.4 (0.6–137)
Tal	g kg^{-1}	3.48 (0.15–44.2)	10.1 (0.3–125)	12.4 (0.3–115)

BD dulk density, *LOI* loss on ignition, *TP* total phosphorus, *TPi* total inorganic phosphorus, *TN* total nitrogen, *TC* total carbon, *TCa* total calcium, *TMg* total magnesium, *TFe* total iron, *TAl* total aluminum

tended to be lowest in the floc layer and highest in the surface soil (0–10 cm layer). This is in contrast to all other published studies of Everglades soils where the floc layer, made up of small unconsolidated detrital material predominantly from periphyton and to a lesser extent emergent vegetation, is often the most biologically active and thus higher with respect to phosphorus content than soils (Neto et al. 2006). In fact, the floc layer tended to have the lowest mean values for all measured parameters save TCa, indicating the significant input of calcareous periphyton detritus in the floc layer of many sites. Calcium is a dominant cation throughout most of the GEE due to proximity of limestone bedrock. Rapid dissolution of calcite with changes in pH (driven by decomposition) can reduce high TCa concentrations in subsurface soils. Further, this trend is also indicative of increasing LOI with depth as TCa, whether as calcite or limestone, makes up the clear majority of inorganic material in ENP soils and other HUs to the north.

Unlike TCa, the other metals in this study all appeared to increase or plateau with depth, suggesting no biological limitation of these micronutrients and thus constant accumulation in soils with depth. These findings are similar to trends reported by other studies on soil properties in the northern Everglades (Reddy et al. 2005).

Further investigation of trends in the data as partitioned by floc or soil depth with respect to TP, a major focal point in both soil and water quality restoration efforts, reveals that only 2% of floc samples exceed the established threshold for P-impacted status of 500 mg kg^{-1} (Scheidt et al. 2000; Bruland et al. 2006; Scheidt and Kalla 2007). Compared to approximately 50% of floc samples in excess of this threshold in WCA-2A, a highly P-impacted area (Rivero et al. 2007), this finding suggests that ENP is not significantly P impacted at this time or that analysis of all floc data combined may be confounding these results. A closer look at the surface soil supports both previous assertions. Forty-nine of the 310 soil samples (0–10 cm layer) in the ENP exceeded the impacted threshold resulting in 16% of the sites being considered enriched. Previous studies of northern Everglades report 21% surface soils impacted in WCA-1 (Corstanje et al. 2006), 39% in WCA-2A (Rivero et al. 2007), and 25% in WCA-3A (Bruland et al. 2006), suggesting that the ENP is the least impacted of the major HUs with respect to soil P enrichment. Due to the relatively high variability associated with properties of soils in ENP relative to other HUs, bulk data analyses based upon soil depth may mask more significant trends. Further investigation of surface soil TP reveals that 33% of the enriched sites fall on the southwestern boundary of the ENP, where brackish water ecotypes become more prevalent. These sites are significantly removed (downstream) from any potential anthropogenic enrichment sources, and within close proximity to the marine environment, which is also evidenced by the elevated TMg content (Fig. 2e). A positive relationship between proximity to the marine environment and soil TP levels in lower SRS soils has been shown previously (Mancera Pineda et al. 2009; Chambers and Pederson 2006; Chen and Twilley 1999), hence removal of these sites from the analysis results in surface soil P enrichment in ENP to be approximately 10.7% of sites sampled. This

