Wetlands and Aquatic Processes

Spatio–Temporal Patterns of Soil Phosphorus Enrichment in Everglades Water Conservation Area 2A

W. F. DeBusk,* S. Newman, and K. R. Reddy

ABSTRACT

The Florida Everglades have undergone significant ecological change resulting from anthropogenic manipulation of historical regimes of hydrology, nutrient loading, and fire. Water Conservation Area 2A (WCA-2A) in the northern Everglades has been a focal point for the study of ecological effects of nutrient loading, especially phosphorus (P), from the nearby Everglades Agricultural Area (EAA). The overall objective of our study was to evaluate recent (1990 to 1998) changes in the spatial extent and patterns of soil P enrichment in Everglades WCA-2A. Surface soil was sampled to a depth of 10 cm at 62 sites within WCA-2A during 1998 for analysis of total phosphorus (TP) content. Geostatistical methods were used to create an interpolated grid of soil TP values across WCA-2A. Comparison of the results of this study with a similar study performed in 1990 showed that the extent of soil P enrichment in surface soil and sediments increased between 1990 and 1998, as evidenced by increased coverage of highly P-enriched soil near the primary surface inflows and a general increase in the concentration of soil TP in the interior regions of WCA-2A. Approximately 73% (31 777 ha) of the total land area of WCA-2A was considered P-enriched (soil total P > 500 mg kg^{-1}) in 1998, compared with 48% of the land area (20 829 ha) in 1990, an average increase of 1327 ha yr^{-1}. Study results indicate that the soil P enrichment "front" has advanced further into the relatively unimpacted interior of WCA-2A during the past several years.

The Everglades, a mosaic of sawgrass marsh, sloughs, and tree islands, once encompassed the vast expanse of southern Florida from Lake Okeechobee to Florida Bay. Essentially all of the modern-day Everglades is contained within Everglades National Park to the south and the Water Conservation Areas (WCAs) to the north. The WCAs were created some 40 to 50 yr ago, primarily for the purposes of water storage, flood control, and recreation (South Florida Water Management District, 1992). Since their creation, the WCAs have experienced sustained inputs of drainage water from the Everglades Agricultural Area, and consequently have shown strong evidence of ecological change (South Florida Water Management District, 1992).

The main focal point of ecological impact has been Water Conservation Area 2A (WCA-2A), where extensive documentation exists for P-related impacts on ecosystem structure and function (Davis, 1991; Koch and Reddy, 1992). Among the more noticeable ecological changes in WCA-2A have been the transformation of native sawgrass (*Cladium jamaicense* Crantz) marsh and openwater sloughs to dense stands of cattail (*Typha domingensis* Pers. and *T. latifolia* L.) (Davis, 1991; South Florida Water Management District, 1992; Jensen et al., 1995) and replacement of endemic periphyton communities by algal species typically associated with more eutrophic waters (McCormick and O'Dell, 1996; McCormick et al., 1996). Soil P concentration in WCA-2A has been strongly linked to productivity and community structure of macrophytes (Newman et al., 1998; Miao and Sklar, 1998; Miao and DeBusk, 1999; Richardson et al., 1999; Vaithiyanathan and Richardson, 1999) and periphyton (McCormick and Stevenson, 1998; McCormick et al., 1998), organic carbon turnover (DeBusk and Reddy, 1998), nitrogen cycling (White and Reddy, 1999, 2000), microbial community structure (Drake et al., 1996), and diatom assemblages (Cooper et al., 1999).

Due to the absence of significant gaseous losses of P via metabolic pathways (in contrast to nitrogen), preferential retention of P has occurred in WCA-2A soils, manifested as increases in both P storage (P mass per unit area of land) and enrichment (P concentration in soil, i.e., mg P kg^{-1} soil). Increased biological production, stimulated by loading of P from external sources, has resulted in accelerated rates of peat accretion, and consequently P storage, in impacted areas near surface water inflows (Reddy et al., 1993; Craft and Richardson, 1993, 1998). Perhaps more significant with respect to biological productivity is the fact that increased sorption and bioconcentration of P in the soil has resulted in widespread P enrichment of the soil (DeBusk et al., 1994). Soil characterization studies of the P gradient in WCA-2A have shown a roughly proportional increase in concentrations of both inorganic (Ca- and Mg-bound) and organic (associated with humic and fulvic acids) P near the major surface water inflow points (Qualls and Richardson, 1995; Reddy et al., 1998).

The overall objective of our study was to evaluate recent (1990 to 1998) changes in the spatial extent and patterns of soil P enrichment (total P concentration) in Everglades WCA-2A. Of particular interest was the progression of soil P enrichment in the northeast quadrant into the relatively unimpacted sawgrass marsh of the interior region. The study was accomplished by con-

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Abbreviations: TP, total phosphorus; WCA, Water Conservation Area.

ducting a comprehensive sampling and analysis of surface soil across WCA-2A, performed in a similar manner to an earlier soil characterization study (DeBusk et al., 1994). Comparison of results of the initial and follow-up studies formed the basis of our analysis of recent spatio–temporal patterns of soil P enrichment.

