Assessment of the Spatial Distribution of Soil Properties in a Northern Everglades Marsh


ABSTRACT

Florida Everglades restoration plans are aimed at maintaining and restoring characteristic landscape features such as soil, vegetation, and hydrologic patterns. This study presents the results from an exhaustive spatial sampling of key soil properties in Water Conservation Area 1 (WCA 1), which is part of the northern Everglades. Three soil strata were sampled: floc, upper 0- to 10-cm soil layer, and 10- to 20-cm soil layer. A variety of properties were measured including bulk density (BD), loss on ignition (LOI), total phosphorus (TP), total inorganic phosphorus (TIP), total nitrogen (TN), total carbon (TC), total iron (TFe), total magnesium (TMg), total aluminum (TAl), and total calcium (TCa). Interpolated maps and model prediction uncertainties of properties were generated using geostatistical methods. We found that the uncertainty associated with spatial predictions of floc, particularly floc BD, was highest, whereas spatial predictions of soil chemical properties such as soil Ca were more accurate. The resultant spatial patterns for these soil properties identified three predominant features in WCA 1: (i) a north to south gradient in soil properties associated with the predominant hydrological gradient, (ii) areas of considerable soil nutrient enrichment along the western canal of WCA 1, and (iii) areas of considerable Fe enrichment along the eastern canal. By using geostatistical techniques we were able to describe the spatial dynamics of soil variables and express these predictions with an acceptable level of uncertainty.

EcoLOGICAL RESTORATION of degraded lands is an emerging challenge arising from the growing recognition of the value of services provided by healthy ecosystems. Restoration efforts range in intensity and complexity aiming to recover previous functions (e.g., to re-establish exogenous flows of water and sediment) and/or landscape patterns (e.g., nutrient status, vegetation structure). Restoration in the Everglades, as enacted under the Everglades Forever Act (State of Florida, 1994), is concerned with maintaining and restoring a habitat mosaic that is comprised of, among others, sawgrass (Cladium jamaicense Crantz) prairies and patches, open water sloughs, tree islands, and marl-forming marshes (Noe et al., 2001). Soil nutrient enrichment has been associated with significant alterations of Everglades wetland ecosystem structure and function (DeBusk et al., 1994, 2001; Davis et al., 2003; King et al., 2004). Nutrient gradients (Davis, 1991; DeBusk et al., 1994) produce a patterned response within the Everglades. For example, cattail (Typha domingensis Pers.) dominates areas close to nutrient inflows, which were also found to contain high levels of water column and soil phosphorus (P) content. This study focuses on Water Conservation Area 1 (WCA 1), which is part of the Loxahatchee National Wildlife Refuge (LNWR) of the Greater Everglades. The area has been designated as “Outstanding Florida Waters” by the State of Florida and contains much of the distinctive habitat favored under the Greater Everglades restoration plans. The conservation area is also a unique hydrologic unit of the Everglades that is a slightly acidic, rain-fed system that sits on deep peat (South Florida Water Management District, 1992). Since it was last sampled in 1991 there is little current knowledge on the movement and distribution of soil nutrients and cations in this particular water conservation area (Newman et al., 1997).

Soils in wetlands often exhibit characteristic, complex spatial patterns that indicate heterogeneity in soil resources and affect patterns of soil process rates (Ettema et al., 1998). These patterns are often a combination of current and historical autochtonous and allochtonous functions that influence wetland systems (Stolt et al., 2001). Commonly, the spatial distribution of soil properties is not uniform. This uneven distribution of soil characteristics, such as nutrient availability, organic content, and mineral content, implicitly reflects the processes that occur within the larger ecosystem. Spatial variability of soil characteristics can strongly affect the outcomes of logical, empirical, and physical models of soil and landscape processes (Lin et al., 2005) including those available to managers and planners in the Everglades restoration efforts. As a result, an adequate understanding of soil variability as a function of space becomes essential. Geostatistics views soil properties as continuous variables and models these as the most likely outcomes of random processes (Webster, 2000). This allows the random variation in soil properties to be formulated mathematically, which minimizes the prediction error for the observed variables and provides confidence in predictions for the unsampled locations. In other words, by designing, executing, and analyzing a spatial study using geostatistics we can quantitatively assess the properties and associated uncertainty of the spatial distribution of soil characteristics. This paper will analyze underlying causes of soil variability, increase our understanding of a soft water system in the Everglades, and support future research efforts aimed at protecting this portion of the Florida landscape.

