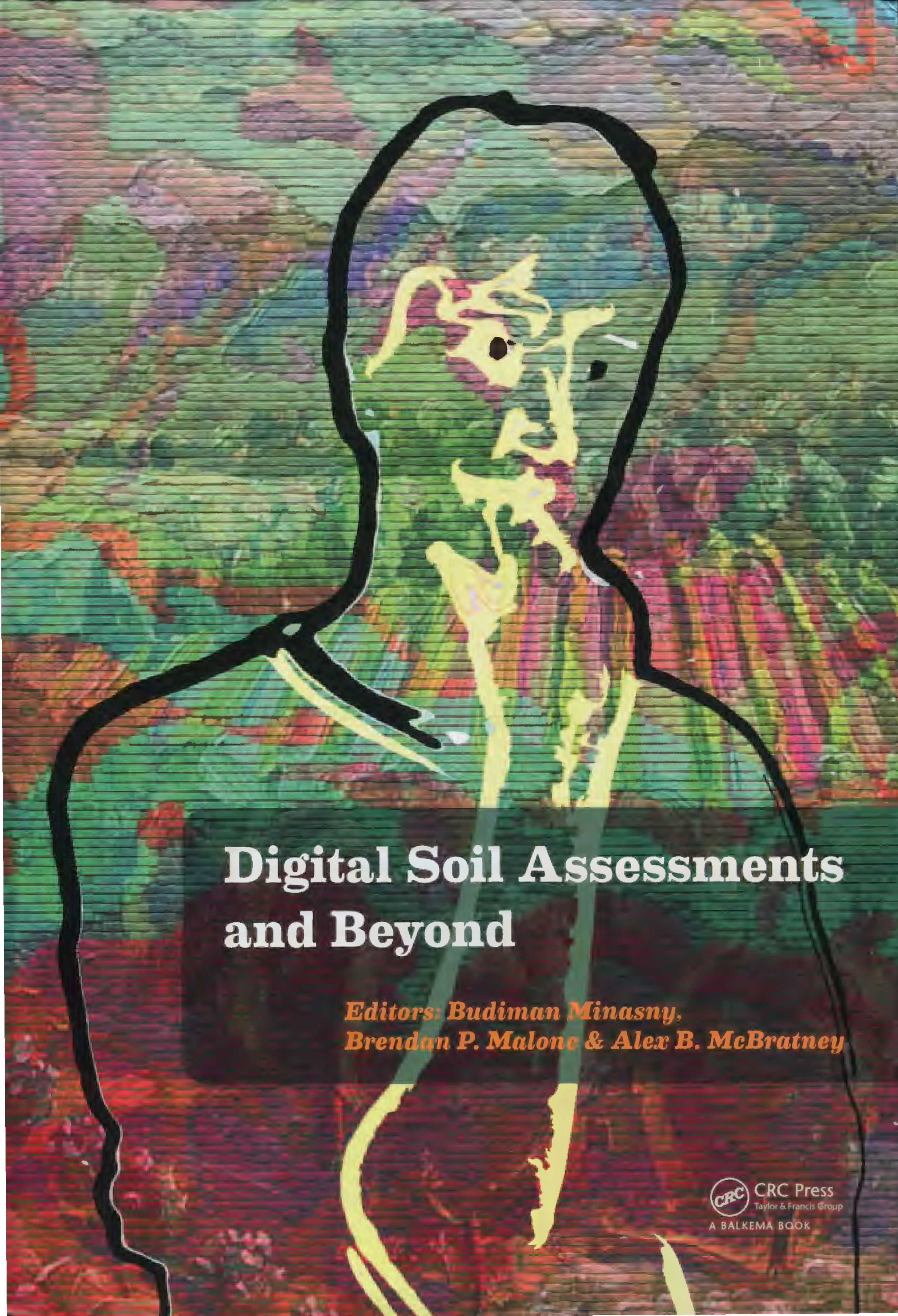

Digital Soil Assessments and Beyond

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Spatial resolution effects of remote sensing images on digital soil models in aquatic ecosystems