MATERIALS AND METHODS

Site Description

Water Conservation Area 2A (WCA-2A) is a hydrologic unit of the northern Everglades encompassing approximately 44 800 ha of wetlands, primarily consisting of shallow-water sawgrass and cattail marshes, in addition to deeper-water slough communities. Surface hydrology is controlled by a system of levees and water control structures along the perimeter of WCA-2A. The major surface water inflow points are the S-7 pump station and the S-10 water control structures (Fig. 1). The S-10A, C, and D structures have been the most significant inflows with respect to nutrient loading to WCA-2A (South Florida Water Management District, 1992). Surface water outflows along the southern boundary of WCA-2A discharge primarily into WCA-3.

Soils in WCA-2A are Histosols (unmapped), and encompass both Loxahatchee and Everglades peat formations (Gleason et al., 1974). Peat depth ranges from about 1 to 2 m, and the age of basal peat is estimated to be 2000 to 4800 yr (Gleason et al., 1974). Soil pH throughout WCA-2A is circumneutral to slightly basic (Reddy et al., 1991). Calcium is abundant relative to iron and aluminum in both soil and water; accordingly, evidence suggests that P mobility in this system is controlled

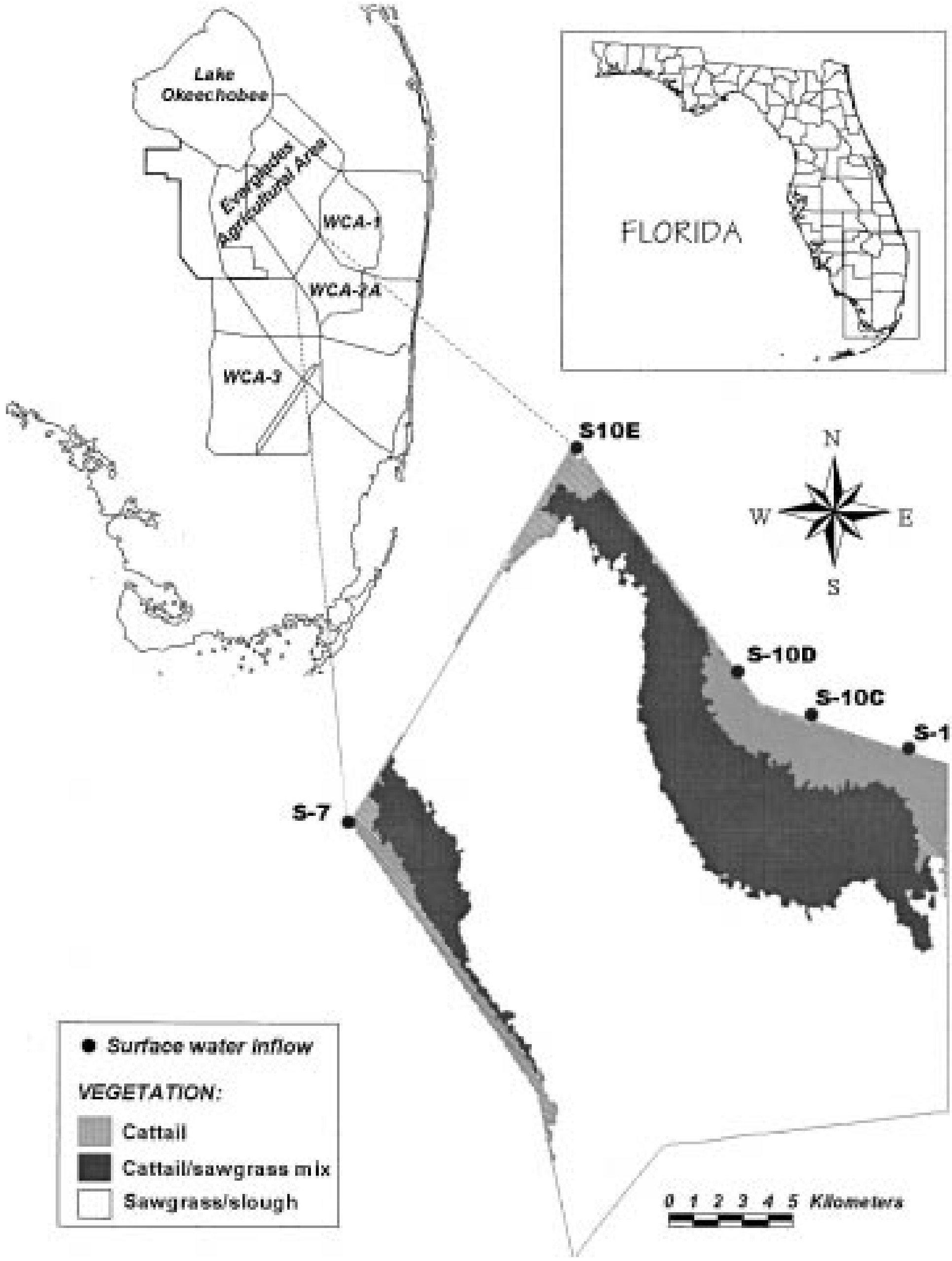

Fig. 1. Location of Water Conservation Area 2A (WCA-2A) in the northern Everglades. The recent extent of encroachment of cattails into the native sawgrass and slough communities is based on the satellite imagery analysis by Rutchey and Vilcheck (1994).

primarily by calcium solubility, as well as organic P mineralization (Qualls and Richardson, 1995; Reddy et al., 1998; Chua, 2000).