The specific objectives of this study were to identify spatial patterns of physical and chemical soil properties in the topsoil and floc (decaying plant

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Abbreviations: BD, bulk density; LNWR, Loxahatchee National Wildlife Refuge; LOI, loss on ignition; TAI, total aluminum; TC, total carbon; TCA, total calcium; TFe, total iron; TIP, total inorganic phosphorus; TMg, total magnesium; TN, total nitrogen; TP, total phosphorus; WCA, Water Conservation Area.
MATERIALS AND METHODS

Site Description

The WCA 1 is a teardrop-shaped 55900-ha area bounded by a 92-km levee and an interior borrow canal. Water Conservation Area 1 is delimited to the west by the Everglades Agricultural Area (EEA) and by heavily urbanized areas to the east (Fig. 1). This conservation area forms part of the 60 250-ha LNWR, which was established in 1951 in an agreement between the South Florida Water Management District and the U.S. Fish and Wildlife Service, under the Migratory Bird Conservation Act. This agreement was later amended to include the 650-ha Strazzulla Marsh, which lies adjacent to WCA 1. In 1978, the Refuge was recognized as “Outstanding Florida Waters,” which affords it greater water quality protection. Currently, WCA 1 contains characteristic Everglades habitat such as open water (114 ha), wet prairies (22 856 ha), sloughs (110 ha), sawgrass (11348 ha), tree islands (8867 ha), cattail (Typha spp.) (2317 ha), and cypress (Taxodium spp.) swamp (162 ha) and some unclassified areas (United States Fish and Wildlife Service, 2004). In the 1960s, cattail coverage was limited to less than 1% of the vegetation community (United States Fish and Wildlife Service, 2004). In response to elevated nutrient inputs from the perimeter canals, the cattail coverage had increased to 4% by 1987 (South Florida Water Management District, 1992) to over 10% in 1991 (Newman et al., 1997).

Restoration efforts have resulted in the construction of stormwater treatment areas (STAs) to treat exogenous inputs of surface runoff from the adjacent areas (Fig. 1). Stormwater...
Field Methods

Floc and soil samples were collected in March 2003 at 120 sites and in August 2004 at 11 sites (Fig. 1). Not all sites that were sampled contained floc. A stratified random sampling design was used, based on a previous soil sampling of the area (Newman et al., 1997) combined with historic ecological and hydrologic data layers (e.g., Normalized Difference Vegetation Index) to determine the strata. The sampling design was optimized to account for short, medium, and long range variability of attributes. The sampling sites were accessed using a float helicopter. A global positioning system with real-time Wide Area Augmentation System (WAAS) was used to ensure a positional accuracy of <3 m to locate the sites. We used a minimum of four satellites and average of six satellites to receive accurate readings of x,y coordinates and minimize the positional dilution of precision (PDOP) measure. Sampling was restricted to herbaceous and open water plant communities. Soils were sampled using a 10-cm (inner diameter) push core tube up to a depth of 20 cm beneath the soil surface. Floc was measured by allowing settling of headspace water in the core, pouring off excess water, then extruding floc to a point of recognizable soil. Floc depth was measured using a graded (cm) tube. Triplicates were obtained at about 10% of the sites. The cores were sectioned into three strata: floc, 0- to 10-cm layer, and 10- to 20-cm layer. Floc was defined as material that would settle within approximately 60 s of the initial sampling disturbance. For our sampling protocol we adopted the definition of floc outlined by DeBusk et al. (2001), as consisting mostly of decaying macrophyte tissue, soil particles, algae, and microbes. Samples were placed and sealed in plastic bags, and stored on ice until they were received at the Wetland Biogeochemistry Laboratory where they were stored at 4°C until analysis.

Analytical Methods

Soil samples were analyzed at the Wetland Biogeochemistry Laboratory, Soil and Water Science Department, University of Florida. After removal of any visible pieces of live and dead plant material, the samples were weighed and homogenized thoroughly. Floc and soil bulk density (BD) was determined on an oven dried (70°C, 24 h), dry weight basis. The soils were then fine ground to 0.01-mm sieve. Loss on ignition (LOI) was measured by allowing settling of headspace water in the tube. Triplicates were obtained at about 10% of the sites. Loss on ignition (LOI) was measured by ashing approximately 0.2 to 0.5 g oven-dried soil in a muffle furnace for 3 to 4 h at 550°C. The ash residue was then digested in 20 mL of 6 M HCl, in a digestion block, until dry. The dry residue was consequently re-dissolved in 2.25 mL of 6 M HCl and filtered through Whatman (Brentford, UK) 41 filter paper and brought to a final volume of 50 mL. Soil total inorganic P (TIP) was determined by extracting 0.5 g air-dried, ground soil, with 25 mL of 1.0 M HCl for 1 h, and followed by vacuum filtration (0.45-µm membrane filters; Reddy et al., 1998). Total phosphorus and TIP were determined using the absorbic acid automated colormetric procedure (Method 365.1; USEPA, 1993a) (Auto-analyzer II; Technicon, Terrytown, NY). Ashed and acidified samples were also analyzed for total Ca (Tca), total Mg (Tmg), total Fe (Tfe), and total Al (Tal) by inductively coupled argon plasma spectrometry (ICAP) (Method 200.7; USEPA, 1993b).

