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Modeling soil parameters using hyperspectral image reflectance in subtropical coastal wetlands

Naveen J.P. Anne[a], Amr H. Abd-Elrahman[a,*], David B. Lewis[b], Nicole A. Hewitt[a]

[a] School of Forest Resources and Conservation – Geomatics, University of Florida, Florida, United States
[b] Department of Integrative Biology, University of South Florida, United States

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ABSTRACT

Developing spectral models of soil properties is an important frontier in remote sensing and soil science. Several studies have focused on modeling soil properties such as total pools of soil organic matter and carbon in bare soils. We extended this effort to model soil parameters in areas densely covered with coastal vegetation. Moreover, we investigated soil properties indicative of soil functions such as nutrient and organic matter turnover and storage. These properties include the partitioning of mineral and organic soil between particulate (>53 μm) and fine size classes, and the partitioning of soil carbon and nitrogen pools between stable and labile fractions. Soil samples were obtained from *Avicennia germinans* mangrove forest and *Juncus roemerianus* salt marsh plots on the west coast of central Florida. Spectra corresponding to field plot locations from Hyperion hyperspectral image were extracted and analyzed. The spectral information was regressed against the soil variables to determine the best single bands and optimal band combinations for the simple ratio (SR) and normalized difference index (NDI) indices. The regression analysis yielded levels of correlation for soil variables with R^2 values ranging from 0.21 to 0.47 for best individual bands, 0.28 to 0.81 for two-band indices, and 0.53 to 0.96 for partial least-squares (PLS) regressions for the Hyperion image data. Spectral models using Hyperion data adequately (RPD > 1.4) predicted particulate organic matter (POM), silt + clay, labile carbon (C), and labile nitrogen (N) (where RPD = ratio of standard deviation to root mean square error of cross-validation [RMSECV]). The SR (0.53 μm, 2.11 μm) model of labile N with R^2 = 0.81, RMSECV= 0.28, and RPD = 1.94 produced the best results in this study. Our results provide optimism that remote-sensing spectral models can successfully predict soil properties indicative of ecosystem nutrient and organic matter turnover and storage, and do so in areas with dense canopy cover.

1. Introduction

Coasts are subject to devastating storms and frequent tidal exchange (Cahoon, 2006), making coastal wetlands vital to preventing shoreline erosion by providing sediment stabilization and water storage (Hardisky et al., 1986). In addition, coastal wetlands process organic and chemical wastes and reduce sediments in water (Rao et al., 1999). In turn, soil quality and composition have a direct effect upon the health of vegetation, especially in wetland environments (Ehrenfeld et al., 2005), and maintaining this reciprocal relationship is essential to preserving coastal habitats. For instance, coastal soils hold large concentrations of organic matter that supplies the N needed to support mangrove forest and salt marsh primary production (Nedwell et al., 1994; Anderson et al., 1997; Alongi et al., 2002), which in turn promotes soil accretion through organic matter production and sediment trapping (Morris et al., 2002). This feedback is critical for maintaining wetland elevation relative to rising sea levels (Kirwan and Mudd, 2012; Morris et al., 2012). Soils are complex and dynamic, both temporally and spatially, requiring numerous physical, chemical, and biological determinants for soil quality assessment. Soil sampling, from specimen collection to the generation of quantitative data, consumes a tremendous amount of time and requires delicate lab procedures.

The premise of estimating soil components using spectral analysis under laboratory conditions was heavily tested along the past few decades. For example, in agricultural settings, soil organic matter (SOM) models were defined through spectral reflectance measured in the laboratory for black soil (Liu et al., 2009), and litchi orchid (Li et al., 2012). Similarly, sand, clay (Minasny et al., 2008; Summers et al., 2011), total C, total N (Morra et al., 1991), and soil

* Corresponding author. Tel.: +1 813 757 2283.
E-mail addresses: nanne@ufl.edu (N.J.P. Anne), aamr@ufl.edu (A.H. Abd-Elrahman), davidlewis@usf.edu (D.B. Lewis), nicolehewitt@ufl.edu (N.A. Hewitt).

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moisture (Dalal and Henry, 1986) were tested in laboratory settings. Shepherd and Walsh (2002) tested topsoil (0- to 15-cm depth) organic C concentration, clay content and sand content through diffuse reflectance spectroscopy (0.35–2.5 μm) on a diverse sample that was acquired from a wide variety of landscape positions, parent materials and landscapes. Yitagesu et al. (2011) tested modeling pure clay material using laboratory based spectral data (2.5–14 μm) and partial least squares (PLS) regression and attained much of the variation in their components. In these studies, strong correlations between spectral reflectance and the field samples were reported. For example, absorption regions of C and N bonds of near-infrared reflectance spectroscopy (NIRS) correlated with soil C and N fractions (Morra et al., 1991). Near-infrared bands attributed to the bending and stretching of O-H bonds in lattice mineral and water molecules were associated with soil clay content (Summers et al., 2011).

Brown et al. (2006) found strong relationships between VINIR and soil organic C, and clay content. They identified the 0.54, 0.55, and 1.91 μm wavelengths, sensitive to H_2O, as important wavelengths in soil organic C estimation. Information in the 2.0– 2.5 μm was found important due to *e.g.* C—O and C—H bond absorptions. Dalal and Henry (1986) concluded that absorption along the near-infrared (NIR) spectra was correlated with moisture content in soil. Summers et al. (2011), and Chang et al. (2001) concluded that the organic matter content of the soil was inversely proportional to albedo along the visible near-infrared (VNIR) region of the spectrum. Bands that significantly correlated with SOM samples were associated to regions in the spectra sensitive to the C—H, N—H, and O—H bonds (Li et al., 2012). These studies used *in situ* or laboratory spectroscopy of bare soils regressed against the laboratory based physically and chemically derived soil properties.