We have previously documented a distinct pattern of widespread P enrichment of soil in WCA-2A, associated with long-term nutrient loading from nearby agricultural areas (DeBusk et al., 1994). Progressive replacement of sawgrass marsh by cattails in the more highly P-enriched areas has also been documented (Jensen et al., 1995; Rutchey and Vilchek, 1999) (Fig. 1).

Soil Sampling and Analysis

Surface peat and overlying sediment were sampled at 62 locations within WCA-2A, during October 1998 (Fig. 2). Selection of the sampling sites was based on the sampling grid used for soil P characterization in WCA-2A in 1990 (DeBusk et al., 1994). Some modification of the original sampling grid was made for the 1998 sampling event to provide higher sampling density for areas previously characterized by high spatial variability of soil P concentration. Typically, a relatively evenly distributed grid of sampling points is the most appropriate sampling design, and provides the most efficient use of the data, where there is a high degree of spatial covariance for that variable (Isaaks and Srivastava, 1989). Since spatially distributed sampling of soil chemical and physical properties typically does not yield independent outcomes, a random sampling design is less appropriate and, moreover, is often inefficient due to clustering of sampling points.

At each of the 62 sampling sites, we obtained an intact soil core using an aluminum coring tube of 75-mm inside diameter. Cores were sampled to a depth of 10 cm, which allowed for comparison of the data with results of our previous soil characterization study in WCA-2A during 1990 (DeBusk et al., 1994). The 10-cm soil layer incorporated peat and, frequently, an overlying layer of flocculent or unconsolidated sediment. A flocculent layer of living and dead periphyton material covers the fibrous peat layer in many areas of the minimally impacted sawgrass marsh in the interior portion of WCA-2A; however, this flocculent layer typically is shallower in the marsh community than in the sloughs. A layer of unconsolidated organic matter also overlies peat throughout much of the highly nutrient-enriched cattail marsh near the S-10 inflows. This flocculent matter apparently originates from decaying macrophytes

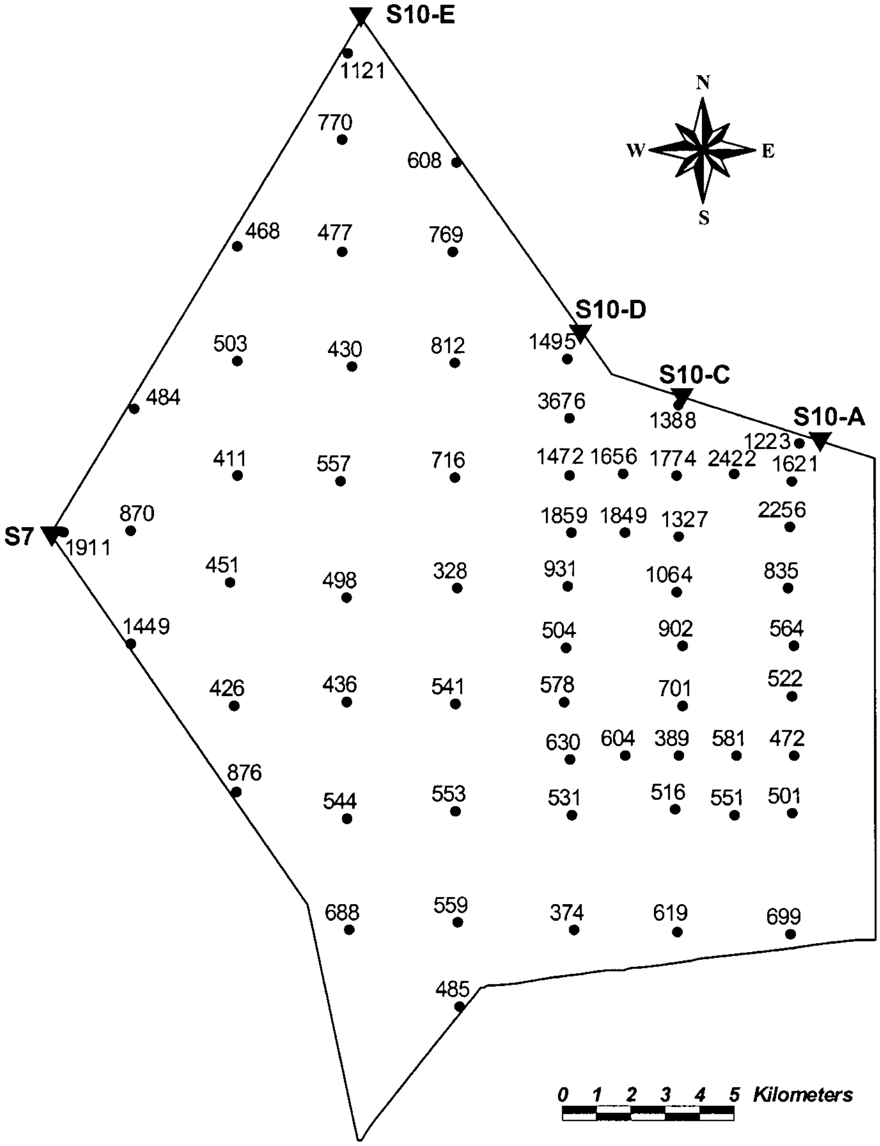

Fig. 2. Results of total P (mg kg^{-1}) analysis of surface soil (0–10 cm depth) sampled at 62 sites in Water Conservation Area 2A (WCA-2A) in 1998.