Data Analysis and Geostatistics

Empirical semivariograms were constructed and model variograms fitted to soil attributes using the ISATIS software (Geovariances, 2005). The following approach was used to analyze measured soil properties. First, we conducted an exploratory analysis including testing for normality and skewness, and the data were transformed when necessary. We then constructed isotropic experimental semivariograms using the following equation:

\[
\hat{\gamma}(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [z(x_i + h) - z(x_i)]^2
\]

where \(z(x_i)\) and \(z(x_i + h)\) represent pairs of observations separated by a distance \(h\) (or lag size), \(n\) is the number of data pairs, and \(\hat{\gamma}(h)\) is the semivariance (Wackernagel, 2003). We tested different lag sizes ranging from 950 to 2000 m. Interactive fitting was used to generate model semivariograms from the experimental semivariogram. Cross-validation was performed and measures of model performance were computed. The model semivariograms were used in ordinary kriging, a weighted local interpolation method, to construct the spatial patterns of each soil property. Empirical semivariance values were fitted with spherical and exponential semivariogram models.

The kriging variance or prediction variance (Webster and Oliver, 2001) was calculated as:

\[
\text{var}[\hat{Z}(x_0)] = E[(\hat{Z}(x_0) - Z(x_0))^2]
\]

\[
= 2 \sum_{i=1}^{N} \lambda_i \gamma(x_i, x_0) - \sum_{i=1}^{N} \sum_{j=1}^{N} \lambda_i \lambda_j \gamma(x_i, x_j)
\]

where \(\hat{Z}(x_0)\) is the estimate of the soil property \(Z\) at the kriging target point \(x_0\), \(\gamma(x_i, x_0)\) is the semivariance of \(Z\) between observations at \(x_i\) and the target point \(x_0\), \(\gamma(x_i, x_j)\) is the semivariance of \(Z\) between observations at locations \(x_i\) and \(x_j\), and \(\lambda_i, \lambda_j\) are kriging weights.

The estimated prediction standard deviations (square root of the variance term in Eq. [2]) were exported to ArcGIS (Environmental Systems Research Institute, 2005). Predictions were made on a grid with 100- × 100-m resolution. For all soil properties, including carbon to nitrogen ratios, point values were first computed and then subjected to geostatistical analysis (i.e., spatial interpolations were generated).

The effectiveness of subsequent interpolation efforts is reported using a set of three statistics: the mean prediction error (MPE), the root mean square error (RMSE), and the G-statistics (Schloeder et al., 2001). The MPE and RMSE are metrics that estimate the deviation of the kriged predictions from the observed predictions. The G-statistic is a test of the effectiveness of the model fit compared to a mean model fit.
average of the physical and chemical properties of the soils sampled in WCA 1 reflected the organic nature of the Histosols prevalent in this area (McCollum et al., 1976), documented by high moisture contents, low BD, and high LOI and TC (Table 1). Generally, LOI and BD increased with depth, whereas moisture content did not change appreciably within the profile. Soil TP and TIP decreased by depth, while soil TC and TN varied little by depth, as indicated by mean values. Floc was present in the majority of the sites (>95%). Average floc TP and TIP concentrations were generally larger than the corresponding soil averages; however, floc BD was much smaller. Floc and soil layers exhibited similar mean physical and chemical characteristics for all other measured properties. For the 0- to 10-cm depth, TP ranged from 113 to 1047 mg kg⁻¹, whereas in the floc, TP ranged from 226 to 1462 mg kg⁻¹, indicating a wide range of soil nutrient conditions, from oligotrophic to nutrient enriched. Wide ranges in values were found for TCa, TMs, TFe, and TAI, whereas BD, LOI, TC, and TN were more homogeneous (Table 1).

The spatial dependence of each soil property was modeled using analysis of semivariance (Table 2, Fig. 2). All properties exhibited spatial autocorrelative structures, indicating that they responded to processes that occur throughout the conservation area. However, spatial dependencies did differ among soil properties, as illustrated by the nugget and sill values, as well as the ranges (Table 2). The range establishes the outer limit at which points in space still interact spatially and the sill represents the total a priori variance, or σ² (Webster and Oliver, 2001). Within the conservation area, soil and floc properties displayed differences in their spatial structures. Floc and soil TCa content exhibited the largest range, indicating significant spatial structure extending over 16.2 and 13.9 km, respectively, which is reflected in the TCa semivariogram (Fig. 2d). With the exception of TCa, all soil ranges were larger than the ranges calculated for floc. Certain soil properties exhibited a nested

Table 2. Semivariogram models, interpolation parameters, and cross-validation statistics.