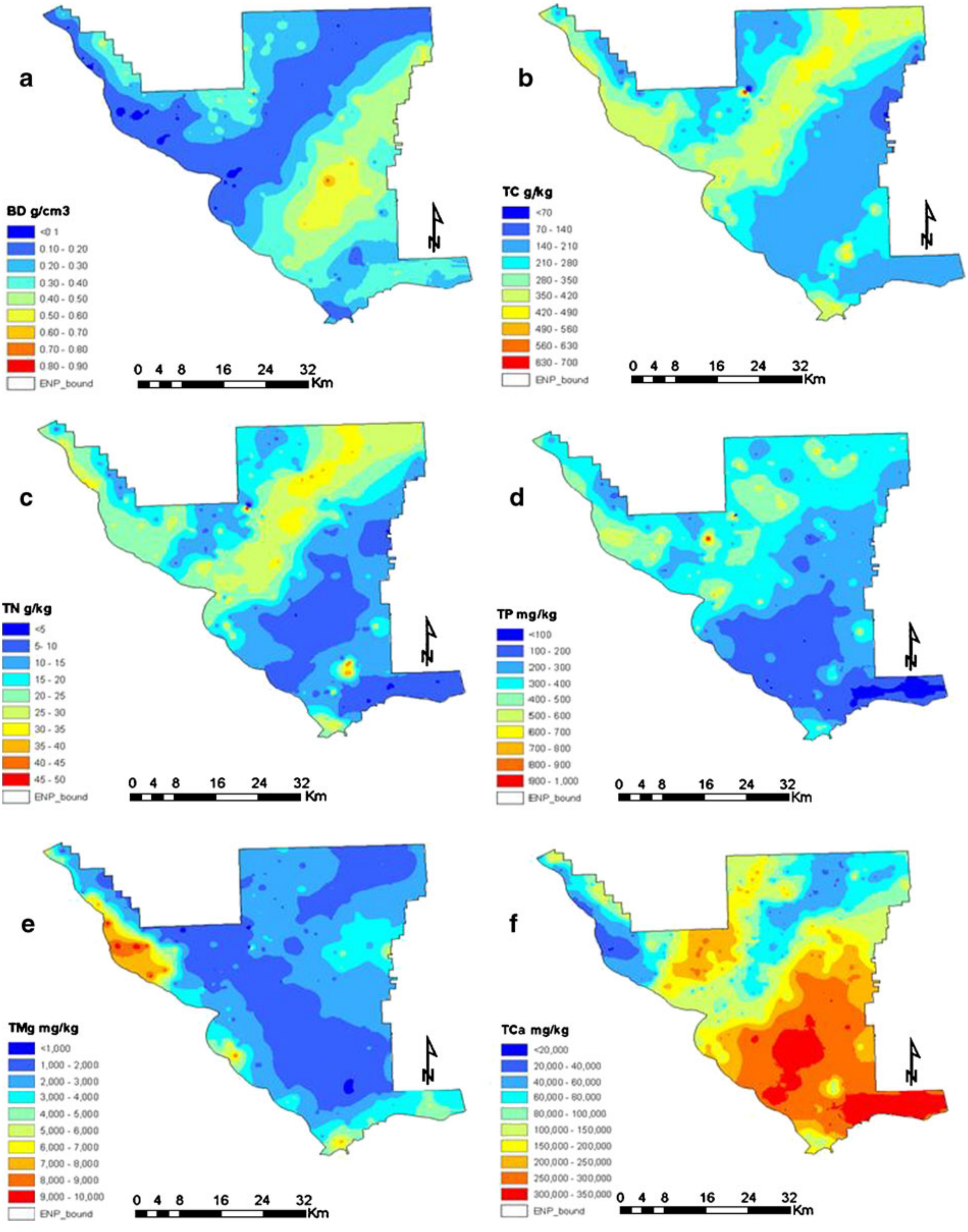

Fig. 2 Spatial distributions of selected 0–10 cm soil properties; **a** soil bulk density (*BD*), **b** soil total carbon (*TC*), **c** soil total nitrogen (*TN*), **d** soil total phosphorus (*TP*), **e** soil total magnesium (*TMg*), and **f** soil total calcium (*TCa*)

finding suggests that both the ENP is relatively unimpacted by anthropogenic P enrichment, and that a straightforward approach to data analysis in the ENP that groups all data irrespective of local drivers of variability, a technique that has been used in other areas of the Everglades, is not suitable for the ENP due to high variability. The significant variability of these parameters is due to the highly diversified ecotypes (hydrologically driven) within the ENP and indicated by the extreme range of values observed. The need to address local drivers of variability will be explored more thoroughly in the following sections.

Spatial distributions of soil attributes

When conducting studies such as this one with the objective of establishing a baseline datum for which to evaluate changes over time by deviation from pre-restoration conditions, it is important to maximize the sampling effort to capture spatial trends and gradients. Unlike other spatial studies of the Everglades, the stratified random sampling design of ENP did not have the benefit of any other spatial data. Most previous data came from a small number of sites within one or maybe two of the five dominant ecotypes in the freshwater portions of ENP (Amador and Jones 1995; Childers et al. 2003; Daoust and Childers 2004). Therefore, without appreciable prior soils data, we attempted to maximize our sampling effectiveness using vegetation and other available information. This resulted in the sampling regime used in this work (Fig. 1). Mapping attributes measured at these locations presented a challenge as the parameters measured contained a large degree of variability not seen previously in Everglades soil mapping endeavors. Due to the high degree of variability associated with floc presence, there were too few floc samples to successfully map attributes and maintain any confidence in those predictions. Likewise, soils deeper than 10 cm, although more abundant, left the MP, WP, and even the northernmost portion of SRS without a reasonable density of samples, thus the choice was made to include only the 0–10 cm surface soil maps. Although the variability was high across the landscape, spatial autocorrelation was likewise greater than that reported in any other HU of the GEE. This suggests that the diversity of landscape conditions or ecotypes, was a very significant driver with respect to soil attributes.