(cattails) as well as algae and bacteria, and is probably best characterized as muck or unconsolidated peat.

Soil samples extruded from the coring tube were placed in water-tight plastic bags and transported on ice to the laboratory. Samples were analyzed for total phosphorus (TP) using a dry-ashing procedure (Andersen, 1976) followed by determination of dissolved reactive P by an automated ascorbic acid method (Method 365.4; USEPA, 1983). Overall, the sampling and analytical procedures for the 1998 sampling event were the same as those used for the 1990 WCA-2A study (DeBusk et al., 1994).

Location (latitude and longitude) of each of the sampling sites was determined by global positioning system (GPS), using post-processing data correction techniques to achieve an accuracy of 1 to 2 m from the true position.

Geostatistical Analysis

Spatial patterns of soil TP concentration for both 1998 and 1990 data sets were determined using geostatistical analysis. Variograms were calculated for each data set to establish the degree of spatial continuity of soil total P among data points (autocorrelation) and to estimate the range (i.e., distance) of spatial dependence for the total P variable. Information generated through the variogram is used to calculate sample weighting factors for spatial interpolation by a kriging procedure (Isaaks and Srivastava, 1989). In contrast to nongeostatistical interpolation methods, kriging accounts for the spatial arrangement (clustering) of sample points as well as the distance of each point from other sample points. An ordinary block kriging procedure (Goovaerts, 1997) was used to create a continuous grid of interpolated data points, or blocks, from the original data points. The block size used for this procedure was 300 × 300 m. Both the variogram and kriging procedures were performed using the GS^+ software package (Gamma Design Software, 2000).

We also used a variation of ordinary kriging, known as indicator kriging (Goovaerts, 1997), to calculate the conditional probability of the occurrence of soil P concentrations in excess of arbitrarily specified thresholds, or cutoff values, that were selected to facilitate comparison over time. The procedure involves substitution of variables that indicate either occurrence (1) or non-occurrence (0) of values greater than the threshold, in place of the actual concentration values. The resulting sets of indicator variables for each threshold value underwent ordinary kriging analysis as described above. The resulting interpolated values for the indicator variables represented the probability, expressed as a value between 0 and 1, that the soil total P concentration at specific locations exceeded the threshold value.

Interpolated grid data generated by geostatistical methods were exported to the ArcView GIS program (Environmental Systems Research Institute, 1999), then converted to grid themes with cell size corresponding to the kriged output (300 m).

RESULTS AND DISCUSSION

Soil Total Phosphorus Concentration

Total P concentration in the surface layer of soil (0–10 cm depth) varied considerably among the 62 sampling sites in WCA-2A (Fig. 2). As previously shown in 1990 (Reddy et al., 1991; DeBusk et al., 1994), a major portion of the soil P enrichment was associated with surface inflows S-10C and S-10D. These two inflow structures are major sources of surface water and nutrient loading, accounting for roughly one-half of the total surface water P loading to WCA-2A (South Florida Water Management District, 1992). The distribution of soil P enrichment to the south of the S-10 inflows is facilitated by an overall north to south flow of surface water in WCA-2A, following a nearly undetectable topographic gradient. As a result, an extensive area of soil P enrichment stretches to the south, over a distance of roughly 7 km, from the S-10 inflows into the interior region of WCA-2A. Another region of soil P enrichment also exists near the S-7 pump station at the western corner of WCA-2A (Fig. 2). Approximately one-third of the total surface water P loading to WCA-2A passes through S-7 inflow (South Florida Water Management District, 1992). However, the area of soil P enrichment downstream from S-7 is less expansive than the area of enrichment associated with the S-10 structures, because most of the flow from S-7 is diverted along an interior perimeter canal toward the S-11 outflows at the southern tip of WCA-2A.

Site-by-site comparisons of 1990 vs. 1998 soil TP concentrations were not performed due to the likelihood that the 1998 site locations did not coincide precisely with the corresponding 1990 sites. The significance of even a relatively small error in relocating the 1990 sampling sites in 1998 was demonstrated by an analysis of local site variability performed in highly impacted and minimally impacted areas of WCA-2A (unpublished data, 1998). Our analysis revealed that the coefficient of variation for soil total P concentration in triplicate samples increased from 9.6% at 0.5-m spacing to 21.6% at 25-m spacing in the impacted area, and from 7.9 to 12.9% at 0.5- and 25-m spacing in the unimpacted area. Based on the sampling scheme used during 1990 sampling of WCA-2A, and repeated for the 1998 characterization study, the most appropriate procedure was to use a spatial interpolation procedure to create high-resolution grids of soil P concentration for both data sets, which could then be directly compared.

Spatio–Temporal Trends in Soil Total Phosphorus

Sample variograms constructed from both the current (1998) and 1990 data sets revealed comparable patterns of spatial continuity for soil total P concentration (Fig. 3). A spherical model provided the best fit for the semivariance function, as determined by both the software's least squares fitting routine and visual comparison of the model output with data points. Model estimates of the range of spatial continuity for soil total P were 11.3 km for the 1998 data set, compared with 9.3 km for the 1990 data. The most conspicuous difference between the 1990 and 1998 variograms was the overall magnitude of the semivariance, which was approximately twice as great for the 1998 data set than for the 1990 data. The maximum semivariance, indicated by the sill of the variogram, is roughly equivalent to the total sample variance. Increased sample variance in the 1998 soil total P data would be consistent with the observed increase in the range of total P concentration in 1998 vs. 1990.