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ABSTRACT: The incorporation of Remote Sensing (RS) data into digital soil models has shown success to improve soil predictions. However, the effects of multi-resolution imagery on modeling of biogeochemical soil properties in aquatic ecosystems are still poorly understood. The objectives of this study were to (i) develop prediction models for various soil properties (total phosphorus, nitrogen, and carbon) utilizing RS images and environmental ancillary data and (ii) elucidate the effect of different spatial resolutions of RS images on inferential modeling of soil properties in a subtropical wetland: Water Conservation Area-2A, the Florida Everglades, USA. Soil cores were collected (n = 108) from the top 10 cm. The spectral data and derived indices from remote sensing images, which have different spatial resolutions, included: MODIS (250 m), Landsat ETM+ (30 m), and SPOT (10 m). Block Kriging (BK) and Random Forests (RF) modeling approaches were compared using a leave-one-out cross-validation method. The RF using RS images derived input variables showed accurate prediction results (>89%) when compared to BK. Results suggest that the spectral data derived from RS images can improve the predictive quality of soil properties in aquatic ecosystem. However, there was no noticeable distinction among different spatial resolutions of RS images to develop prediction models of soil properties.

1 INTRODUCTION

There is an increased use of remote sensing (RS) in digital soil mapping (DSM) due to its capabilities to directly or indirectly infer on biotic properties (Grunwald, 2009). Remote sensing data provide dense spectral grids over a large area at once. An integrated approach using RS in addition to various statistical or geostatistical methods has great potential for developing soil prediction models. Numerous studies have shown accuracy improvement of soil property prediction models utilizing a variety of RS imagery compared to traditional soil assessment without RS. The majority of studies have been conducted in upland systems and fewer RS supported DSM studies have been conducted in aquatic ecosystems.

There are increasing demands for accurate and precise data to predict biogeochemical properties in wetland soils. Subtropical wetland soils are highly heterogeneous, due to their complex composition of water, soil, floc/detritus, macrophytes, and periphyton intermixed within complex slough-ridge topography. A RS-based modeling approach has much value in wetlands, where field sampling is challenging and site-access limited. Our objectives in this research were to (i) develop prediction models for various soil properties (total phosphorus—TP, nitrogen—TN, and carbon—TC) utilizing RS images and environmental ancillary data in a subtropical wetland and (ii) elucidate the effect of different spatial resolutions of RS on inferential modeling of soil properties.

2 METHODS AND MATERIALS

2.1 *Study area, field sampling, and measuremens*

The study was conducted in WCA-2A (418 km^2), which is a subtropical freshwater marsh located in the northern part of the Everglades, Florida (Fig. 1). Historically the Everglades was an oligotrophic ecosystem characterized by low surface-water concentrations of phosphorus (P) and other nutrients. However, extensive drainage and the construction of levees and canals has resulted in a degradation of water resources. Changes in

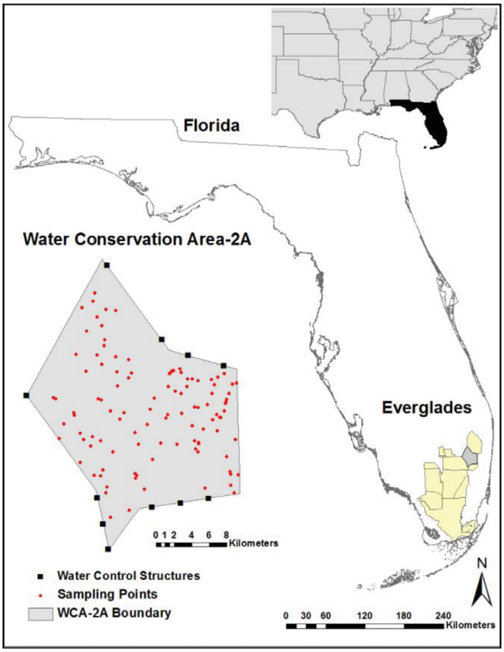

Figure 1. Location of the Water Conservation Area-2A within the Everglades in Florida, U.S. and soil core sampling points.

hydrology combined with increased nutrient loading, especially P, have led to significant changes in ecosystem structure in the wetland (Bruland et al., 2007). Soils in the area are Histosols. Typical landforms are primarily ridges and sloughs with scattered tree islands of various sizes.