The spatial distribution of BD and TC (Fig. 2a and b, respectively) are the most descriptive in terms of approximating the delineation of the ecotypes as presented in Fig. 1. Bulk densities are lowest in the peat accreting areas of SRS and in the MI. This corresponds to the areas of longest hydroperiods (lowest elevations) and thus greatest ability to retain organic matter. East of SRS, the MP are dominated by higher BD soils, due to a large part from marl formation and the short hydroperiods that deter any substantial accretion of organic matter. Taylor Slough is just barely discernable based on the distribution of BD. This may be in part due to the relatively narrow nature of TS at the landscape scale and the resulting relatively low number of sampling points capturing attributes of this drainage feature. To the west of SRS, the distribution of BD values suggests the WP have somewhat greater mineral content than their SRS counterparts, but do not approximate MP in soil densities. Similarly, TC patterns also outline these ecotypes very well, with TC being highest in SRS and MI areas, followed by WP and TS. The MP soils are clearly lowest in TC content. East to west gradients in both BD and TC are clear and denote the transition from short-hydroperiod marl-dominated areas into the long-hydroperiod peat-accreting SRS.

As observed with the comparison of soil depths, TN tended to follow the trends of TC and BD. As the TC/TN ratio remains fairly constant (15–17) so does the spatial distribution of TN (Fig. 2c). As expected, TN displays a similar trend as TC, suggesting maximum storage in peat-accreting areas of SRS, MI, WP, and to a lesser extent TS. As with TC, MP-dominated areas are very low in TN. Visual inspection of models of TC and TN (Fig. 2b and c, respectively) reveals a noticeable instance where two neighboring sites have extremely differing values (western edge of SRS). This observation, while rare in this data set, is an important observation as it suggests there may be unique areas of ENP which exhibit increased spatial heterogeneity of soil properties and/or landscape characteristics. Spline model surfaces are much more sensitive with respect to the modeled surface meeting the actual point values and thus these nuances are apparent where they may otherwise be smoothed in kriging models. Because these maps will serve as CERP baselines of soil biogeochemical condition, it was our objective to create the most reliable prediction maps based on the data collected to make future change detection more reliable.

The intended use of these soil maps was for documentation of baseline conditions of edaphic attributes in the ENP prior to CERP or other restoration activities. Because of intense focus on P with respect to restoring soil and water quality (Koch and Reddy 1992; Reddy et al. 1993; Davis 1994; Newman et al. 1996; Noe et al. 2001), the map of TP across the ENP was anticipated to be highly variable and gradient dependent, suggesting similar ecosystem drivers influence TP as they do TC and TN. These ecosystem drivers, hydroperiod, vegetation, and landscape position are all interrelated and central to the maintenance of a peat-accreting system (Davis and Ogden 1994; Newman et al. 1998; Ogden 2005). The results of the TP mapping effort (Fig. 2d) suggest that this is not the case. The expectation of TP to be sequestered in soils of SRS, TS, and MI, and to follow the same general patterns as TC and TN, was found to be partially true. Relative levels of TP in soils of WP suggests that there is somewhat greater potential of WP soils to store TP, while TS areas did not appear to deviate greatly from the MP or low-TP areas of WP. This was an interesting finding as TS was thought to have a longer hydroperiod and thus capable of peat accretion similar, although to a lesser extent, to SRS. Also of interest is the lack of strong gradients visible in storage patterns of soil TP in the MP. While TN and TC, as well as BD, suggest a fairly static delineation of SRS, TP patterns tended to grade more gradually from SRS to MP, suggesting that TP is well conserved in these areas, even if significant soil-forming processes are not present. With respect to P enrichment, the spatial patterns associated with soil TP in ENP do not reflect gradient-driven enrichment similar to what has been observed and reported for HUs in the northern Everglades (Koch and Reddy 1992; DeBusk et al. 1994; Qualls and Richardson 1995; Newman et al. 1997). The spatial distribution of TP further suggests that the MI does contain a significant amount of P relative to the other areas of ENP; however, this trend is only observed in half of the MI landscape from the eastern edge of SRS west. The other portion of the MI east of SRS tends to be very low in TP, respectively, suggesting again that the TS outflow is not exporting a significant amount of P to that area. Marine and brackish systems, such as the southernmost portions of the ENP are often not as P limited due to the influence of marine water chemistry; rather N limitation tends to be more significant here. This makes the low TP patterns observed at the terminus of TS very interesting as this area is also mangrove dominated and brackish in nature.