| Property† | Units | Depth | Lag distance | Model | Nugget | Sill | Range | MPE§ | RMSE§ | G|| |
|-----------|-------|-------|--------------|-------|--------|------|-------|------|-------|-----|
| Moisture content | % |杨 | 125 | exponential | 5.4 | 27.20 | 12513 | 0.021 | 4.3 | 25 |
| BD | g cm⁻³ | 杨 | 1450 | exponential | 0.23 | 0.36 | 3722 | 0.003 | 0.02 | 8 |
| LOI | % | 杨 | 1150 | spherical | 0.08 | 0.15 | 3105 | 0.003 | 0.02 | 60 |
| TP | mg kg⁻¹ | 杨 | 1050 | exponential | 0.07 | 0.13 | 5693 | 33 | 227 | 28 |
| TCa | mg kg⁻¹ | 杨 | 1250 | spherical | 0.06 | 0.07 | 3290 | 17 | 134 | 25 |
| TIP | mg kg⁻¹ | 杨 | 1050 | exponential | 0.16 | 0.26 | 7174 | 15 | 81 | 21 |
| TFe | mg kg⁻¹ | 杨 | 1750 | exponential | 0.07 | 0.16 | 7780 | 8 | 44 | 7 |
| TAI | mg kg⁻¹ | 杨 | 1500 | spherical | 0.01 | 0.15 | 16242 | 366 | 5034 | 74 |
| C to N ratio | | 杨 | 1500 | exponential | 3.4 | 5.61 | 5532 | 0.0013 | 2.6 | 11 |
| TFe | mg kg⁻¹ | 杨 | 1050 | spherical | 0.10 | 0.24 | 2796 | 131 | 1024 | 14 |
| TAI | mg kg⁻¹ | 杨 | 850 | spherical | 0.09 | 0.10 | 3230 | 170 | 1093 | 11 |

† TP, total phosphorus; TIP, total inorganic phosphorus; TCa, total calcium; TFe, total iron.
‡ These properties were natural log transformed, semivariogram characteristics computed on the transformed observations.
§ Mean prediction error (MPE) and root mean square error (RMSE) were calculated on the original scales, data were back transformed where needed.
¶ Goodness of prediction (G), as defined by Schloeder et al. (2001).
spatial structure that was modeled with two spherical semivariogram models containing two ranges. Soil BD, TP, and TFe demonstrated nested spatial model structures with ranges between 9.9 and 12.7 km for the long-scale model and 3.1 to 3.3 km for the short-scale model. Considering that the conservation area is 22 km wide from east to west and spans 36 km north to south, the spatial autocorrelation structure of most soil properties covered most of the conservation area.

The nugget semivariance at distance $h = 0$ represents a composite of the portion of fine-scale spatial variability that has not been sampled, uncertainty introduced by the field and experimental approaches, and random variability. The partial sill variance represents the portion of the total semivariance that comprises spatial autocorrelation. Large nugget values, relative to the sill variance, were found for BD, TIP, and TP of floc, and TP, TFe, and C to N ratio of soil, which indicate that other factors influ-
ence the variability of these measurements. In other soil properties, spatial dependencies constituted a large contribution, particularly in TCa and in floc depth.

The values of the statistics pertaining to the quality of the fitted models indicated that the floc BD predictions were by far the most uncertain. Other properties that exhibited relatively high degrees of uncertainty were TIP and TFe, for both strata. The uncertainty of predictions was lower for other properties. According to the G-statistics, the kriging model generally outperformed the mean model for all properties except for floc BD. The kriging models performed best for soil BD (0- to 10-cm soil) with a G-value of 60, floc and soil TCa with G-values of 74 and 59, respectively, and moderately well for the other properties.

The interpolated floc depth, floc BD, and soil BD are presented in Fig. 3. The inserts illustrate the uncertainty associated with the predictions of these properties. Predictions of floc depth in areas (approximately 14% of the total area) in the southern and western part of the conservation area were highest, with floc depths ranging from 11 to 17 cm. A small number of localized floc concentration areas, with maximum predicted floc depths between 15 and 17 cm, were found along the southwestern fringe of WCA 1, covering an estimated 1% of the total area. Floc and soil BD spatial patterns were uniform over the conservation area. The northern portions of the marsh generally exhibited high floc BD predictions, exceeding the median of 0.07 g cm\(^{-3}\), and high soil BD predictions, exceeding the median of 0.07 g cm\(^{-3}\). Similarly, spatial patterns of LOI (data not shown) showed the same north-to-south gradient. Predicted floc and soil LOI in the northern areas of WCA 1, which ranged from 81 to 85% and 85 to 88%, respectively, was lower than the predicted floc and soil LOI in the southern areas, which ranged from 92 to 99% and 94 to 98%, respectively. The inserted maps plot the standard deviations associated with the interpolated predictions to indicate the uncertainty associated with these predictions. The results from the performance statistics for floc BD (Table 2) confirmed the relatively high uncertainty depicted in the insert in Fig. 3b. These maps also highlight that uncertainties close to sampling sites were small but increased with distance from sampling sites. Along the edges of WCA 1 the uncertainties tended to be high due to sparser sampling.

