

## Spatial Patterns of Labile Forms of Phosphorus in a Subtropical Wetland

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### ABSTRACT

Phosphorus (P) has been identified as the key constituent defining wetland productivity, structure, and function. Our goal was to investigate the spatial patterns of total P and three labile forms of P (labile organic, inorganic, and microbial biomass P) across a subtropical wetland located in east-central Florida, the Blue Cypress Marsh Conservation Area (BCMCA), and link spatial patterns to ecosystem processes. The wetland received a continual input of nutrients primarily from the south and intermittently from the west and east, respectively, which ceased in the mid-1990s. Since then the marsh system has been undergoing natural succession. We used (i) ordinary kriging to characterize the spatial patterns of total P and labile P forms across the wetland, (ii) local, moving spatial correlations to investigate relationships between total P and labile P forms, and (iii) a clustering technique to link the identified spatial patterns to biogeochemical processes. The spatially explicit analyses revealed patterns of total P and labile P forms as well as changing relationships between variables across the marsh. We were able to distinguish P-enriched areas from unaffected ("natural") areas and intermediate zones that are currently undergoing change as P is mobilized and translocated. We also identified areas that are at risk, showing a shift toward a more P-enriched status. Our results improve our understanding of P and its labile components within a spatially explicit context.

MANY WETLANDS are end-points of water and nutrient flowpaths and integrate environmental conditions in a watershed. Nutrient cycling has been identified as one of the key regulators of wetland structure and function (Newman et al., 2001). Phosphorus (P) loading to wetlands has been shown to regulate primary productivity (Davis, 1991), species composition (Davis, 1994), and cycling of carbon, nitrogen, and other nutrients (Newman et al., 2001). Detrimental changes associated with allochthonous nutrient inputs can significantly hamper the capacity of wetlands to function effectively within a watershed. While P biogeochemical cycling is well documented at a site-specific scale (Reddy et al., 1998; White and Reddy, 2000; Fisher and Reddy, 2001; Craft and Chiang, 2002), our understanding of biogeochemical patterns at landscape scale is still limited (Grunwald et al., 2004). Wetland soils are not uniform and concurrent transformations and transport processes are responsible for emerging spatial patterns of biogeochemical properties. Intrinsic processes such as P immobilization or mineralization, as well as extrinsic forcing functions such as fires, hurricanes, nutrient inputs from

anthropogenic sources, and airboat activity (e.g., in Florida wetlands), contribute to the spatial heterogeneity of soil biogeochemical properties in wetlands. Exogenous P tends to accumulate near the input sources, generating distinct horizontal spatial gradients (DeBusk et al., 1994, 2001; Grunwald et al., 2004). Typically, vertical gradients of P along soil profiles decline from top to bottom profiles, where the topsoil (0–10 cm) integrates external nutrient loading effects over longer time periods (10–15 yr or more) (Reddy et al., 1999).

Once the external P loading is curtailed, internal P flux from soils to the overlying water column can redistribute P, generating new spatial patterns in soil P and its labile and nonlabile constituents (Fisher and Reddy, 2001). The mobility of P in wetland soils can be defined as a function of the soil characteristics, associated soil and water P-pool sizes, and the biotic action on soil P, such as organic matter decomposition and P mining by macrophytes (White et al., 2004). Inorganic P forms are regulated by pH, redox potential, and mineralogical composition of soils (Stumm and Morgan, 1996). Typically, large quantities of organic P are immobilized in wetland soils and only a small portion of the total organic P is biologically accessible. Therefore, to assess the P dynamics in a wetland system and to evaluate its propensity to export or reallocate P, the bioavailable P pool is the primary constituent of interest.

The mosaic of system structures and functions distributed across a wetland represents the combined effects and interactions of a variety of biotic and abiotic factors. As a result, existing landscape patterns implicitly contain information about the processes that generated these spatial patterns (Holling and Gunderson, 2002), which can be quantified using geostatistical methods (Webster and Oliver, 2001; Wackernagel, 2003). The estimation of soil properties from soil samples (point observations) on a continuous grid that shows gradual variation of values across a wetland can be used to document spatial landscape patterns. The spatial relationships (spatial covariation) between properties might differ at fine and coarse scales. To analyze those scale-dependent spatial relationships is of interest to gain a better understanding of wetland ecology.

Our objectives were to describe the spatial patterns and interrelationships of selected P pools (labile organic phosphorus [ $P_o$ ], microbial biomass phosphorus [MBP], and labile inorganic phosphorus [ $P_i$ ]) and the total phosphorus (TP) in the surface soils of a subtropical wetland that is recovering from historical nutrient impact. To synergize our results we linked the identified spatial patterns to biogeochemical processes.

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**Abbreviations:** BCMCA, Blue Cypress Marsh Conservation Area; MBP, microbial biomass phosphorus;  $P_i$ , inorganic phosphorus;  $P_o$ , organic phosphorus; TP, total phosphorus.

## MATERIALS AND METHODS

### Study Area

The study area comprised 4800 ha of freshwater wetland within the Blue Cypress Marsh Conservation Area (BCMCA), located in the headwater region of the St. Johns River in east-central Florida (Fig. 1). Since the late 1990s there have been major efforts by the St. Johns River Water Management District to restore the natural hydrologic cycles and reduce nutrient inputs to wetlands in the upper St. Johns River Basin. The BCMCA is a subtropical marsh, which received considerable point source inputs of nutrient-laden agricultural runoff. The marsh has been the object of numerous studies to evaluate its recovery (Ollila et al., 1995; D'Angelo et al., 1999; Corstanje et al., 2003). Recent work (Corstanje et al., 2003) indicated that a significant element in the recovery process is the spatial redistribution of P over the marsh.

The BCMCA has inflows from Fort Drum Marsh Conservation Area to the south, and lesser inputs from two subbasin tributaries from the west and east. The BCMCA includes areas impacted by nutrient enrichment from these inflows as well as unimpacted zones. The nutrient inflows from agricultural activities ceased in the mid-1990s and its predominant plant communities are currently undergoing a state of natural succession. Native vegetation in the study area is predominately a mosaic of sawgrass (*Cladium jamaicense* Crantz) and maidencane (*Panicum hemitomon* Schult.) flats yet it also contains significant areas of scrub-shrub vegetation (e.g., the coastal plain willow, *Salix caroliniana* Michx.), cattail marshes (*Typha* spp.), and deep-water slough communities (e.g., *Nymphaea* spp.). Drying of the marsh permitted the expansion of woody vegetation (e.g., coastal plain willow) into areas previously occupied by herbaceous, wetland marsh plants. Since the early 1970s, coastal plain willow has been expanding from the

southern to the northern part of the study area. A digital orthophoto and land use map is shown in Fig. 2.

### Soil Sampling and Analyses

We collected soil samples at 266 sites within the BCMCA in March and April 2002. Each sample was the composite of two soil cores (0–10 cm depth) taken with a stainless steel core tube. Samples were placed and sealed in plastic bags, and stored on ice until received at the laboratory where they were stored at 4°C until analysis. The sampling design is shown in Fig. 1. In the southern part of the study area, a few sites were not accessible due to dense scrub-shrub vegetation. Our measured soil properties are summarized in Table 1. Soil samples were extracted using the chemical fractionation scheme described by Ivanoff et al. (1998). All extraction periods pertained to the length of times the tubes were shaken on a reciprocating mechanical shaker. All extracts were centrifuged at 7000 rpm for 15 min and filtered through Whatman (Maidstone, UK) filter paper no. 41 before P determination. In all cases, inorganic P was determined by colorimetric method of Murphy and Riley (1962). Organic P in all extracts was calculated as the difference between TP and inorganic P (Ivanoff et al., 1998). The lab error for all phases was between 5 and 10%. Operationally defined labile  $P_1$  and labile  $P_0$  forms were extracted with  $\text{NaHCO}_3$  (pH = 8.5). Alkaline extracts were analyzed for soluble reactive P and TP. Labile organic P was determined as the difference between TP and inorganic P in the extracts. Microbial biomass P was determined using the chloroform fumigation techniques. Microbial biomass P was not corrected for extraction efficiency, as our earlier studies have shown that the use of an efficiency factor overestimates the organic P pool in organic soils (Chua, 2002). Total soil P was determined using the ashing method (Anderson, 1976). Phosphorus content in all solutions