A total of 108 soil cores were collected in July and October 2009 and mid March 2010 using airboats, to a depth of 10 cm beneath the soil surface based on a random-stratified sampling design described in Rivero et al. (2007). Sampling locations within the study area are shown in Figure 1.

The soil samples were analyzed for (i) TP utilizing association of official analytical chemists (AOAC) 978.01 method, (ii) TN utilizing LECO combustion method, and (iii) TC utilizing dry combustion method using a Shimadzu SSM-5000a.

2.2 *Spectral/geospatial environmental ancillary data and modeling approach*

Three satellite images were selected to investigate the effects of different spatial resolutions: MODIS, Landsat ETM+, and SPOT 5 images. The MODIS image (February 2010) obtained from Land Processes Distributed Active Archive Center, U.S. Geological Survey Earth Resources Observation and Science (EROS) Center has blue, red, near-infrared (NIR), and mid-infrared (MIR) bands with 250 m spatial resolution. The Landsat ETM+ image (February 2010) obtained from the USGS EROS Center has blue, green, red, NIR, and two MIR bands with 30 m and a thermal infrared band with 60 m spatial resolution. The SPOT image (January 2009) donated by Planet Action, a non-profit ASTRIUM GEO initiative, has green, red, NIR, and shortwave-infrared (SWIR) bands with 10 m spatial resolution. All images (MODIS, Landsat ETM +, and SPOT) were projected to the Universal Transverse Mercator (UTM) map projection (Zone: 17; Datum: World Geographic System, WGS 84) and geometircally rectified with USGS digital orthophoto quadrangles (DOQQ) using ERDAS Imagine 2010 (Earth Resource Data Analysis System Inc., Atlanta, GA). The root mean square error (RMSE) was less than 0.5 pixel for all images.

The derived spectral vegetation indices for different satellite images depending on their spectral bands were the following: (i) from MODIS—Enhanced Vegetation Index (EVI), Moisture Stress Index (MSI), Normalized Difference Vegetation Index (NDVI), Simple Ratio (SR), and Transformed Vegetation Index (TVI); (ii) from Landsat ETM+—Mid-infrared index (MidIR), MSI, NDVI, Normalized Difference Vegetation Green Index (NDVI green), Normalized difference water index (NDWI), Reduced simple ratio (RSR), SR, and TVI; (iii) from SPOT—MSI, NDVI, NDVI green, NDWI, RSR, SR, and TVI. The formulas to derive indices are given in Table 1.

Various environmental properties including topography, hydrology, lithology, and geography were considered as factors to infer spatially-explicit nutrients in wetland soils. The environmental data layers included the elevation surveyed in 2007 by USGS, distance to water control structures (WCSs) produced using the Euclidean distance function in ArcGIS (Environmental Systems Research Institute—ESRI, Redlands, CA), geophysical properties collected in 1999, and geographic coordinates collected during field sampling. The environmental properties and the spectral indices were included as predictor variables for model development.

Data values from each image and environmental data layer were extracted for each sampling point (i.e., x and y location) and merged with site-specific soil properties using ArcGIS 9.3 (ESRI, Redlands, CA).

The prediction models were developed using block kriging (BK; 10 by 10 m) and random forests (RF) methods. The leave-one-out cross-validation method was employed to evaluate model performances and the coefficient of determination (R^2) and the root mean squared deviation (RMSD) were compared with each other. Block kriging

Table 1. Summary of remote sensing spectral indices.