The spatial distribution of floc and soil forms of P (TP and TIP, Fig. 4a, 4b, 4c, and 4d) generally show a gradient from west to east, with P enrichment on the western edge with predicted maxima of 1153 mg kg\(^{-1}\) in floc TP and 633 mg kg\(^{-1}\) soil TP. In comparison, the observed maximum for the sampled soil TP was 1047 mg kg\(^{-1}\) (Table 1). This discrepancy is the result of divergent observations (e.g., 1047 and 286 mg kg\(^{-1}\)) at close distances (150–600 m) generating an overall predicted maxima that is lower than the observed (sampled) maxima. Localized P enriched areas that exceeded 500 mg kg\(^{-1}\) were found adjacent to canal L-7, with a predicted average of floc TP (829 mg kg\(^{-1}\)) and TIP (182 mg kg\(^{-1}\)), which were about twice as high as in the underlying predicted soil averages (554 mg kg\(^{-1}\) for TP and 88 mg kg\(^{-1}\) for TIP respectively). The area in which the upper 10 cm of soil TP exceeded the threshold of 500 mg kg\(^{-1}\), identified by the State of Florida as “impacted areas” for the Everglades (State of Florida, 2005), covered approximately 5% of the total area and was confined to the western edge, along canal L-7. Floc TIP patterns exhibited a southward extension that was less pronounced than the floc TP patterns and mirrored the patterns found for floc depth (Fig. 2a). Soil TP and TIP enrichment was found primarily along the western edge of the conservation area (Fig. 4d and 4e), with a relatively random mottled pattern in the interior. The inserted uncertainty maps indicate that for both TP and TIP, the uncertainty associated with the floc predictions were higher when compared to the corresponding predictions for the soil layer.

Floc TCa (Fig. 4c) exhibited a more localized pattern of enrichment, with little spatial variability in the...
interior of the marsh. Soil TCa (Fig. 4f) was also spatially affected by the enrichment from the western edges originating from canal L-7. This is superimposed on a north-to-south gradient, in which the lowest predicted values were found in the southeastern portion of WCA 1. The uncertainties associated with the interpolations of TCa were low for both floc and soil (inserts in Fig. 4c and 4f). The spatial variability of floc and soil C to N ratios across the conservation area, depicted in Fig. 5, represent a combination of the spatial dynamics prevalent in these two soil properties. High ratio values imply a relatively high TC respective to TN content. The spatial distribution of soil TC exhibited a gradient north to south with the highest predicted values in the southern areas of WCA 1 (average TC of 452 mg kg$^{-1}$ in the northern half to 504 mg kg$^{-1}$ in the southern half). These spatial patterns were much the same in the floc, where the average predicted floc TC content was 410 g kg$^{-1}$ in the northern half and 500 g kg$^{-1}$ in the southern half. Floc TN exhibited more complex patterns in which the lowest predicted TN values (ranging from 26 to 28 g kg$^{-1}$) were found along the western edges of the marsh. Slightly higher predicted values (ranging from 28 to 33 g kg$^{-1}$) occurred along the northern-most and southern-most tips of the area and a band of higher predicted TN values across the center (ranging from 33 to 39 g kg$^{-1}$). Soil TN patterns were similar to those of the floc TN in that the lowest predicted values were found on the western edge of the area (ranging from 27 to 28 g kg$^{-1}$), superimposed on a north-to-south gradient, with the highest predicted values in the northern areas of the marsh (averaging 37 g kg$^{-1}$ in the north and 30 g kg$^{-1}$ in the south). The combined effect of the spatial patterns of these two soil properties (TC and TN) can be seen in Fig. 5. The highest predicted floc and soil C to N ratios were found in the west as a result of the low N values and in the south as a result of the C gradient. The uncertainty associated with the floc C:N layer was found to be higher than that associated with the soil layer (inserts in Fig. 5a and 5b). The spatial distribution of the predicted floc and soil TFe (Fig. 6)

Fig. 4. Spatial distribution of floc total phosphorus (TP) (a), total inorganic phosphorus (TIP) (b), total calcium (TCa) (c), soil total phosphorus (TP) (e), total inorganic phosphorus (TIP) (f), and calcium (Ca) (d) in Water Conservation Area 1 (WCA 1), sampled in March 2003 and August 2004. The scale bar shows the extent of the estimated properties.
presents a gradient east to west with a focal point along the eastern edge of the area (from canal L-40). The uncertainty associated with the floc TFe predictions was higher than that associated with soil TFe predictions, as seen in the upper bound standard deviations (inserts, Fig. 6a and 6b).