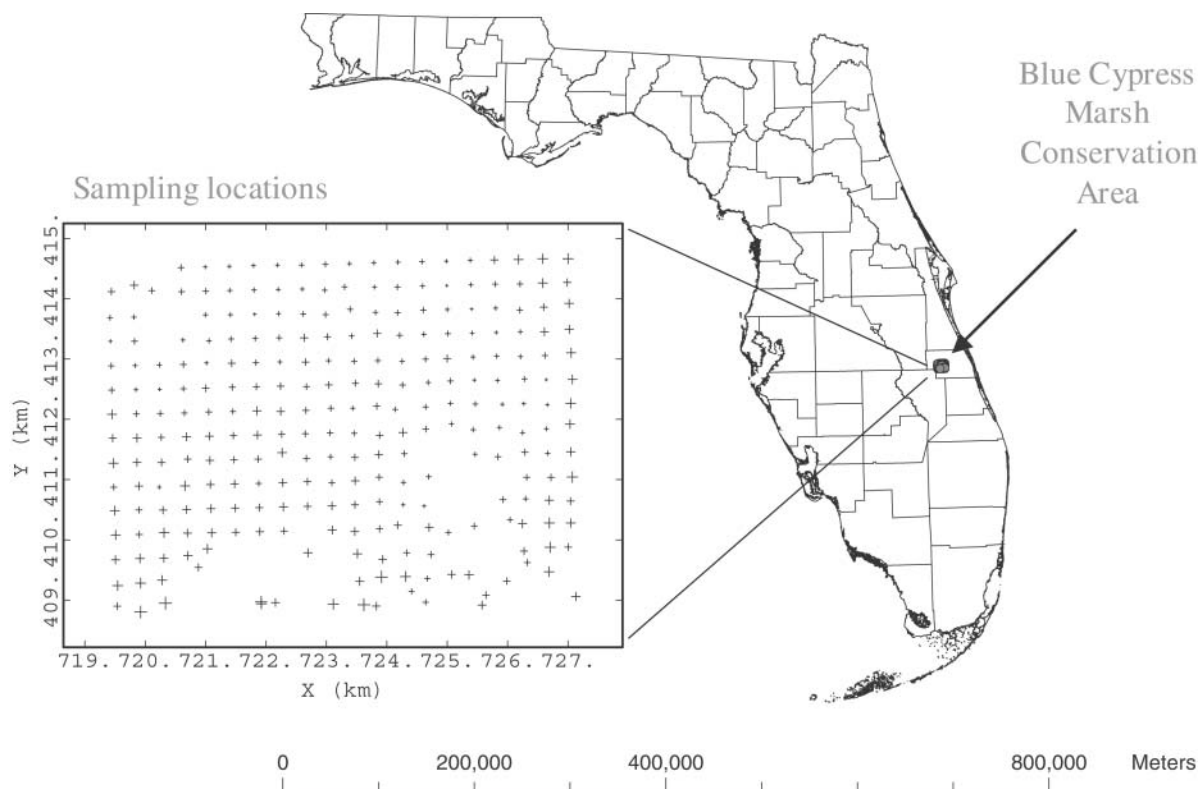
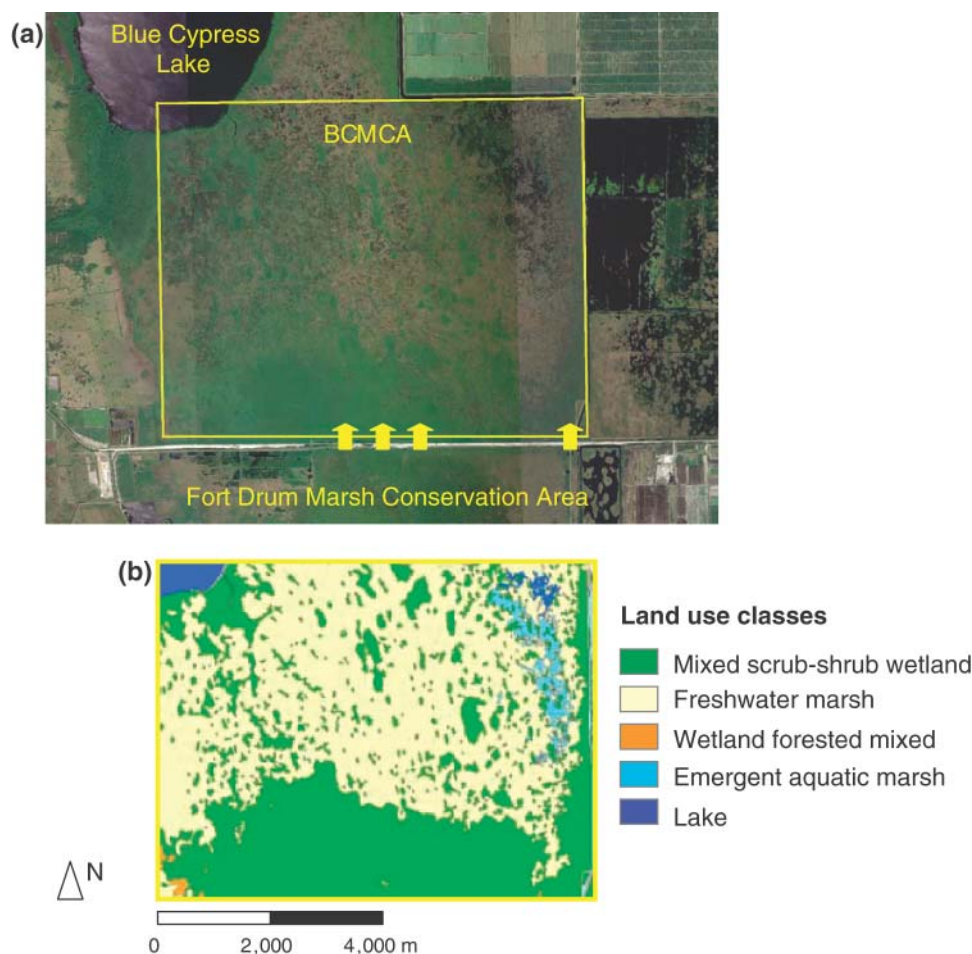


Fig. 1. Geographic location of the Blue Cypress Marsh Conservation Area (BCMCA) and soil sampling locations.



**Fig. 2.** (a) Digital Orthophoto Quarter Quads with 1-m spatial resolution from 2004 (data source: St. Johns River Water Management District) (yellow arrows represent water control structures). (b) Land use classes derived from aerial photographs (1997), map scale 1:12 000 (data source: St. Johns River Water Management District).

including those extracted and digested was analyzed using an automated colorimetric analysis (Method 365.1; USEPA, 1993). All analyses for this study followed National Environmental Laboratory Accreditation Conference (NELAC) quality control and quality assurance protocols.

### Spatial Analyses

We used the ISATIS software (Geovariances, 2005) for the semivariogram analyses and kriging. An initial data screening was conducted, including testing for normality. All measured properties showed approximate normal distributions. Subsequently, we calculated isotropic experimental semivariograms using Eq. [1]:

$$\gamma(h) = \frac{1}{2n(h)} \sum_{\alpha=1}^n [z(x_{\alpha} + h) - z(x_{\alpha})]^2 \quad [1]$$

where  $z(x_{\alpha} + h)$  and  $z(x_{\alpha})$  represent the pairs of values separated by a distance  $h$  (or lag size),  $n$  is the number of values separated by  $h$ , and  $\gamma(h)$  are the semivariance estimates (Wackernagel, 2003). Anisotropic semivariograms were generated to identify potential spatial directional structures of variables but no distinct spatial directional patterns were found. We optimized the lag classes for each soil property. This is a common procedure before proceeding with fitting of variogram models (compare textbooks Goovaerts, 1997; Webster and Oliver, 2001). The goal was to generate a smooth experimental variogram model. Model semivariograms were fitted interactively using experimental semivariograms. Cross-validation was used to assess spatial modeling errors. Validation was performed by splitting the dataset into 67% for model development and 33% for validation using a random number generator.