The ordinary kriging interpolation procedure, which

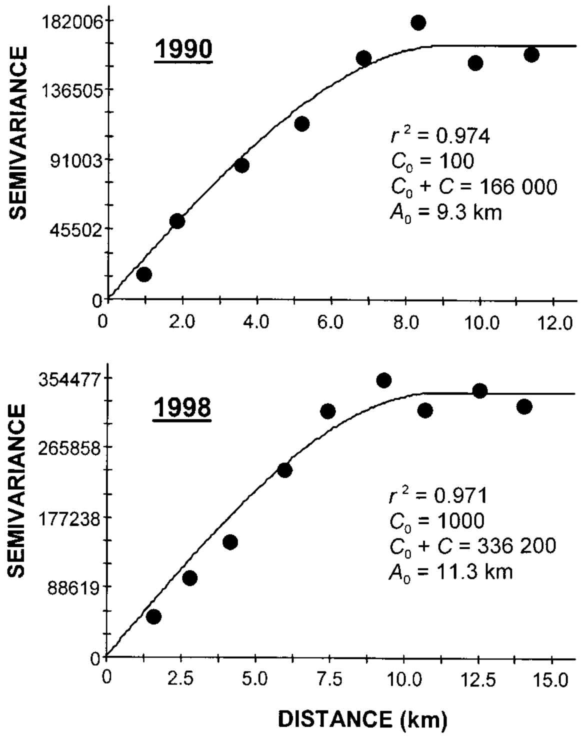

Fig. 3. Sample variograms for 1990 (DeBusk et al., 1994) and 1998 Water Conservation Area 2A (WCA-2A) soil total P data sets. Both variograms were fit to a spherical model; parameter values are indicated on graphs (A_0 = range, in km, of spatial autocorrelation for total P; C_0 + C = sill, or maximum semivariance; C_0 = nugget semivariance).

effectively subdivided the land area of WCA-2A into a uniform grid of equally sized cells, provided a means for unbiased evaluation of the overall distribution, or frequency of occurrence, of soil TP concentration. By calculating the distribution of interpolated data points (N = 4176) among equal intervals of soil TP concentration, we generated a plot of the relative areal extent of soil TP, the equivalent of a probability distribution curve for soil TP (Fig. 4). A comparison of the distribution of soil TP values in 1990 and 1998 suggested two distinct recent trends in soil P enrichment in WCA-2A. The first is an increase in the coverage of what would be considered moderate to highly P-enriched soil (i.e., concentration greater than about 1000 mg kg^{-1}), reflected by an increase in the area under the right-hand tail of the curve. The second obvious change between 1990 and 1998 is the widespread increase in low-level soil P enrichment, reflected by the shift in the primary peak of the curve in Fig. 4. In effect, this has resulted in an increase in the "background" concentration of soil TP, and may be an indication of a breakthrough of P from saturated or overloaded soils near the S-10 inflows. A general southward (downgradient) shift in P enrichment along the north–south S-10C transect has been indicated by a succession of soil P characterization studies during the past 10 yr (Reddy et al., 1998).

It should be noted that kriging tends to attenuate the range of values in the sample data set, due to the spatial averaging effects of this procedure. Thus, extremely high or low values in the sample data set may not be reflected in the distribution of interpolated data. It should also be pointed out that one sampling point in the 1998 data set, with a TP value of 3676 mg kg^{-1}, was identified as an extreme outlier during analysis of the sample variogram cloud plot (Isaaks and Srivastava, 1989), and was subsequently excluded from the model parameterization procedure for spatial interpolation (kriging). An extreme outlier point can dominate the estimation of the sample variogram to the extent that the resulting model fails to adequately represent the true spatial structure of the sample variable.

Mapping based on the interpolated grids developed from 1990 and 1998 soil total P data clearly showed an increase in the areal extent of soil P enrichment during the period 1990–1998 and, most notably, confirm the expansion of the P-enriched area south of the S-10 inflows (Fig. 5). The 1998 map also indicates that soil TP concentrations in a substantial portion of the interior sawgrass marsh have increased since the 1990 sampling

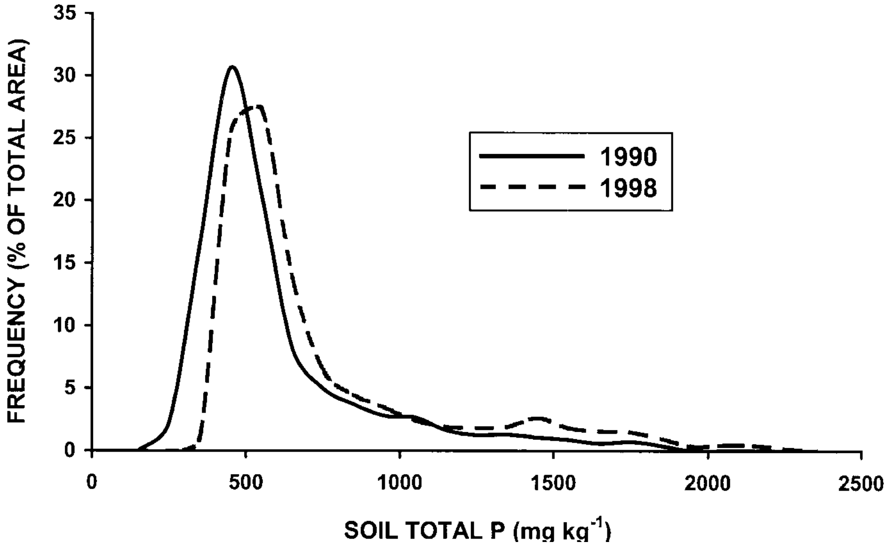

Fig. 4. Frequency distribution curves for soil total P concentration in Water Conservation Area 2A (WCA-2A), for both 1990 and 1998 data sets, based on spatially interpolated grid data (N = 4176). Frequency of occurrence is expressed as percent of total land area.