Most soil properties were shown to be weakly correlated (Table 3). The strongest correlation coefficients

Fig. 5. Spatial distribution of floc (a) and soil (b) carbon to nitrogen ratios in Water Conservation Area 1 (WCA 1), sampled in March 2003 and August 2004. The scale bar shows the extent of the predicted properties.

Fig. 6. Spatial distribution of floc (a) and soil (b) iron (Fe) in Water Conservation Area 1 (WCA 1), sampled in March 2003 and again in August 2004. The scale bar shows the extent of the predicted properties.
(Spearman’s r) were found between observations pertaining to measures such as BD and LOI (−0.96) or TP and TIP (0.93) for properties that are, in any case, known to be inherently correlated. Other properties that were strongly, positively correlated were TCa and TMg (r = 0.89). Pairs of properties that show a tight positive correlation can be expected to exhibit very similar spatial patterns, which was the case when overlaying the TCa and TMg maps. Inversely, pairs of properties that have strong, significant negative correlations are expected to exhibit spatial patterns that are mirror images as with TC and LOI or TC and TP.

**DISCUSSION**

The spatial modeling undertaken for this study resulted in a detailed description of the spatial variability of the soil properties that we sampled and revealed that the predictions for the floc layer contained considerably higher uncertainty than those of the soil layer(s). Generally, the floc component can be viewed as being far more dynamic and responsive than the bulk soil (Reddy et al., 1999), which, as a result, also makes it more variable. However, floc variability is also higher due to the fact that it is more difficult to sample than soil, thus compounding the uncertainty. Within the soil properties sampled, spatial predictions of the soil BD exhibited the most uncertainty, whereas the model derived for soil TCa seemed the most reliable.

Spatial patterns observed in the Everglades landscape mosaic and associated environmental driving forces have been the focus of a significant amount of research (Davis and Ogden, 1994; David, 1996; Busch et al., 1998). A number of broadly defined physical and biological factors have been identified that influence the formation of the Everglades landscape mosaic (DeAngelis and White, 1994; DeAngelis, 1994; Gunderson, 1994), including hydropattern, fire, storms, and water chemistry. In WCA 1, one of the least studied areas in the Everglades, some of the most prominent physical processes are affected by hydrology and water chemistry (Newman et al., 1997). The spatial soil patterns that we observed reflect the current and historical processes that have predominated in WCA 1.

Of the three WCAs in the Everglades, WCA 1 is unique in that it is mainly rainwater-fed (South Florida Water Management District, 1992). Until recently, one of the other water inputs was canal water, which generally has a higher pH (Table 4) than the water in the marsh interior. The canal water was fed by pump structures S-5A and from S-6 (Fig. 1). A tertiary hydrological input was the ACME pump and its associated drainage basin to the east of WCA 1. The S-5A pumps drains a 59,570-ha basin, while S-6 drains a 37,810-ha basin in the EEA. The ACME pump drains the ACME drainage basin, a 2800-ha area that is composed of a mix of urban and recreational land use areas. Currently, these inputs are either, in the case of S-6, diverted, or in the case of S-5, filtered through a STA.

The soils in the WCA 1 are domed in shape and raised relative to the surrounding canals (Swift and Nicholas, 1987), hence influx of canal water into the area is dependent on canal stage levels. At high canal stage levels, canal water enters the area along the periphery. At low stage levels, the only water input to the area is rainfall. The water chemistry in the interior of WCA 1 tends to be of a lower pH (Table 4). The acidity of surface water in the interior of WCA 1 is the result of greater depth of peat than in other areas of the Everglades, and from WCA 1 being a precipitation dominated, weakly buffered system. The variations in P water chemistry between canal water and the interior of the marsh for the period 1993–2001 (Table 4) were less than the historic

**Table 3.** Correlation matrix of aggregated soil properties over the total sampled profile (floc, 0–10, and 10–20 cm).‡