Ordinary kriging (Webster and Oliver, 2001) was used to create spatial estimations of soil properties. We coded a

**Table 1.** Descriptive statistics of biogeochemical soil properties for total phosphorus (TP), labile organic phosphorus (bicarbonate-extractable inorganic phosphorus) ( $P_o$ ), labile inorganic phosphorus (bicarbonate-extractable organic phosphorus) ( $P_i$ ), and microbial biomass phosphorus (MBP).

Variable	Sites (count)	Minimum	Maximum	Mean	Median	Standard deviation	Skewness
mg kg <sup>-1</sup>							
TP	266	349.6	1013.7	620.5	602.8	128.0	0.52
Labile $P_o$	256	13.8	187.2	42.2	38.5	16.9	0.80
Labile $P_i$	251	0.0	75.1	21.1	20.5	11.6	0.81
MBP	254	2.2	395.6	151.2	145.2	51.7	0.79



program in Java to compute moving correlations to investigate localized spatial relationships between soil properties. The continuous, estimated soil property maps generated by the kriging procedure were used as input in our moving correlation program. The program takes the kriged estimates from two soil variables (e.g., TP and MBP) across a window of user-specified size and computes either experimental or standardized covariances (i.e., correlations) at each grid center point using all raster pixel values (soil variable estimates) in the window around the grid center point. Experimental covariances were computed using Eq. [2]:

$$s_{12} = \frac{1}{N} \sum_{\alpha=1}^n (z_1^\alpha - m_1^*)(z_2^\alpha - m_2^*) \quad [2]$$

where  $z_1^\alpha$  are all values of the first variable in the window,  $z_2^\alpha$  are all values of the second variable in the window,  $m_1^*$  and  $m_2^*$  are the means of the first and second variables in the window,  $N$  is the number of values in the window, and  $s_{12}$  is the covariance (Wackernagel, 2003). When the residual of variable  $z_1$  tends to have the same sign as the residual of  $z_2$  on average, the experimental covariance is positive, while when the two residuals are of opposite sign on average, the covariance is negative. When a large value of one residual is on average associated with a large value of the residual of the other variable, the covariance has a large positive or negative value. Thus, the covariance is a measure of the strength of the association between two environmental variables both in its magnitude and direction. When the units of the variables are not comparable, especially when they are of different type (e.g., kg, cm, %), it is preferable to standardize each variable  $z$ , centering its values around the center of mass by subtracting the mean, and subsequently normalizing the distances of the values to the center of mass by dividing them with the standard deviation. The standardized variable  $\tilde{z}$  is calculated according Eq. [3]:

$$\tilde{z} = \frac{z - m^*}{s} \quad [3]$$

where  $m^*$  is the mean and  $s$  the standard deviation over the entire grid of the variable being standardized. The covariance of two standardized variables  $\tilde{z}_1$  and  $\tilde{z}_2$  is a normed quantity  $r_{ij}$ , called the experimental correlation coefficient, with bounds  $-1 \leq r_{ij} \leq 1$  (Wackernagel, 2003).

The moving correlation coefficients were derived by moving a user-defined window across the whole wetland rasters. The numbers of raster cells in the  $x$  (easting) and  $y$  (northing) directions characterized each window. For example, the extent of a  $7 \times 7$  window was defined by 7 raster cells (pixels) in the  $x$  direction and 7 pixels in the  $y$  direction. We calculated moving correlation coefficients for three different window sizes of 7, 11, and 23 pixel lengths. A small window of  $7 \times 7$  pixels represented a tight local area whereas a larger window of  $23 \times 23$  pixel lengths represented a larger local area. A cluster analysis was used to aggregate and integrate data and link spatial patterns to ecosystem processes. The three different correlation coefficients of TP-labile  $P_i$ , TP-labile  $P_o$ , and TP-MBP were grouped by performing a clustering analysis using a combination of the Schwarz's Bayesian criterion and Ward's cluster method over two window sizes (7 and 23). For each cluster the means for all variables were calculated. Then, for each case, the squared Euclidean distance to the cluster mean was calculated. These distances were summed for all the cases. At each step, the two clusters that merge were those that result in the smallest increase in the overall sum of the squared within-cluster distances.

## RESULTS AND DISCUSSION

### Semivariogram Models and Estimated Values

Descriptive statistics for all soil properties are listed in Table 1. Mean TP content of the soil was  $620 \text{ mg kg}^{-1}$ , with a minimum of  $350 \text{ mg kg}^{-1}$  and maximum of  $1014 \text{ mg kg}^{-1}$ , indicating that the BCMCA comprised nutrient-enriched areas resulting from historical nutrient loading. Soil TP values exceeding  $550 \text{ mg kg}^{-1}$  can be viewed as elevated, deviating from natural wetland conditions with organic soils (DeBusk et al., 2001). The highest labile  $P_i$  and labile  $P_o$  observed were 187 and  $75 \text{ mg kg}^{-1}$ , respectively. The labile  $P_i$  levels were approximately twofold higher than the labile  $P_o$  (Table 1). The MBP ranged from 2 up to  $396 \text{ mg kg}^{-1}$  with a mean of  $151 \text{ mg kg}^{-1}$ .

We fitted the model semivariograms shown in Fig. 3 and 4, providing the best fit to the experimental semivariograms (Table 2). We used a spherical semivariogram for TP, an exponential and Bessel-J for labile  $P_i$ , spherical for labile  $P_o$ , and a nested cubic and power semivariogram for MBP. The model semivariogram characteristics are summarized in Table 2. The *range* describes the distance at which observations are spatially autocorrelated. A short *range* indicates that only observations separated by short distances are autocorrelated,

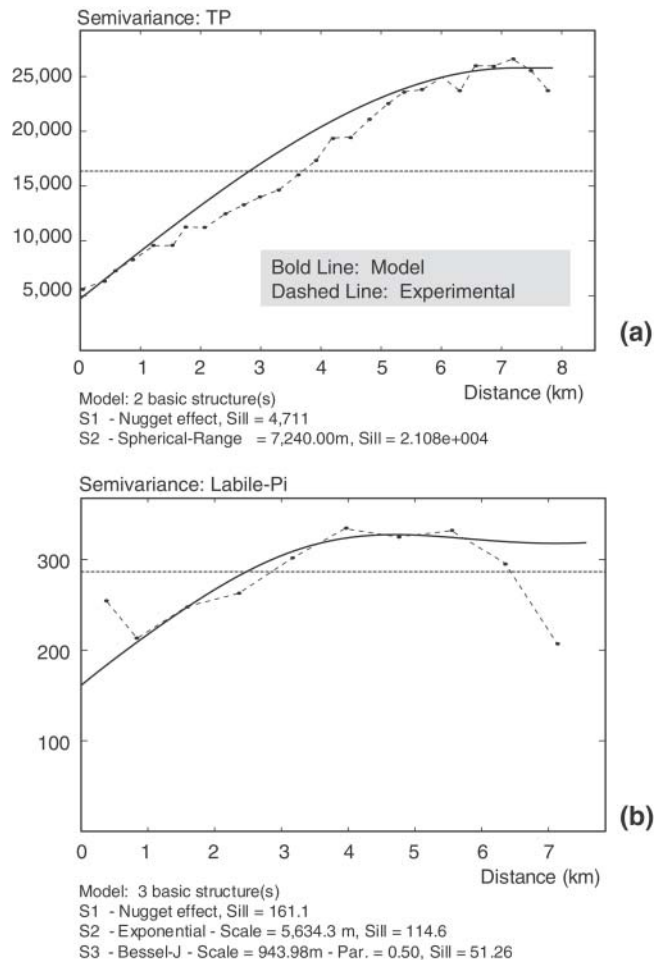
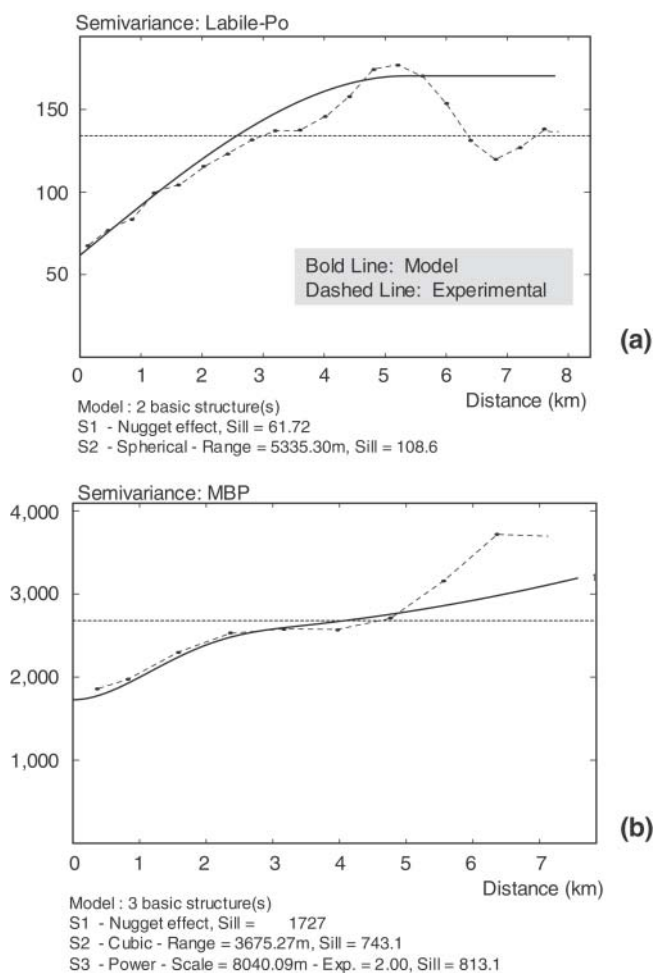