Indices†	Formula	References
EVI‡	$G\dfrac{\text{NIR}-\text{Red}}{\text{NIR}+C_1\text{Red}-C_2\text{Blue}\ +\ \text{L}}(1+L)$	Huete et al., 1997
Mid-infrared index	$\dfrac{\text{MidIR}_{\text{Landsat Band5}}}{\text{MidIR}_{\text{Landsat Band7}}}$	Musick and Pelletier, 1988
MSI	$\dfrac{\text{MidIR}}{\text{NIR}}$	Rock et al., 1986
NDVI	$\dfrac{\text{NIR}-\text{Red}}{\text{NIR}+\text{Red}}$	Rouse et al., 1974
NDVI green	$\dfrac{\text{NIR}-\text{Green}}{\text{NIR}+\text{Green}}$	Gitelson et al., 1996
NDWI	$\dfrac{\text{NIR}-\text{SWIR}}{\text{NIR}+\text{SWIR}}$	Gao, 1996
RSR	$\dfrac{\text{NIR}}{\text{Red}}\left(1-\dfrac{\text{SWIR}-\text{SWIR}_{\text{min}}}{\text{SWIR}_{\text{max}}-\text{SWIR}_{\text{min}}}\right)$	Brown et al., 2000; Chen et al., 2002
SR	$\dfrac{\text{NIR}}{\text{Red}}$	Cohen, 1991; Chen et al., 2002; Colombo et al., 2003
TVI	$\left(\dfrac{\text{NIR}-\text{Red}}{\text{NIR}+\text{Red}}+0.5\right)^{1/2}\times 100$	Rouse et al., 1974

†EVI, enhanced vegetation index; MidIR, mid-infrared; MSI, moisture stress index; NDVI, normalized difference vegetation index; NDVI green, normalized difference vegetation green index; NDWI, normalized difference water index; NIR, near-infrared; RSR, reduced simple ratio; SR, simple ratio; SWIR, shortwave-infrared; TVI, transformed vegetation index.
‡Empirical parameters for EVI of MODIS: $C_1 = 6.0$; $C_2 = 7.5$; $G = 2.5$; $L = 1.0$.

was performed using ISATIS software package (Geovariances Inc., France) and RF analysis was performed using the "randomForest" package for the R statistical language (R Development Core Team, 2006).

3 RESULTS AND DISCUSSION

3.1 *Modeling approach*

Descriptive statistics of soil properties are shown in Table 2. Total P showed higher variability (observed data range of 1,529 mg kg^{-1}) than other soil properties (i.e., TN and TC) in WCA-2A. The error assessment of the models for soil properties using BK and RF with SPOT, Landsat ETM+, and MODIS images derived input variables and environmental ancillary data are shown in Table 3.

The observed versus predicted values for the BK and RF model for soil properties are shown in Figure 2 and 3. Block kriging showed good prediction results for TP and TC, but not for TN. Total N showed weak spatial dependence (nugget-to-sill ratio >40%; data not shown) that can be explained by the different biochemical behavior of N, which has various gaseous forms and complex cycle processes creating a heterogeneous patchwork of hotspots and hotmoments.

Table 2. Descriptive statistics for soil properties observed in water conservation Area-2A.

Property	Unit	Mean	Min.	Max.	Median	St. dev.	Skewness
TP	mg kg^{-1}	601.4	165.4	1,694	478.8	336.7	1.25
TN	g kg^{-1}	29.7	21.3	38.2	30.0	3.35	–0.19
TC	g kg^{-1}	410.5	262.8	492.3	413.2	35.6	–1.2

The RF using various spectral and environmental data greatly increased the prediction results for all soil properties ($R^2 > 0.89$) when compared to BK. The variable importance of RF, which suggests useful variables to infer on soil properties, showed high rank of RS derived spectral and vegetation indices: (i) the TVI, NDVIg, and EVI ranked high for TP prediction and (ii) PCs and EVI ranked

Table 3. Summary of model performance assessment for soil properties†.