<table>
<thead>
<tr>
<th>Property</th>
<th>Floc depth</th>
<th>Moist</th>
<th>BD</th>
<th>LOI</th>
<th>TP</th>
<th>TIP</th>
<th>TN</th>
<th>TC</th>
<th>TCa</th>
<th>TMg</th>
<th>TFe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floc depth</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moist</td>
<td>−0.24‡</td>
<td>1</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>0.21‡</td>
<td>−0.96‡</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOI</td>
<td>0.11</td>
<td>0.13</td>
<td>−0.11</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>−0.11</td>
<td>0.49‡</td>
<td>−0.50‡</td>
<td>−0.32‡</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIP</td>
<td>−0.11</td>
<td>0.52‡</td>
<td>−0.52‡</td>
<td>0.34‡</td>
<td>0.93‡</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TN</td>
<td>0.00</td>
<td>0.10</td>
<td>−0.10</td>
<td>0.23‡</td>
<td>−0.10</td>
<td>−0.05</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>0.27‡</td>
<td>−0.19</td>
<td>0.22‡</td>
<td>0.73‡</td>
<td>−0.60‡</td>
<td>−0.60‡</td>
<td>0.24‡</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TCa</td>
<td>0.16</td>
<td>−0.51‡</td>
<td>0.47‡</td>
<td>−0.61‡</td>
<td>0.04</td>
<td>0.04</td>
<td>−0.39‡</td>
<td>−0.34‡</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TMg</td>
<td>0.08</td>
<td>−0.33</td>
<td>0.29</td>
<td>−0.68‡</td>
<td>0.24‡</td>
<td>0.22‡</td>
<td>−0.42‡</td>
<td>−0.53‡</td>
<td>0.89‡</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>TFe</td>
<td>−0.07</td>
<td>−0.05</td>
<td>0.05</td>
<td>−0.14</td>
<td>−0.02</td>
<td>0.03</td>
<td>0.21‡</td>
<td>−0.05</td>
<td>0.03</td>
<td>−0.14</td>
<td>1</td>
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<tr>
<td>TAl</td>
<td>−0.10</td>
<td>−0.36</td>
<td>0.37</td>
<td>0.48‡</td>
<td>−0.11</td>
<td>−0.08</td>
<td>0.12</td>
<td>−0.30</td>
<td>0.32‡</td>
<td>0.32‡</td>
<td>0.33‡</td>
</tr>
</tbody>
</table>

‡ Moist: moisture content; BD, bulk density; LOI, loss on ignition; TP, total phosphorus; TIP, total inorganic phosphorus; TN, total nitrogen; TC, total carbon; TCa, total calcium; TMg, total magnesium; TFe, total iron; TAI, total aluminum.

Significant at the 0.0001 probability level.
values reported by Newman et al. (1997) for the period from 1978–1983. In the 1978 to 1983 period, canal water TP, total soluble P, and soluble reactive P were reported as 0.09 ± 0.01, 0.06 ± 0.01, and 0.05 ± 0.01 mg L⁻¹, respectively, which are slightly higher than the values reported for the period 1993–2001 (Table 4).

During the 1993 to 2001 period STA-1E filtered P, resulting in lower P loads in the canal water entering WCA 1. Other water chemistry properties were invariant over the time period. The P levels in the water sampled in the interior of the marsh have increased when compared to the results obtained from Newman et al. (1997). This indicates that water chemistries in canals and the marsh interior are now more similar (Table 4).

A comparison of soil properties between the 1991 sampling (Newman et al., 1997) and the current sampling campaigns is confounded by the fact that the previous sampling did not differentiate floc, which was specified in this study. Soil TC and TN did not vary much between the sampling efforts (1991–2003), although in the current study soil N was 3 g kg⁻¹ higher across both layers.

The signatures in the spatial soil and floc property distributions reflect both historic and current hydrologic conditions. Newman et al. (1997) found for their 1991 sampling that areas adjacent to the western perimeter canal (L-7) were enriched with P, patterns that are similar to those depicted in Fig. 4.

Phosphorus has been recognized as the limiting nutrient in the Everglades ecosystem (Davis, 1991; Davis and Ogden, 1994) and its dynamics and occurrence throughout many areas in the Everglades have been described extensively (DeBusk and Reddy, 1998; Newman et al., 2001). The P in the canal water that is introduced into this ecosystem is initially captured locally through processes such as precipitation, sorption, and biological uptake (Qualls and Richardson, 2000). Subsequently, P gradients are formed by continual influx of P, P saturation on the soils, and P remobilization and dispersion. In 1991 in WCA 1 P showed a limited gradient from canal L-70 extending into the marsh interior (Newman et al., 1997). We found that the same areas on the western portion of WCA 1 were still P enriched when compared to the interior areas of the marsh. However, formal comparison of the overall soil properties between the two studies is confounded by the fact that the previous sampling did not distinguish between floc and soil, which was specified in this study.

DeBusk et al. (2001) identified a soil TP threshold value for WCA-2a of 450 mg kg⁻¹ beyond which the P enrichment resulted in structural changes (e.g., cattail incursions) in the marsh vegetation communities. Only 10% of the total area in WCA 1 exceeded that threshold, which is equivalent to an area of 55 ha. These areas visually coincide with the areas containing cattail communities as identified by Newman et al. (1997) in 1991. Further efforts should be directed at including a more current vegetation community map. This would enable the quantification of the effect of the prevailing vegetation communities on the observed soil patterns beyond cattail incursion, which is particularly important in the case of studying the relationships between existing soil characteristics and indigenous vegetation communities.