Fig. 3. Semivariograms for total phosphorus (TP) ( $\text{mg kg}^{-1}$ ) and labile inorganic phosphorus ( $P_i$ ) ( $\text{mg kg}^{-1}$ ).



**Fig. 4.** Semivariograms for labile organic phosphorus ( $P_o$ ) ( $\text{mg kg}^{-1}$ ) and microbial biomass phosphorus (MBP) ( $\text{mg kg}^{-1}$ ).

whereas a long *range* is indicative of spatial autocorrelation over long distances. Labile  $P_i$  and MBP exhibited two ranges, translating into two spatial autocorrelation structures for each soil property. Labile  $P_i$  had a short range of 944 m and long range of 5634 m; MBP showed a short range of 3675 m and long range of 8040 m. The range of soil TP was 7240 m and labile  $P_o$  5335 m, respectively. The nugget to sill ratio was narrower for labile  $P_i$  and MBP when compared to TP and labile  $P_o$ . The identified nested spatial structures for labile  $P_i$  and MBP suggest that multiple concurrent ecosystem processes operate at different spatial scales. Overall, labile P components showed shorter ranges than TP, possibly caused by surface and subsurface hydrologic or biogeochemical processes.

Cross-validation results are shown in Fig. 5. Plots of sample (observed) vs. estimated values highlight under- and overestimations. In case of cross-validation standardized errors exceeding a certain threshold, the outliers are located outside the corresponding confidence limit of a normal distribution. The points for which the cross-validation standardized error remains within this  $[-\text{threshold}; +\text{threshold}]$  interval are usually called robust. We selected the threshold 2.5 (interval  $[-2.5;$

**Table 2.** Semivariogram characteristics for total phosphorus (TP), labile organic phosphorus (bicarbonate-extractable inorganic phosphorus) ( $P_o$ ), labile inorganic phosphorus (bicarbonate-extractable organic phosphorus) ( $P_i$ ), and microbial biomass phosphorus (MBP) (all models were isotropic).

Variable	Lag	Nugget	Models	Range	Sill
				m	
TP	300	4711.0	spherical	7240.0	21 080.0
Labile $P_i$	800	161.1	exponential	5634.3	114.6
			Bessel-J	943.9	51.3
Labile $P_o$	400	61.7	spherical	5335.3	108.6
MBP	800	1727.0	cubic	3675.3	743.1
			power	8040.1	813.1

+2.5]), which defines outliers as being outside the 99% confidence limit of a normal distribution. The few bold dots (Fig. 5) highlight nonrobust data outside the selected confidence limit. For labile  $P_i$ , labile  $P_o$ , and MBP there was a slight tendency to overpredict large values. Most of the data pairs for all variables scatter along the line of equal values indicating a relatively good fit. Ideally the standard error variance should be close to 1. The standard error variance for TP was 0.984, for labile  $P_i$  1.256, for labile  $P_o$  1.000, and for MBP 0.998. These are all excellent standard error variances except for labile  $P_i$ , which is still reasonably close to 1.

The estimated soil properties at 100-m pixel resolution are shown in Fig. 6 and 7. The lower soil TP estimate values were found in a crescent-shaped area in the northwestern area of the BCMCA and highest estimated values were found in the southern and eastern fringes. This is consistent with the historical point source inputs of P from agricultural activities, which contributed to the relatively high TP values with a maximum of  $1013 \text{ mg kg}^{-1}$ . Only 27% of estimated TP values were below  $550 \text{ mg kg}^{-1}$  and 73% exceeded  $550 \text{ mg kg}^{-1}$ .

The highest level of labile  $P_i$  was found in the southern portion coinciding with the high TP values. The central areas of the marsh showed relatively high labile  $P_i$  with values in the range of 55 to  $60 \text{ mg kg}^{-1}$  whereas smaller estimated values ( $25 \text{ mg kg}^{-1}$ ) were computed for the northern areas of the marsh. Labile  $P_o$  showed similar spatial patterns when compared to TP and labile  $P_i$ ; however, high values were estimated in an area slightly off to the west. Labile organic P estimated values were as high as  $50 \text{ mg kg}^{-1}$  and showed a median of  $39 \text{ mg kg}^{-1}$ . Due to nutrient enrichment caused by increased primary productivity such areas are characterized by high labile P fractions. The labile  $P_o$  fraction is the result of a bicarbonate extraction and has been traditionally associated to the easily mineralizable organic P fraction that is relatively bioavailable (Ivanoff et al., 1998). Distinct different spatial patterns emerged for MBP, which showed highest values in the western portion and smallest values in the eastern portion of BCMCA. The mean of all MBP estimations was  $147 \text{ mg kg}^{-1}$ , which closely matched the observed mean of  $151 \text{ mg kg}^{-1}$ . About 50% of estimated MBP were below and 50% above the estimated mean value.

Validation results are summarized in Table 3. The mean error of TP was  $-0.52$ , of labile  $P_i$   $-0.19$ , labile  $P_o$   $-0.06$ , and MBP  $0.10$ . Mean standardized errors were