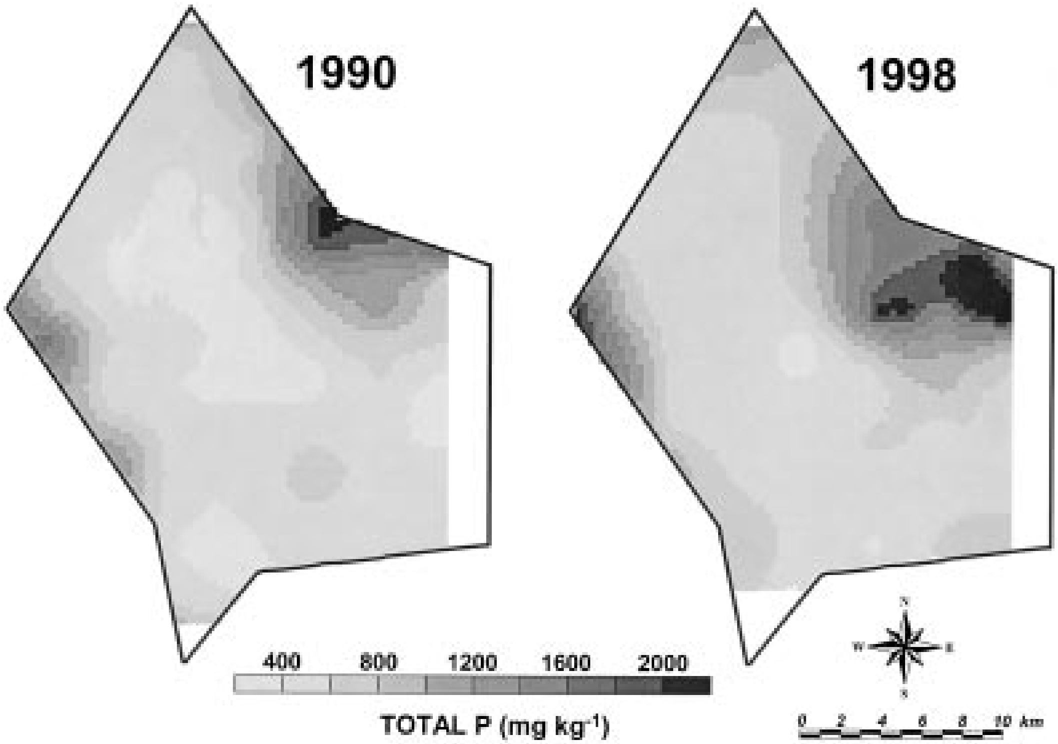

Fig. 5. Spatial distribution of soil total P in Water Conservation Area 2A (WCA-2A), based on spatially interpolated (kriged) data from recent (1998) and 1990 (DeBusk et al., 1994) sampling events. The white areas at the right and bottom of each map represent areas for which data were not collected.

event. From our 1990 soil characterization data for WCA-2A we estimated that the historical background TP concentration (i.e., the concentration not impacted by anthropogenic P loading) for surface soil (0–10 cm depth) in WCA-2A was approximately 500 mg kg^{-1} (DeBusk et al., 1994). Under this assumption, using our spatial interpolation procedure, 48% of the total area of WCA-2A would have been considered P-enriched in 1990, compared with 73% of the total area by late 1998 (Fig. 4). In a similar fashion, changes in the spatial extent of moderately to highly enriched areas during the 1990–1998 period can be calculated. For example, the area for which soil P concentration exceeded 1000 mg kg^{-1} increased from 10.5 to 18.0% of the total area of WCA-2A, an increase of 393 ha yr^{-1} (assuming a linear increase over time). Moreover, the proportion of land area with a soil total P concentration greater than 1500 mg kg^{-1} (i.e., *highly P-enriched*), increased from 2.6 to 7.3% of the total area, representing an annual increase of 246 ha yr^{-1}.

Wu et al. (1997) used a classified SPOT satellite image of 1991 vegetation distribution (Rutchey and Vilchek, 1994) and soil TP data from 1990 (DeBusk et al., 1994) to develop a probabilistic model for predicting cattail invasion into the indigenous sawgrass marsh of WCA-2A. Their model estimated that a soil TP concentration of 650 mg kg^{-1} would elicit cattail invasion in WCA-2A. In other words, for regions of the sawgrass marsh where soil TP concentration increased above this value, replacement of sawgrass by cattail in WCA-2A was a near-certain occurrence. Wu et al. (1997) also determined that the annual rate of cattail invasion, or conversion of sawgrass marsh to cattails, in WCA-2A increased from about 1% in the early 1970s to approximately 4% during the late 1980s. In comparison, our study results indicated that the area of land for which soil TP concentrations exceed 650 mg kg^{-1} increased from 10 944 ha (25% of total area) in 1990 to 16 344 ha (37.8% of total area) in 1998, an average annual rate of increase of 5.0%.