Technological advances in remote sensing have allowed for the development of cost-efficient and effective alternative methods of soil assessment (Mulder et al., 2011). The transition from lab to remote sensing analysis of soils involves accounting for the effects of atmospheric influences, geometric distortions, spatial resolution, and scale (Mulder et al., 2011). Several surface soil properties including organic matter were modeled from airborne hyperspectral imagery (Hbirkou et al., 2012; Ben-Dor et al., 2002) and aerial color photographs (López-Granados et al., 2005). Airborne hyperspectral imagery was used to build SOM models for agricultural clay-loam soil (Uno et al., 2005). Such models were successfully constructed using field samples and aerial hyperspectral data (HyMap and Airborne Visible/Infra-Red Imaging Spectrometer) of bare soil fields for estimating SOM, sand, silt, clay, and other soil properties (Palacios-Orueta and Ustin, 1998; Selige et al., 2006).

Chabrillat et al. (2002) showed the use of AVIRIS and Hyperspectral Mapper (HyMap) imagery and matched filtering algorithm for successful mapping of exposed clay minerals. Combined sampling of dry bare ground and pasture was used in modeling soil organic carbon using the spaceborne measurements and Hyperion hyperspectral imagery (Lu et al., 2012; Gomez et al., 2008). Mulder et al. (2013) aimed at the characterizing and improving the mapping of mineral variability at a regional scale from remote sensing imagery on a diverse lithological setting that included sedimentary, igneous, and metamorphic rock types. ASTER, multiple linear regressions (MLR), and different smoothing techniques were used to evaluate clay mineral and attained moderate R^2 values of 0.57 and 0.45. Shi et al. (2014) used HyMap airborne hyperspectral imagery and field samples to map soil acidity in coastal areas. Their study used PLS regression and mineral mapping as an indicative of soil acidity.

Although numerous studies have focused on modeling soil properties from remote sensing technologies either directly from bare soil, or by inferring soil properties through vegetation cover (Huete, 2005; Kooistra et al., 2004). However, utilization of remote sensing technology in quantification of under-canopy soil properties remains limited. Ben-Dor et al. (2002) developed methods to quantify under-canopy soils properties, but did so with interpolation techniques such as kriging (López-Granados et al., 2005) that were based on models built with open-surface soil samples. Spatial interpolations, however, present accuracy problems in mapping applications (Selige et al., 2006). In other studies, soil properties were mapped from partially vegetated fields through spectral unmixing of hyperspectral data for estimating clay (Ouerghemmi et al., 2011) and soil organic carbon (Bartholomeus et al., 2011). The research on inferring soil properties through vegetation cover is in its infancy, as only a few studies have investigated the relationship between soil properties and vegetation reflectance (Kooistra et al., 2004; Piekarczyk et al., 2012). Kooistra et al. (2004) estimated substrate (vegetation covered) SOM and soil moisture in addition to a few other properties through field measured hyperspectral vegetation reflectance data. Gomez et al. (2008) focused on establishing the relationship between Hyperion spectra and *in situ* soil samples of bare soil and pasture. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) were used to infer few substrate soil properties, including reflectance through vegetation (Piekarczyk et al., 2012).

While the application of remote sensing to soils continues to grow in terms of context (*e.g.*, modeling sub-canopy soils), it is also at its infancy in terms of information value for ecosystem function. Remotely sensed soil characteristics evaluated to date (cited above) are important components of ecosystem structure, and are relevant to global change issues (*e.g.*, total soil C storage). They are not, however, the most important soil characteristics for functions such as nutrient recycling, primary production, and soil CO_2 emissions. For these functions, soil indicators of nutrient recycling and organic matter recalcitrance would be more useful. Such indicators include (a) the fractionation of mineral and organic soil between particulate (>53 μm) and fine size classes, as particle size can regulate the availability of soil organic matter to microbial decomposers and can mediate rates of N immobilization in soil (Sollins et al., 1996; Stewart et al., 2007; Castellano et al., 2013), and (b) the partitioning of soil organic carbon and nitrogen between stable and labile (readily-mineralized) fractions, which is thought to regulate the capacity of soil to retain these elements (Kaye et al., 2002). Labile stores of soil carbon and nitrogen are readily transformed to CO_2 and nitrogen oxides, which can pose air and water quality problems. We are aware of no studies that evaluate whether these functional soil characteristics correlate with spectral reflectance.

The goal of this study is to develop statistical models that estimate soil parameters related to nutrient and organic matter storage and turnover from the Hyperion and Thematic Mapper satellite imagery, providing a practical method for remotely monitoring soil composition in coastal wetland environments. We hypothesize that soil characteristics are affected by plant cover, which in turn correlates with image spectra. In this context, this study encompassed areas of dense vegetation to investigate the levels of correlation between hyperspectral/multispectral band reflectance and eighteen soil parameters such as particulate organic matter (POM), mineral associated organic matter (MAOM), labile carbon (labile C), and labile nitrogen (labile N), which require significant resources and extended field sampling procedures. To our knowledge, many of the soil properties investigated in this study have not been previously studied through the vegetation reflectance technique.

2. Materials and methods

2.1. Soil sampling

Soils were sampled from three intertidal sites (Fig. 1) at intervals of about 4.4 km along the coast of west-central peninsular Florida,