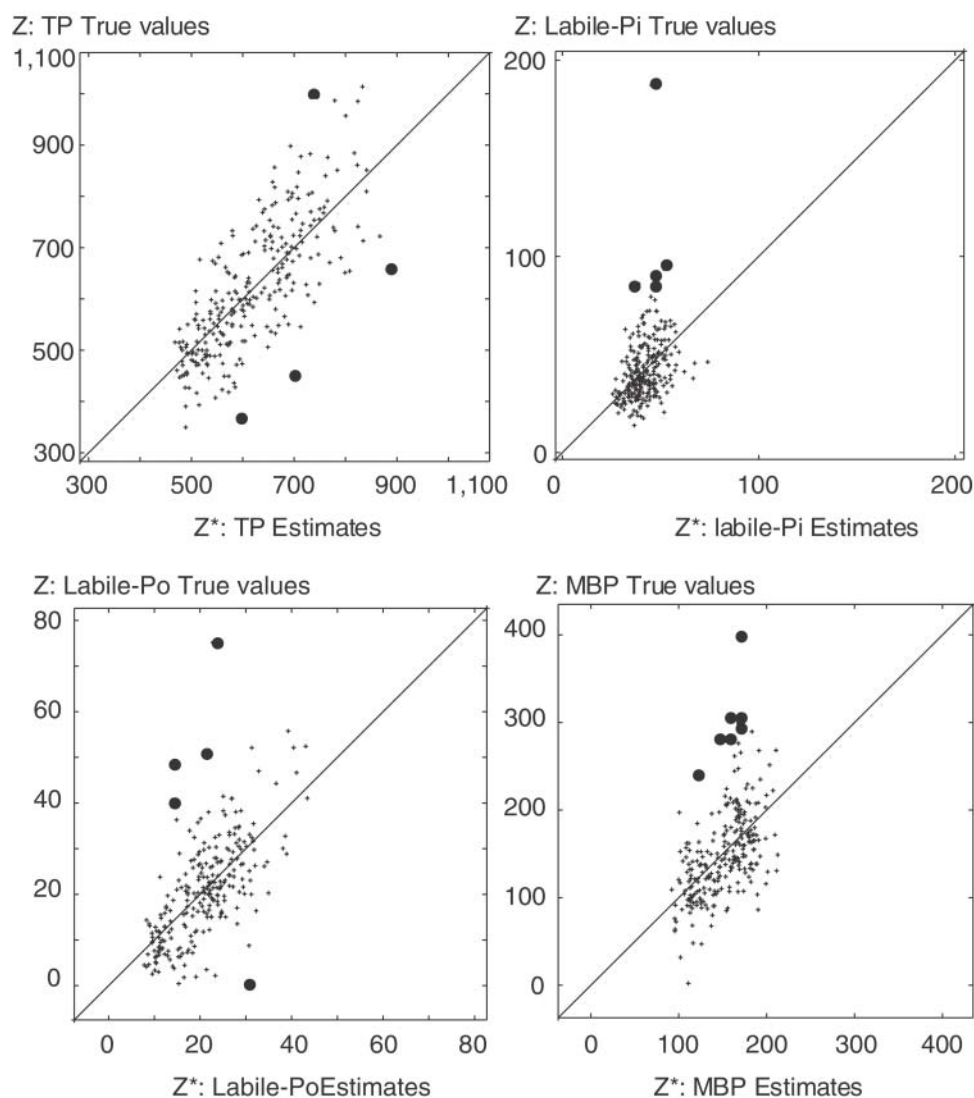


Fig. 5. Scatter diagrams of sample data versus estimated values of total phosphorus (TP), labile inorganic phosphorus ( $P_i$ ), labile organic phosphorus ( $P_o$ ), and microbial biomass phosphorus (MBP).

small for all soil properties indicating that sufficient observations were available to generate robust estimations.

### Spatial Relationships between Variables

Global correlation coefficients ranged from 0.148 between MBP and labile  $P_o$  to 0.534 between TP and labile  $P_i$ . Overall, correlation coefficients across the entire conservation area were low, translating into weak relationships between soil properties. This is not uncommon for soil characteristics across entire wetland systems (White and Reddy, 2000) as differential effects of nutrient dynamics tend to be localized, producing a patterned response within a wetland (Davis, 1991; Reddy et al., 1993; DeBusk et al., 1994).

Therefore, we computed local spatial correlations between the labile and biomass components of P and TP to further explore the changing spatial P dynamics across the marsh. The local spatial interrelationships between soil properties were computed with local,

moving correlation coefficients that revealed changing relationships between variables across the BCMCA. Results of the spatial analyses between TP and labile  $P_i$  are shown in Fig. 8 for the window sizes 7, 11, and 23. The smaller window size 7 considered a local neighborhood of  $7 \times 7$  pixels with length 100 m resulting in an area of 49 ha, whereas the window size 23 considered a larger local neighborhood area of 529 ha. In contrast, the total study area comprised  $60 \times 80$  pixels covering an area of 4800 ha. The map depicting the computed local correlations using a window size of 7 (Fig. 8a) showed patchy areas with negative correlations ( $-0.2$ ) across the conservation area within a matrix of weak positive correlations of mostly 0.2 to the highest values of 0.4.

The local correlations between labile  $P_i$  and TP (Fig. 8) and between labile  $P_o$  and TP (Fig. 9) were greatest in the south and east, which coincided with areas showing highest estimated TP values. However, over most of the BCMCA the moving correlations were

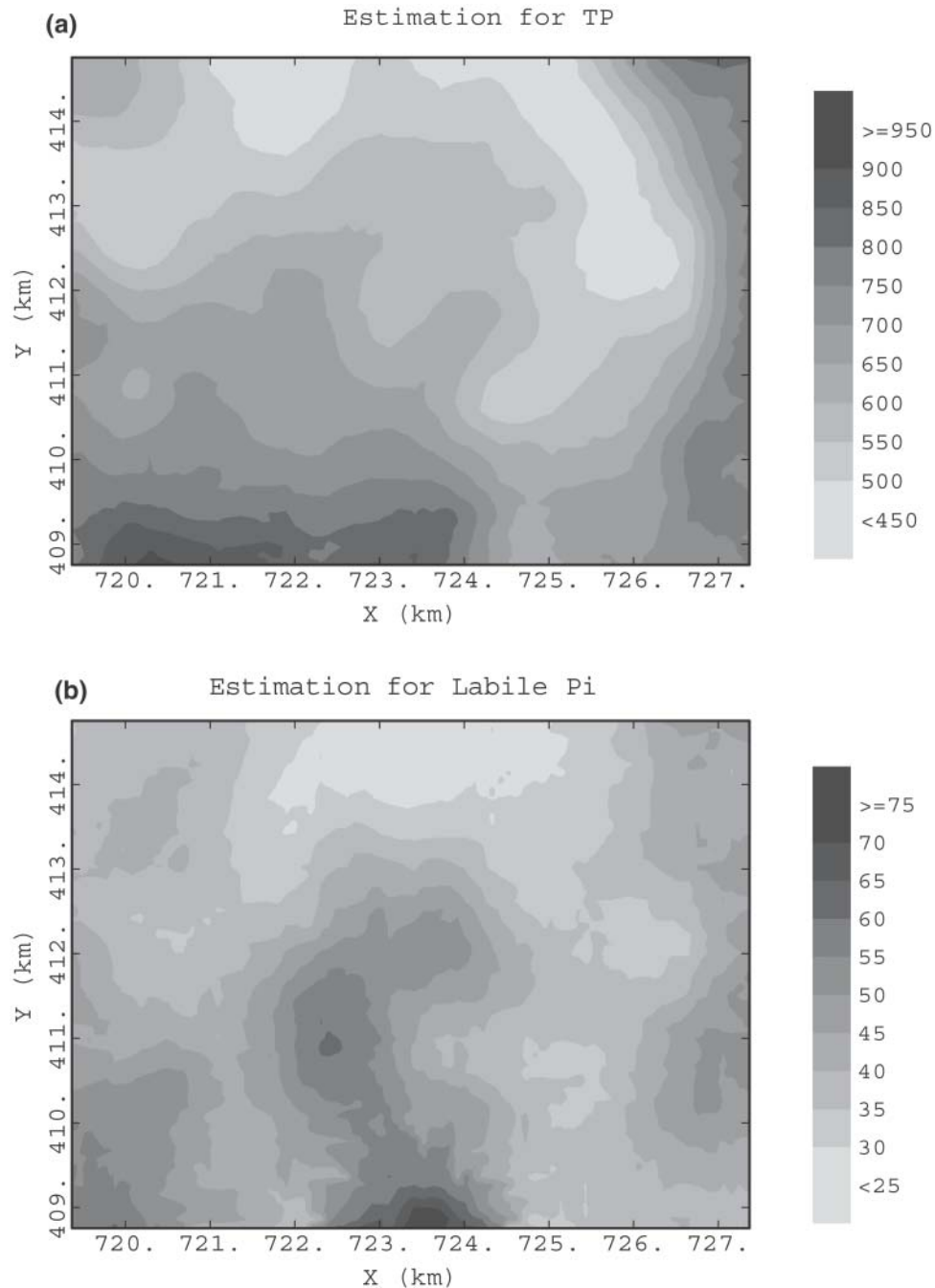


Fig. 6. Estimations for total phosphorus (TP) and labile inorganic phosphorus ( $P_i$ ).