Perhaps more striking is the increase in the total area considered as *P-enriched*, that is, the area for which soil P concentration is greater than 500 mg kg^{-1}, which has been suggested as the upper limit of historical background soil P concentrations (McCormick et al., 1999). Using those criteria, about 73% of the total area (31 777 ha) would be considered *P-enriched* in 1998, compared with 48% of the land area (20 829 ha) in 1990. Thus, the rate of increase of the P-enriched area, or alternatively, the rate of decrease of the unimpacted area during the period 1990–1998, was estimated to be 1327 ha yr^{-1}, or 5.25% yr^{-1}.

Indicator Kriging

The interpolated grids created by the ordinary kriging procedure represent an optimized estimate of soil TP concentration for points where no data (measurements) are available. In theory, if not in practice, ordinary kriging (i) provides an unbiased estimator, because it drives the mean residual toward zero and (ii) minimizes the overall variance of the estimation error (Isaaks and Srivastava, 1989). However, there is no straightforward method to provide a measure of the uncertainty in individual estimates. One measure of uncertainty associated with kriged values is the error variance (Isaaks and Srivastava, 1989). The value of this parameter is dependent on the covariance model used in the kriging procedure and the spatial configuration of the data points. However, the kriging error variance does not depend on the actual data values, a major shortcoming for determining the local spread of estimation errors.

A more useful and statistically valid procedure for conveying the uncertainty associated with the interpolated values of soil total P concentration is the use of indicator kriging (Goovaerts, 1997). This nonparametric kriging technique can be used to approximate a conditional cumulative probability distribution function (ccdf) for the parameter under study, by calculating for each grid cell the probability of exceeding each of a number of threshold values (e.g., deciles). Rather than construct a detailed ccdf, we used a series of five evenly distributed threshold values for soil TP concentration to visually evaluate changes in the distribution of soil total P. The threshold values selected were 500, 750, 1000, 1250, and 1500 mg P kg^{-1}.

The series of plots presented in Fig. 6 provides a visual evaluation of changes in the spatial extent and patterns of soil P enrichment at several levels (thresholds) of total P concentration. The probabilistic approach used here allows the observer to assign any level of uncertainty to the interpolated values in the kriged grids, and thus may be considered to be analogous to risk assessment. The use of indicator kriging provides clear evidence of the differences in soil TP enrichment between 1990 and 1998. For example, these data highlight the considerable expansion of low-level P enrichment (>500 mg kg^{-1}) throughout most of WCA-2A. Also noteworthy is an apparent shift of the more highly P-impacted area (i.e., TP $>$ 1500 mg kg^{-1}) toward the south. As previously discussed, this could be attributed to a breakthrough of P from saturated soils close to the S-10 structures. Alternatively, this may be a manifestation of a substantial diversion of flow from S-10C toward the east and south along the interior canal, then back toward the west along numerous well-used airboat trails. Field observations in the vicinity of S-10C suggest that the accelerated peat accretion and increased density of herbaceous and woody vegetation in the highly P-enriched area along the interior canal has resulted in increased hydraulic resistance along the southerly flow path into the WCA-2A marsh.

Areal expansion of P-enriched soils in WCA-2A may be viewed as a P front advancing southward from the S-10 inflows across the unimpacted interior sawgrass marsh and slough region. Given that the P enrichment gradient is relatively broad, however, the front is actually quite diffuse and therefore difficult to map as such. If the P enrichment front is defined by the extent of the proposed soil P concentration that facilitates cattail invasion (650 mg kg^{-1}) (Wu et al., 1997), its location has progressed from about 5.5 km south of S-10C in 1990 to 9.1 km in 1998. The movement is equivalent to an average rate of 436 m yr^{-1} into the interior marsh