Spatial distribution of TMg observed in the 0–10 cm soil layer suggests that Mg is not conserved over the diverse ecotypes in ENP (Fig. 2e). Rather, the elevated areas of TMg occur in the MI, an area subject to brackish and saline water incursions from Florida Bay. This pattern suggests that MI soils are mostly influenced by marine water chemistry, which appears to be the most significant on the far western portion of the ENP in an area drained by Turner and Lostman's Rivers. These natural water conveyances, as well as numerous smaller streams, likely allow more frequent influence from marine waters in this area.

Although Ca is also abundant in marine and brackish waters, the clear driver of soil TCa in the ENP is from limestone dissolution and marl formation (Fig. 2f). The MP in the east and WP in the west contain the highest levels of TCa in the ENP and are the shallowest to limestone areas in the park. Note that the high level of periphyton activity in SRS is not significant relative to TCa in ecotypes with exposed limestone drainages. Also of interest is the area on the southwestern portion of the MI where TMg is highest. In this area TCa is relatively low, even with a clear marine influence. This observation further supports the assertion that exposed limestone areas exert the most influence over TCa storage in ENP soils.

Comparison by ecotypes

Several factors associated with landscape scale investigations can cause the introduction of error. The sampling design and density can introduce error in the interpretation of data if key locations are not sampled or if some ecological drivers are not considered when creating the sampling design. As previously stated, the sampling design of ENP for this study did not have the benefit of significant soils information, therefore sampling was designed to best cover the landscape and reveal potential gradients. Further, methods and scale of data investigation can bring about misconceptions about spatial patterns and scale of distributions across large areas. The results of this work when viewed as a whole (soil depth comparisons) reveal only a small portion of the potential information contained in the data. The first presentation of this data by soil depth revealed a large amount of variability as seen in the range of edaphic properties measured. By interpolating patterns across the landscape, the picture of soil property partitioning becomes more clear. These interpolations suggest that a closer look may be necessary to better understand and predict relationships of soil attributes with dominant ecotypes in the ENP landscape which may have bearing on how future change detection and assessment is approached.

To accomplish this, attributes of the 0–10 cm surface soils were grouped by ecotype for a more focused investigation of eco-partitioning (Table 2). As expected, BD of SRS and the MI had the lowest mean values observed (0.18 and 0.13 g cm^{-3}, respectively); however, MI coefficient of variation (C_v) was high (0.77), suggesting a wide range of observed values in this area. Surprisingly, BD values of TS were very similar to WP instead of SRS. This finding suggests that TS, although a significant drainage feature on the ENP landscape and similar in hydrology to SRS, is intermediate with respect to soil formation and retention potential and is significantly influenced by the surrounding MP (marl formation). As indicated by the interpolated maps of TC and TN, these parameters were inversely related to BD, resulting in partitioning of TC and TN in the longest hydroperiod ecotypes, MI and SRS. Similarly, TS and WP ecotypes were significantly lower in TC and TN than SRS and MI. The similarity of TS and WP ecotypes further supports the assertion that the MP proximate to TS influence this ecotype greatly. As expected MP ecotype was lowest in terms of TC and TN content due to reduced soil forming and retention potential. The partitioning of TCa and TMg followed the expected order of partitioning as suggested by the spatial distributions (Fig. 2e and f). The highest levels of TMg were found in the MI followed by MP and SRS. Taylor Slough and WP were similar and had lowest observed concentrations of TMg. Partitioning of TCa was found to be highest in MP, followed by TS and WP. The significantly lower levels of TCa in SRS and MI suggest that even though these ecotypes have appreciable periphyton activity, it is not conserved in the soil to the extent of other ecotypes.

Of greatest interest with respect to restoration planning and assessment, TP partitioning among ecotypes did not follow expected trends. It was thought that MI and SRS would retain the most P on the landscape, and while MI did have the highest mean value (439 mg kg^{-1}), WP (350 mg kg^{-1}) surpassed SRS (330 mg kg^{-1}) in terms of TP retention in surface soils. Further, TS (194 mg kg^{-1}) was very similar to MP (175 mg kg^{-1}), suggesting little P retention in soils. The disparity between SRS and TS values suggest that TS is not comparable to SRS in terms of ecological function, or at the

Table 2 Mean observed values of soil properties by ecotype in Everglades National Park