extremely weak with low positive and negative correlation coefficients in the range of 0 to 0.2 and 0 to  $-0.2$ , respectively. We noted an increase in the magnitude of the correlation coefficients as the window size increased. The spatial correlations calculated with a window size of 23 were as high as 0.8 to 1.0 for labile  $P_i$  and TP as well as for labile  $P_o$  and TP (Fig. 8 and 9). As shown on the bottom of the map in Fig. 8, the correlations between labile  $P_i$  and TP calculated using a window size 23 showed only a small portion in the southern part in the range of 0 to  $-0.2$ . This area coincided with dense scrub-shrub vegetation of coastal plain willow. In contrast,

labile  $P_o$  and TP within window size 23 showed negative correlation values in the western portion of BCMCA. Adjacent to this area we found very high positive correlations ( $>0.8$ ) between labile  $P_i$  and TP as well as between labile  $P_o$  and TP. Global correlations computed over the entire BCMCA were all positive and failed to reveal the changing strengths and directions (positive or negative) of spatial interrelationships between soil properties across the study area (Table 4). Throughout the interior of the marsh, over the different window sizes, we did not find TP and labile P components to be highly correlated. The results from this analysis confirm



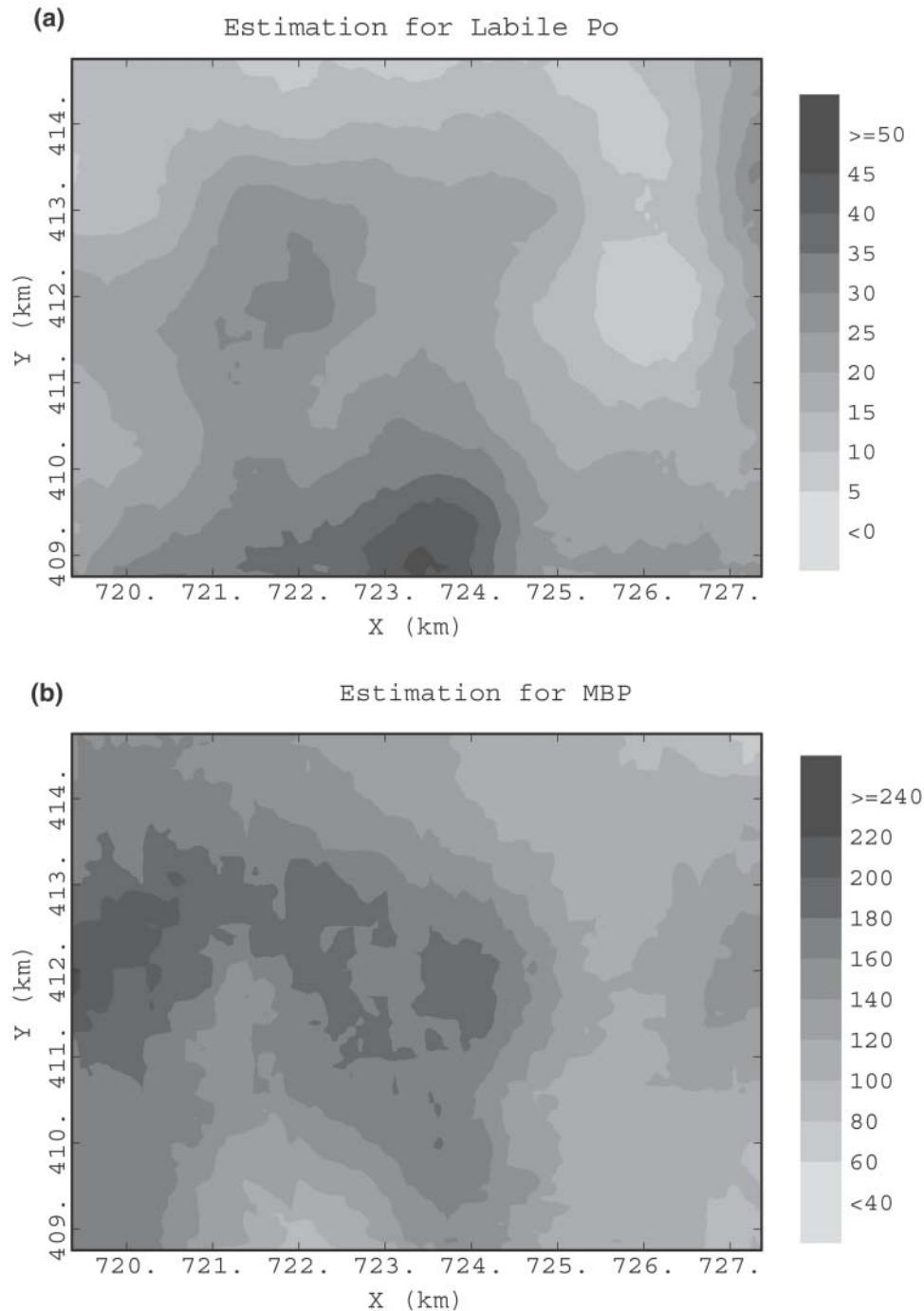


Fig. 7. Estimations for labile inorganic phosphorus ( $P_o$ ) and microbial biomass phosphorus (MBP).

the overall amplifying effect that nutrient enrichment has on all forms of P.

The computed local, moving correlations between TP and MBP are shown in Fig. 10. The correlation coefficients within a window size of 7 showed small negative ( $-0.2$ ) to small positive ( $0.2$ ) values. Spatial correlations within window size 23 showed negative values in the southwest of up to  $-0.4$  and an elongated patch in the east of up to  $0.4$ . The northern tip of the elongated patch coincided with areas predominated by open water (i.e., sloughs) (Fig. 2). Overall, the extent of

Table 3. Validation results for total phosphorus (TP), labile organic phosphorus (bicarbonate-extractable inorganic phosphorus) ( $P_o$ ), labile inorganic phosphorus (bicarbonate-extractable organic phosphorus) (P), and microbial biomass phosphorus (MBP).

Variable	Error		Standardized error	
	Mean	Variance	Mean	Variance
TP	-0.51951	6989.34767	-0.00397	1.00211
Labile $P_i$	-0.18735	256.48048	-0.01373	1.25598
Labile $P_o$	-0.06412	80.86073	-0.00609	1.00017
MBP	0.10311	1908.73425	0.00019	0.99752



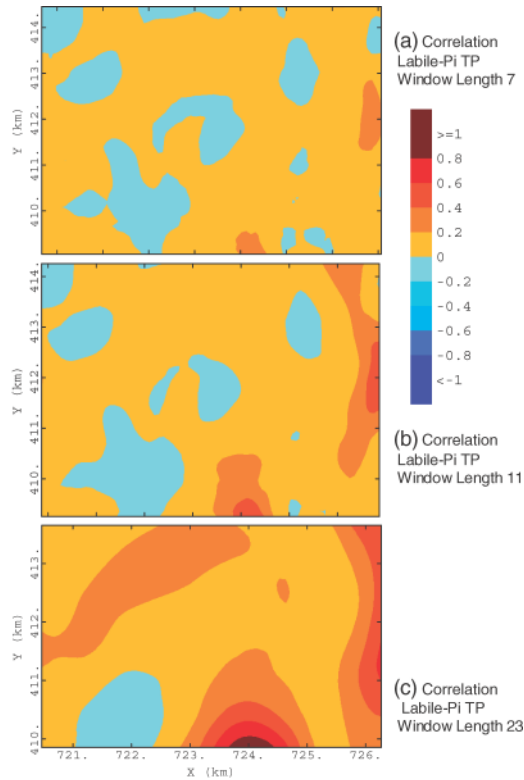


Fig. 8. Moving correlations between labile inorganic phosphorus ( $P_i$ ) and total phosphorus (TP) for window sizes of 7, 11, and 23.