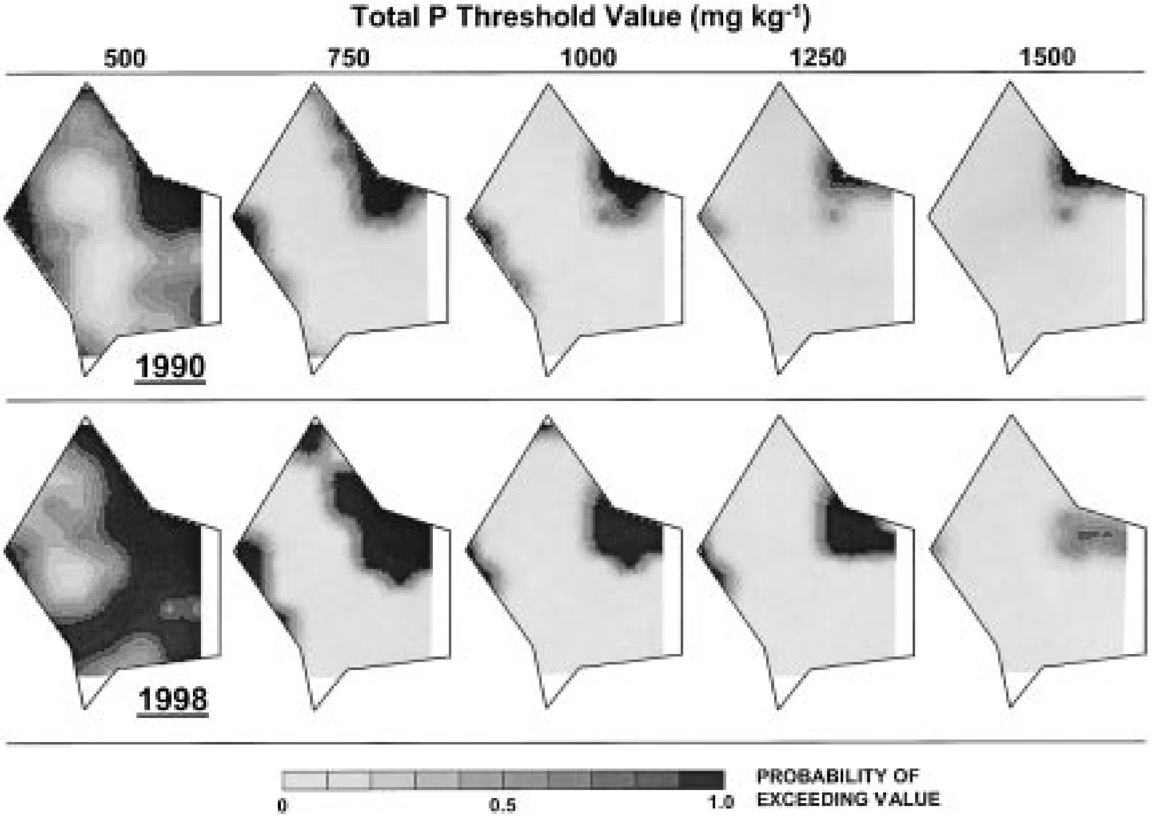

Fig. 6. Probability of soil total P concentration exceeding threshold values of 500, 750, 1000, 1250, and 1500 mg kg^{-1} in 1998 (current study) vs. 1990 (DeBusk et al., 1994).

of WCA-2A. Using a similar approach we estimate that the 1000 mg P kg^{-1} front has advanced from 4.2 to 6.0 km to the south of S-10C during the same period, equivalent to a rate of 218 m yr^{-1}.

Recent efforts have been made to estimate the long-term, or sustainable, P assimilation capacity of WCA-2A using empirical models based on historical P loading and removal data (Walker, 1995; Richardson et al., 1997; Richardson and Qian, 1999; Kadlec, 1999). Short-term rates of P removal in newly P-impacted wetlands, including treatment wetlands in the startup phase, are governed principally by sorption reactions (adsorption and precipitation) within the soil and vegetation and by plant uptake. Long-term removal of P in WCA-2A, and in wetlands as a rule, is a function of accretion of recalcitrant organic or inorganic P compounds, for example peat formation.

Both Richardson and Qian (1999) and Kadlec (1999) used a similar approach, but contrasting assumptions regarding model parameterization, to arrive at an approximate location, in terms of distance from the S-10 inflow, of the boundary between the region of nonsustainable ("impacted" area) and sustainable P assimilation ("unimpacted" area). The former study yielded an estimated distance of 5.1 km from S-10C and the latter generated a value of approximately 16 km. Both studies are based on the assumption, drawn from historical surface water quality data, that a steady-state condition exists between P loading and assimilation in WCA-2A (i.e., that the P enrichment front is stationary). A recent study suggests that the surface water P front may not be stationary and marsh TP concentrations vary in response to inflow TP concentrations, water depth, and flow (Smith and McCormick, 2001). While surface water TP concentrations appear to have declined in the 1990s (Smith and McCormick, 2001), our results indicate that the soil P enrichment front has been dynamic during recent years. These results may reflect a certain degree of downstream redistribution of soil P, for example by way of upstream P desorption and/or mineralization and downstream assimilation. Regardless of the mechanism, our results are indicative of a progressive P impact, in the form of soil P enrichment, to the south of the S-10A and S-10C inflows.

CONCLUSIONS

Several decades of loading of nutrient-laden agricultural drainage is reflected in the now widespread P enrichment of surface soils in WCA-2A. Historical and current spatial patterns of soil P enrichment indicate that the main source of P loading has been the S-10 surface inflow structures along the northeastern boundary of the study area. A secondary source of P loading and subsequent soil P enrichment has been the area downstream of the S-7 pump station, at the western corner of WCA-2A. However, soil P enrichment in association with the S-7 inflow has not increased in areal extent as rapidly as enrichment associated with the S-10 structures, probably due to natural surface flow patterns (generally north to south) within WCA-2A.

Geostatistical analysis and comparison of current spatial patterns of soil P enrichment with spatial patterns circa 1990 have indicated that the extent of soil P enrichment increased over an 8.25-yr period from 1990 through 1998. The change in spatial distribution of soil P enrichment between 1990 and 1998 suggest that the soil P concentration gradient south of S-10C has become more diffuse as the overall extent of soil P enrichment has increased.

Soil P enrichment above historical background concentrations can be considered an indicator of ecological change. Dynamic patterns of soil P enrichment have been closely aligned with documented changes in vegetation patterns, most notably the change from native sawgrass marsh to cattail marsh. Results of this soil characterization study, showing a substantial increase in the extent of moderate soil P-enrichment, is indicative of the magnitude of recent increases in the ecologically impacted area of WCA-2A.

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