Ecotype	Sample (n)	BD	TC	TN	TP	TMg	TCa
		g cm^{-3}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	g kg^{-1}	g kg^{-1}
SRS	98	0.18 (0.23)	339 (0.32)	23.9 (0.25)	330 (0.30)	2.28 (0.24)	54 (0.44)
TS	23	0.23 (0.43)	249 (0.40)	15.4 (0.36)	194 (0.29)	1.96 (0.51)	169 (0.41)
MP	66	0.52 (0.27)	166 (0.23)	8.6 (0.37)	175 (0.38)	2.61 (0.36)	277 (0.28)
WP	80	0.28 (0.40)	241 (0.24)	17.5 (0.32)	350 (0.21)	1.99 (0.39)	167 (0.30)
MI	43	0.13 (0.77)	359 (0.28)	24.3 (0.29)	439 (0.27)	4.86 (0.30)	58 (0.21)

Parentheses ( ) denote coefficient of variation (C_v)

very least, the relatively small size of TS and the broad spatial nature of this investigation did not detect TP levels suggestive of long-term peat storage and accretion. This is further supported by the results of BD, TC, and TN. Both ecotype comparisons and interpolated maps suggest that SRS and WP are the most impacted areas with regard to soil TP in the ENP (12% and 13% of soils exceed 500 mg kg^{-1} threshold for P impact status, respectively). Because the MI is heavily influenced by the marine environment (Rivera-Monroy et al. 2011), the higher TP values (37% meet criteria for P impact) in this area are not considered to be of anthropogenic origin. Chen and Twilley (1999) reported MI soils in the range of 500–1,000 mg kg^{-1}. Similarly, Chambers and Pederson (2006) reported soils in this area to have TP values from 800–894 mg kg^{-1}, presumably from interaction with brackish waters. Koch and Snedaker (1997) reported a high soil TP value of 1,434 mg kg^{-1}, which was not attributed to anthropogenic sources nor was there any note of ecosystem degradation in these areas.

Hence, the elevated TP values of soils in the MI are thought to reflect the natural accumulation and burial of P from mangrove primary production (Poret et al. 2006; Rivera Monroy et al. 2011).

Unlike MI sites, SRS and WP, due to their proximity to and potential for impact from degraded water quality upstream, are of great interest. The interpolation of surface soil TP combined with the result of the eco-partitioning investigation suggest that these areas are important focal points for investigation of change detection, as much work has been done to understand the ecological significance of P enrichment in these areas (Noe et al. 2002; Childers et al. 2003; Daoust and Childers 2004; Neto et al. 2006). This is especially the case in WP where little soil TP accretion was expected.

A finding of particular interest concerning soil TP, was the lack of signature in TS in both the eco-partitioning and interpolation results. Data pooled into TS ecotype showed no samples exceeded the threshold for P impact. This is supported by Childers et al. (2003) who monitored soil transects in TS in 1999 and reported soil TP to range from 150 to 250 mg kg^{-1}. However, more recent investigations (2007) of TS soils (Reddy and Osborne, unpublished data) revealed significant anthropogenic P enrichment in the upper reaches of TS, ranging from 450 to 1,200 mg kg^{-1} with an enrichment front extending 7 km downstream of inflow from the S-332 control structure and contained within the slough channel. The disparity of TP from these two studies clearly identifies sampling location as a very important factor when dealing with TS. The 2007 study (Reddy and Osborne, unpublished data) sampled within the main channel of TS, where as Childers et al. (2003) sampled just upslope (within the marl prairie) from the peat-accreting areas in TS (evidenced by significantly different BD). The distance from channel to marl prairie type floodplain was less than 200 m, suggesting that in this particular area, TP enrichment is contained to the TS channel. A significant implication for this study is that while we were able to sample the ENP at a density to accurately depict the spatial distribution of soil properties, without the benefit of incorporating the understanding of local drivers of variability within ecotypes, in this case the narrow band of peat soils in TS, we were unable to detect the changes occurring in TS. From this finding we have learned the relative value of local, small-scale heterogeneity (and the consideration of such) in the context of eco-partitioning and thus contend that future sampling and interpretation of soils in TS require adequate sampling of the TS channel.

Finally, this work provides a spatially thorough survey of soil properties across the ENP and provides the baseline condition from which to evaluate change from future restoration efforts, a critical component for restoration success. Spatial distributions of edaphic properties suggest that the ENP is relatively unimpacted with respect to soil TP in comparison to northern HUs. The results of the investigation of eco-partitioning suggest that future monitoring efforts should focus intensive sampling on ecotypes where observation of changes has the highest potential, namely WP, SRS, and TS channel. By using information concerning ecotypes and associated eco-partitioning of soil constituents combined with spatial modeling, a more focused, and thus more reliable, interpretation of the impact to soils from future restoration efforts is possible.

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