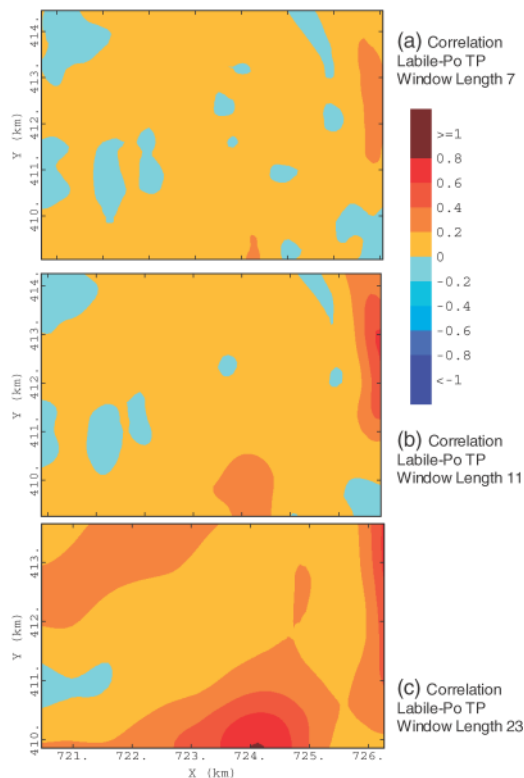


Fig. 9. Moving correlations between labile organic phosphorus ( $P_o$ ) and total phosphorus (TP) for window sizes of 7, 11, and 23.

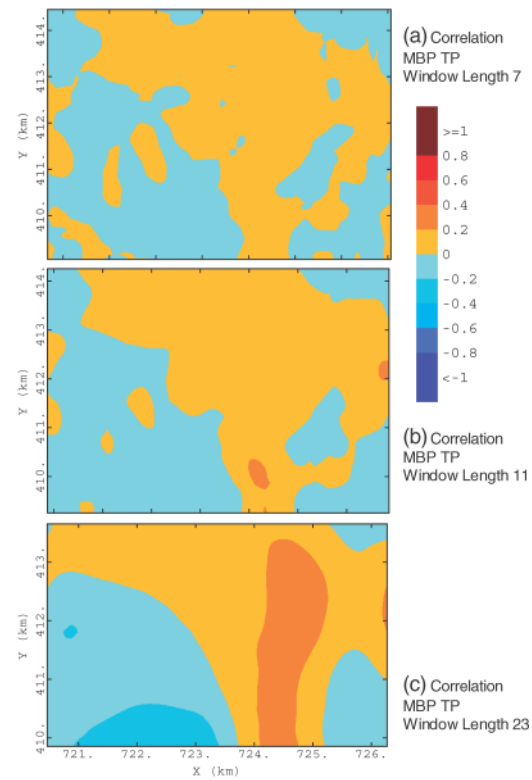


Fig. 10. Moving correlations between microbial biomass phosphorus (MBP) and total phosphorus (TP) for window sizes of 7, 11, and 23.

the area containing negative correlations between TP and MBP was much larger than between TP and labile  $P_i$  as well as TP and labile  $P_o$ . The negative local, moving correlations between TP and MBP contrasted the global correlation coefficient of 0.21. Microbial biomass phosphorus, with the exception of certain local areas in the south and northeast over the larger window sizes, showed no strong associations with TP throughout BCMCA. Microbial biomass has been shown sensitive to changes in nutrient loading with implications for soil quality (Jordon et al., 1995; McLatchey and Reddy, 1998; Corstanje, 2003). The eutrophication in marsh systems has been generally associated with increases in biomass content (Qualls and Richardson, 2000). In most of the areas, the level of microbial biomass in the BCMCA system primarily seemed to be responding to factors other than total levels of P. Reddy et al. (1998) suggested that P enrichment enhances the system primary productivity and increases the sizes and turnover rates associated with the different P pools. This was

Table 4. Global correlations of total phosphorus (TP), labile organic phosphorus (bicarbonate-extractable inorganic phosphorus) ( $P_o$ ), labile inorganic phosphorus (bicarbonate-extractable organic phosphorus) ( $P_i$ ), and microbial biomass phosphorus (MBP).

Variable	Labile $P_i$	Labile $P_o$	MBP
TP	0.5340	0.5225	0.2071
Labile $P_i$	1.0	0.2603	0.3165
Labile $P_o$		1.0	0.1483
MBP			1.0

confirmed in our study by finding high local correlation coefficients between TP and labile variables in the nutrient-enriched area to the south. We found P-enriched zones at the southern fringe of the study area close to historic P entry points gradually extending northward following hydrologic flow paths. Similar patterns of gradually declining P from point (control structures) and/or lines (canals) to the interior of a marsh were found by DeBusk et al. (1994) in Water Conservation Area 2A and Newman et al. (1997) in Water Conservation Area 1 in the Everglades. In the BCMCA we expect that the fringe areas surrounding the nutrient enrichment zones will be moving northward following an established hydrological gradient south to north into the Blue Cypress Lake. As a result, certain P forms will show preferential enrichment over others as P is transported from the impacted areas into the interior of the marsh. Currently, the marsh interior seems to be unaffected by nutrient enrichment reflecting only endogeneous pedogenic processes and vegetative patterns.

Reddy et al. (1998) provided data of TP and labile P components along a gradient from high to low TP sites in Water Conservation Area 2A, Everglades, Florida. Though no correlation coefficients were documented they found that bicarbonate-extractable organic and inorganic P followed the same trend gradient as TP. Interestingly, in high TP areas the proportion of HCl-extractable inorganic P (Ca- and Mg-bound P) was much higher when compared to the labile P components. In contrast, at sites low in TP the proportion of HCl-extractable inorganic P was comparable to the bicarbonate-extractable P components. Reddy et al. (1999) found in another study that in Water Conservation Area 2A the mean TP representing disturbed sites (DS) close to a point inflow was  $1461 \text{ mg kg}^{-1}$  and mean TP at undisturbed sampling (US) stations was  $484 \text{ mg kg}^{-1}$ . The bicarbonate-extractable P (labile P) at DS was  $23 \text{ mg kg}^{-1}$  and at US 7

$\text{mg kg}^{-1}$  indicating that correlations between TP and labile P components were similar at disturbed and undisturbed sites. In contrast MBP at DS was  $0.08 \text{ mg kg}^{-1}$  and at US  $76 \text{ mg kg}^{-1}$ . These findings indicated that P loading increased the microbial population size and microbial biomass pool of surface soils. Amador and Jones (1995) indicated previously that microbial activity can provide a sensitive indicator of nutrient loading and that additions of low levels of P to a P-limited system, such as the BCMCA, can increase microbial activity.

To better explain the changing spatial relationships between soil properties across the conservation area, we aggregated the different levels of information present in this study. The goal was to associate the occurrence of spatial patterns of P components to potential ecosystem processes. The three different correlation coefficients of TP-labile  $P_i$ , TP-labile  $P_o$ , and TP-MBP were grouped by performing a clustering (Fig. 11). Three different clusters were distinguished using the correlation maps for window length 7 and five different clusters were identified using the correlation maps for window length 23. The cluster analysis aggregated our previous findings highlighting zones that are most similar in their correlative behavior in terms of labile  $P_i$ , labile  $P_o$ , and MBP with regard to TP. Our goal was to associate each cluster with ecosystem processes to better explain emerging spatial patterns of TP and P components. The clustering and spatial distribution of these clusters identified areas in which diverse factors influence P dynamics.

The cluster centroids for different window lengths are shown in Table 5 and 6. Centroids for cluster window length 7 were closer together and Cluster 3 covered about 80% of the area. The two window sizes differed in the interpretation of the P dynamics toward the interior and north of the marsh. The clusters obtained for window size 23 were more distinct (further apart in multivariate space) and the overall spatial structure provided