The largest portion of P in WCA 1 soils is organic with the minor portion being inorganic P, which is consistent with Everglades soils (Newman et al., 1997; DeBusk et al., 1994; Qualls and Richardson, 1995). The largest inorganic P pool was found in the floc layer (approximately 25% of TP), with a slightly smaller pool in the soil layer (approximately 20% of TP). In other areas in the Everglades (e.g., Water Conservation Area 2a), inorganic P is co-precipitated with Ca and Mg, as a result of the exposed limestone bedrock and relatively high water column pH (DeBusk et al., 1994; Qualls and Richardson, 1995). In WCA 1, this binding behavior might be more prevalent along the edges of the system, which are influenced by the canal water, than in the more acidic interior. These dynamics were reflected in the spatial distributions of TIP and TCa (Fig. 4) as areas enriched in TIP also showed relatively high TCa levels. Further penetration of Ca into the conservation area might be possible as Ca is not as readily taken up by biota as P. The TCa maps showed higher Ca concentrations south of the western levee. In acidic systems, on the other hand, Al and Fe chemistry controls P soil dynamics (Richardson, 1999). We found areas of Fe enrichment along the fringe of L-40 (Fig. 6), presumably from the ACME drainage basin. Urban storm water runoff can contain elevated levels of dissolved and colloidal Fe (Grout et al., 1999). In a smaller, localized area, coinciding with the highest TFe levels, we found an increase in soil BD (Fig. 3) and a decrease in LOI and soil TC content, presumably the result of the ACME basin inputs and/or localized disturbances. However, TFe enrichment was not accompanied by P enrichment. Likewise other soil properties including metals showed dissimilar spatial patterns.

Based on the hydroperiod and ponding depths predicted by the South Florida Water Management Model (SFWMM; Stober et al., 2001), the southern portion of WCA 1 has the longest flood periods, which steadily decrease on the south-to-north axis. Hydropattern, including the duration, degree, and frequency of flooding, affects carbon decomposition (DeBusk and Reddy, 2003). The hydropattern is, therefore, possibly the predominant factor influencing TC, TN, TAl, LOI, and BD spatial patterns as soil mineralization rates are higher in the northern areas of the marsh. This might also be related to the higher soil C to N ratio in the southern areas of the marsh (Fig. 5). Nitrogen is limiting to microbial activities in high TP soils (Amador and Jones, 1995, 1997). However, nitrogen content had not previously been found to vary considerably over nutrient gradients in the Everglades (Koch and Reddy, 1992; Newman et al., 1997; Craft and Richardson, 1998; Vaithiyanathan and Richardson, 1999). We found that the areas high in TP and TCa were also relatively low in TN, which was expressed in terms of high localized floc and soil C to N ratios (Fig. 5), possibly alluding to an increased N demand in these areas. In other areas of the Everglades, N dynamics are closely associated with the presence of nitrogen fixing cyanobacterial periphyton mats (Inglett et al., 2004), but as...
WCA 1 is a soft water system, other algal consortia probably dominate the water column. The scale at which the samples were taken in this study is probably too coarse to conclusively relate a particular N process to the prediction patterns. A detailed, finer spatial study focused on N cycling in these areas would be a more effective way to overcome these divergences in scale (Bierkens et al., 2001). In a previous study in the same area, Newman et al. (2001) documented that P enrichment of soils in LNWR result in increased NH$_4^+$ concentrations in the porewater and attributed this to mineralization of organic N in response to removal of P limitation. This porewater N pool was subsequently depleted below background levels, presumably in response to plant growth.

CONCLUSIONS

The spatially explicit analyses of floc and soil properties in WCA 1 enabled the identification of distinct patterns likely to correspond to a variety of ecosystem processes such as nutrient cycling, resuspension, precipitation, N fixation, and others. The prediction of certain properties, such as floc BD, had a high degree of uncertainty. In contrast, soil properties generally exhibited lower uncertainty than floc properties. The predominant hydrological north–south gradient in this area could be discerned in the spatial distribution of a number of the mapped geographic soil properties. Also evident in these patterns were distinct zones that have developed by the incursion of canal water resulting in east–west gradients of soil and floc properties. We identified areas with enhanced levels of TFe with the highest levels found adjacent to canal L-40. At approximately the same location, soil BD was also locally high. Areas exhibiting soil and floc nutrient enrichment were identified on the western side of the marsh, with the highest concentrations adjacent to canal L-7. Less than 5% of the area exceeded a 450 mg kg$^{-1}$ soil TP threshold. This study characterized the spatial variability of physical and chemical soil properties in WCA 1 providing baseline values for future studies. Considering the mapped geographic soil patterns obtained in this study, and associations to environmental processes, this research supports ongoing restoration efforts by: (i) detecting vulnerable areas and (ii) identifying collocated patterns of soil characteristics, which can suggest hypotheses, or support underlying soil processes models. This paper was not able to address the effect of vegetation communities on the observed spatial patterns or the relationship between the soil dynamics and plant/algal communities, but will effectively supply the foundation from which these more detailed studies can be executed for WCA 1.

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REFERENCES


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