Property	Error metrics‡	BK	RF_{SPOT}	RF_{ETM+}	RF_{MODIS}
TP	R^2	0.60	0.92	0.92	0.89
(mg kg^{-1})	RMSD	213.7	102.1	102.2	120.3
TN	R^2	0.30	0.95	0.94	0.91
(g kg^{-1})	RMSD	2.88	1.45	1.44	1.56
TC	R^2	0.70	0.94	0.96	0.89
(g kg^{-1})	RMSD	22.5	15.9	15.3	16.5

†BK, block kriging; $RF_{SPOT,EMT+,MODIS}$, random forests using SPOT, Landsat ETM+, and MODIS image derived input variables, respectively.
‡R^2, coefficient of determination; RMSD, root mean squared deviation.

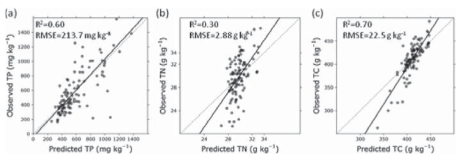

Figure 2. Scatter plots showing the relationship between observed and predicted soil properties using block kriging: (a) total phosphorus (TP), (b) total nitrogen (TN), and (c) total carbon (TC) in topsoil.

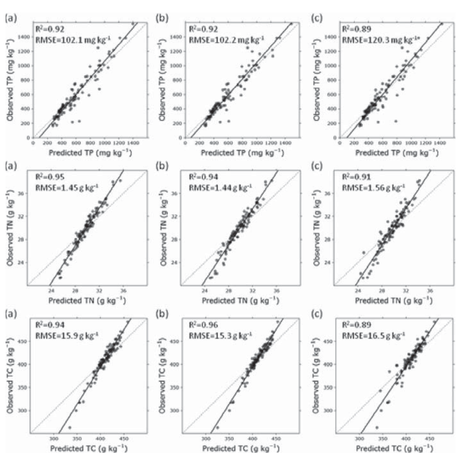

Figure 3. Scatter plots showing the relationship between observed and predicted soil properties using random forests from spectral input variables derived from: (a) SPOT, (b) Landsat ETM+, and (C) MODIS images, respectively, combined with environmental ancillary data.

high for TN and TC prediction. It suggests that the variability of soil properties can be explained by various wetland components which can be captured by RS images. The spectral data infer on the chlorophyll content (e.g., red and green wavelength energy), stress (e.g., MSI), and composition of vegetation (e.g., NDVI), which are correlated with soil biogeochemical properties. Our result suggests that multivariate models that incorporate spectral and environmental ancillary data are more accurate in predicting continuous variation of soil properties in wetland soils than univariate models only relying on field observations.

3.2 *Comparison of spatial resolution*

The spatial models of soil properties using SPOT and Landsat ETM + image derived input variables showed slightly better prediction results as measured by R^2 and RMSD than the model using MODIS image derived input variables combined with environmental data (Table 3). However, the differences of R^2 to estimate soil properties were marginal: 3% for TP, 4% for TN, and 7% for TC, although the spatial resolutions of the RS images were quite different. The RF models using higher resolution SPOT and Landsat ETM+ images derived input variables showed very similar result with high R^2 and small RMSD. Many other studies have reported improved prediction results using high-resolution RS images when compared to coarser resolution RS images (Peng et al., 2003). Interestingly, in this study the MODIS-based soil prediction models nearly achieved the same results as the higher-resolution RS soil prediction models. This suggests that the vegetation-water-floc properties depicted from space, even at the coarsest spatial resolution of 250 m, resembled the heterogeneity in WCA-2A. The high correlations between spectral and soil properties indicate that spatial patterns of soils and above ground features coincided well. This interpretation is supported by the fact that spatial autocorrelations were 9,064 m (TP), 7,607 m (TN), and 2,293 m (TC) exceeding the 250 m resolution of MODIS.

4 CONCLUSIONS

This study showed that RS data can be successfully used to predict biogeochemical soil properties with environmental ancillary data. The RF with varying spatial resolutions of RS images showed substantial improvement of prediction accuracy when compared to BK to predict soil TP, TN, and TC in WCA-2A. The RF results suggest that soil properties are highly dependent on biotic/vegetation properties that can be inferred by RS. However, the effect of varying spatial resolutions to develop prediction models for soil properties in wetland soils was marginal (<7%).

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