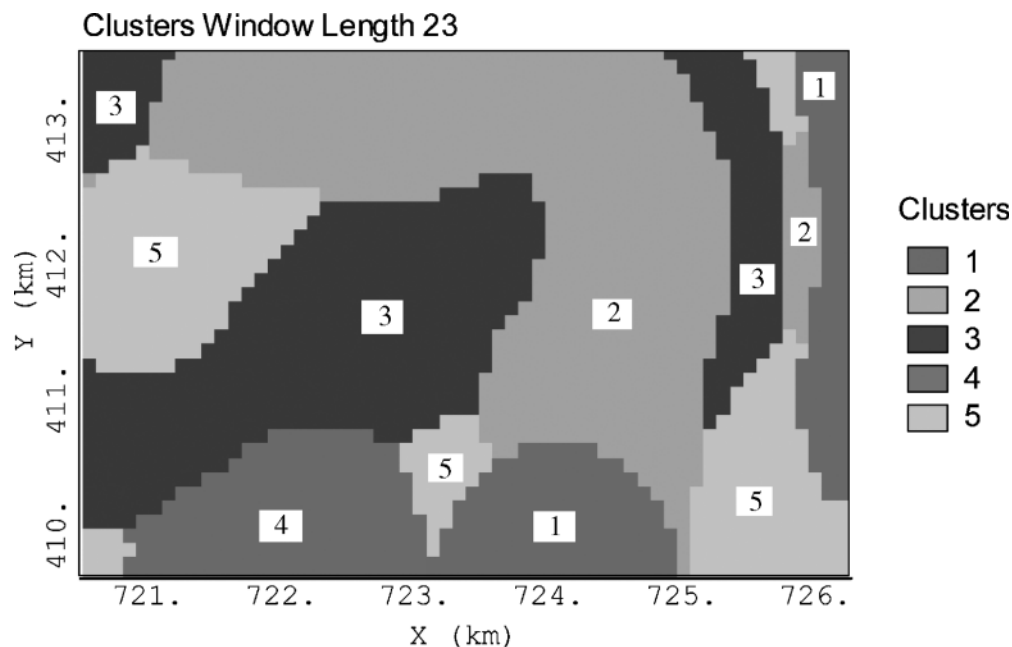


Fig. 11. Spatial distribution of clusters for window size 23.

**Table 5. Centroids of clusters window length 7 for total phosphorus (TP), labile organic phosphorus (bicarbonate-extractable inorganic phosphorus) ( $P_o$ ), labile inorganic phosphorus (bicarbonate-extractable organic phosphorus) ( $P_i$ ), and microbial biomass phosphorus (MBP).**

Cluster	TP-MBP	TP-labile $P_i$	TP-labile $P_o$
1	0.0626	0.1259	0.1415
2	-0.0308	0.0609	0.0622
3	0.0036	0.0325	0.0170

more details when compared with window lengths 7 and 11. Thus, the subsequent section focuses on the results from the analysis using only window size 23 to avoid redundancies in discussion.

Cluster 1 showed relatively high positive correlation coefficients (centroids) for labile  $P_i$ , labile  $P_o$ , and MBP with TP. The cluster was associated with high TP, labile  $P_i$ , labile  $P_o$ , and MBP observations and estimated values. These findings confirm results by Reddy et al. (1999) who found high labile P in nutrient-enriched zones in the Water Conservation Area 2A in the Everglades of 23 mg kg<sup>-1</sup>, whereas only 7 mg kg<sup>-1</sup> were found on reference (natural) sites. This cluster identified the most affected areas by nutrient enrichment in BCMCA, in which all parameters are enhanced by the external nutrient inputs, resulting in overall positive correlations between all the forms of P and TP. Likewise, Cluster 4 occurred in areas with high TP values, representing a second area that may be indicative of further enrichment. The centroid for TP-labile  $P_o$  was positive with 0.2017 whereas negative centroids were computed for TP-labile  $P_i$  with -0.0257 and TP-MBP -0.2369. Despite the high TP levels in this area the microbial biomass levels were relatively low. Results suggest that this area is probably a late phase transitional area, where the overall macro-structural changes associated with eutrophication have not fully developed. As a result, this area cannot yet sustain high microbial biomass levels.

Cluster 2 represented the overall natural background dynamics of BCMCA, with an average TP of 416 mg kg<sup>-1</sup>. In this area all moving correlations (centroids) were positive. Relatively high MBP was observed and estimated within Cluster 2 averaging 145 mg kg<sup>-1</sup>. Both labile  $P_i$  with an average of 40 mg kg<sup>-1</sup> and labile  $P_o$  of 16 mg kg<sup>-1</sup> values were very low within Cluster 2. We have observed the relatively high levels of microbial biomass in other studies in BCMCA (Corstanje, 2003), ascribing this to an interaction of the predominant hydrology and vegetation (a mixture of maidencane and sawgrass). These areas are wet prairies and tend to be relatively dry with little standing water (5–10 cm)

**Table 6. Centroids of clusters window length 23 for total phosphorus (TP), labile organic phosphorus (bicarbonate-extractable inorganic phosphorus) ( $P_o$ ), labile inorganic phosphorus (bicarbonate-extractable organic phosphorus) ( $P_i$ ), and microbial biomass phosphorus (MBP).**

Cluster	TP-MBP	TP-labile $P_i$	TP-labile $P_o$
1	0.0883	0.5055	0.5159
2	0.1749	0.1898	0.2067
3	-0.0109	0.1067	0.0724
4	-0.2369	-0.0257	0.2017
5	-0.0878	0.2132	0.2044

allowing for considerable oxygenation of the sediment. Furthermore, maidencane tends to have a very dense root colonization of the surface soil. Both of these factors allow for significant microbial biomass content in these soils. The areas to the east and south are deeper areas of the marsh, which historically were slough areas with sawgrass stands. The nutrient enrichment effectively displaced the slough areas with cattails that altered the hydrologic conditions (raised the sediment surface) and introduced coastal plain willow. The microbial communities responded to the increase in primary productivity and the altered environment, effectively resembling the interior, nutrient-limited areas.

Clusters 3 and 5 covered intermediate areas between the nutrient-altered areas and the central areas of the marsh. Moreover, these are areas that are currently undergoing change as P is mobilized from the nutrient-enriched areas along the overall hydrologic gradient toward the lake in the northwest. Both showed negative centroids for TP-MBP and positive centroids for TP-labile  $P_i$  and TP-labile  $P_o$ . These are areas that resemble Cluster 2 but have been altered by a continual influx of P from the impacted areas, resulting in positive correlations between labile  $P_i$ , labile  $P_o$ , and TP as these P pools increase in size. However, processes are masked producing spatial patterns that are fuzzier than for the other clusters. Cluster 3 occurred on areas averaging 700 mg kg<sup>-1</sup>, whereas TP values for Cluster 5 averaged only 525 mg kg<sup>-1</sup>. Our findings indicated that across a wide range of TP values from as low as 525 mg kg<sup>-1</sup> to as high as 870 mg kg<sup>-1</sup> the relationships TP-labile  $P_i$  and TP-labile  $P_o$  are similar; however, the strength of the relationships differed. The areas covered by Clusters 3 and 5 are those of highest concern as their capacity to abate the nutrient flux from the areas covered by Clusters 1 and 4 will determine the capacity of BCMCA to function effectively in the near future. Fortunately, the aerial coverage of Clusters 1 and 4 is relatively small. The overall mass of P to which these areas will be exposed might be not significant enough to alter the system constraints as it recovers through internal P redistribution (Corstanje, 2003).

## CONCLUSIONS

We used a dataset of 266 observations to investigate the spatial distribution of soil P and its components and interrelationships. Our moving correlation analysis revealed the spatially localized interrelationships between soil P properties and the strength of relationships. Spatial relationships between TP and P variables were heterogeneous throughout the marsh. Even in the unimpacted northern part of the study area, where TP values averaged less than 450 mg kg<sup>-1</sup>, spatial interrelationships were not robust changing from weak positive to zero local, moving correlations between TP-labile  $P_i$ , TP-labile  $P_o$ , and TP-MBP. In the nutrient-enriched southern and eastern part of BCMCA positive and negative correlations between soil properties coexisted.

Many soil processes are not well understood. By mapping and investigation of spatial correlation and

structure we are able to expose patterns. Such patterns can be interpreted and used to form hypotheses on potential underlying processes. Developed hypotheses can then be tested by controlled experiments and numerical modeling. Only a spatially explicit analysis can reveal the variability and complexity of spatial relationships across a wetland. Spatial patterns were found to be more complex than anticipated from previous biogeochemical wetland studies. We were able to describe spatially explicit nutrient dynamics and distinguish areas in BCMCA that exhibit characteristics identified as nutrient enriched and areas that can be identified as “natural” (or reference). Areas were also identified that are at “risk” in that the P dynamics seem to be shifting toward a more P-enriched status. Spatial patterns of biogeochemical soil properties across wetlands are still poorly understood, making it challenging to understand operating ecosystem processes. More research is needed to address this missing link.

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