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# Building spectral libraries for wetlands land cover classification and hyperspectral remote sensing

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## Abstract

Recent advances in remote sensing provide opportunities to map plant species and vegetation within wetlands at management relevant scales and resolutions. Hyperspectral imagers, currently available on airborne platforms, provide increased spectral resolution over existing space-based sensors that can document detailed information on the distribution of vegetation community types, and sometimes species. Development of spectral libraries of wetland species is a key component needed to facilitate advanced analytical techniques to monitor wetlands. Canopy and leaf spectra at five sites in California, Texas, and Mississippi were sampled to create a common spectral library for mapping wetlands from remotely sensed data. An extensive library of spectra ($n = 1336$) for coastal wetland communities, across a range of bioclimatic, edaphic, and disturbance conditions were measured. The wetland spectral libraries were used to classify and delineate vegetation at a separate location, the Pacheco Creek wetland in the Sacramento Delta, California, using a PROBE-1 airborne hyperspectral data set (5 m pixel resolution, 128 bands). This study discusses sampling and collection methodologies for building libraries, and illustrates the potential of advanced sensors to map wetland composition. The importance of developing comprehensive wetland spectral libraries, across diverse ecosystems is highlighted. In tandem with improved analytical tools these libraries provide a physical basis for interpretation that is less subject to conditions of specific data sets. To facilitate a global approach to the application of hyperspectral imagers to mapping wetlands, we suggest that criteria for and compilation of wetland spectral libraries should proceed today in anticipation of the wider availability and eventual space-based deployment of advanced hyperspectral high spatial resolution sensors.

*Keywords:* Wetlands; Remote sensing; Spectral library; Spectroscopy; Hyperspectral; Mapping vegetation; Landuse classification

## 1. Introduction

High quality remote sensing data for mapping and monitoring are the optimal tool for rapid wetlands assessment and proactive management. Wetlands, in particular, are difficult to monitor, are often difficult to access, especially their inner reaches, and are sometimes home to both dangerous wildlife and endemic diseases. Developing a global inventory of wetlands has proven to be a large and difficult undertaking. Current efforts (Lehner and Döll, 2004) are based on best available data, but both classification and spatial resolution may be inadequate for regional or site-specific management decision-making. Improved remote sensing information, with an ability to monitor more detailed changes in vegetation structure and species composition, will facilitate expanded efforts in wetland monitoring and mapping. This is especially relevant as we expect to see shifts in species composition in response to environmental changes induced by climate change, land use, and other anthropogenic impacts.

The ability to map and monitor wetland vegetation at higher spatial and spectral resolutions allows changes in vegetation cover and composition to be precisely mapped using advanced geospatial approaches. This is useful not only as an indicator of change, but provides information on the nature

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and direction of change, which can indicate major driving forces. Flooding frequency and duration, along with the salinity level are currently the most important variables that control plant distribution within tidal salt and brackish marshes. Rising temperatures from climate warming may bring invasions of warmer water species within colder zones. Recent advances in mapping invasive species (Underwood and Ustin, 2003; Underwood et al., 2006) illustrate opportunities for developing methods applied to wetlands.

Current efforts using today's remote sensing satellites may not have sufficient resolution, either spatially or spectrally, to monitor wetland conditions. Within a Landsat image (28.5 m resolution) a majority of pixels are mixtures of several plant species or vegetation types in various proportions, because the steep environmental gradients in wetlands produce short ecotones and sharp demarcations between communities. Increasing the number of ''pure pixels'' through improved spatial resolution removes a large source of error in the remote sensing analysis. Species level mapping works well for monotypic stands, which occur in large stratifications. Where species are more randomly distributed or patchy at fine scales (grain), accurate map classifications are difficult to obtain. In wetlands with heterogeneous vegetation communities, species distributions must be delineated at the coarser community level or using sub-pixel species abundance categories (Rosso et al., 2005).

Recent advances in airborne imaging sensors, in particular high spatial resolution hyperspectral platforms such as AVIRIS (http://aviris.jpl.nasa.gov/) and HYMAP (http://www.hyvista.com/), provide opportunities to operationalize remote sensing assessment and monitoring in wetlands. Unfortunately, these instruments are not universally available today. Limited hyperspectral data are available from NASA (e.g., AVIRIS) and other international agencies (e.g., ESA), and there is renewed NASA interest in developing a global observing hyperspectral satellite with sufficient spatial resolution to support mapping in coastal wetlands. Additionally, more private companies are flying airborne hyperspectral instruments that have begun to make these data more widely available.

Results from studies of various vegetation types and biomes (Underwood and Ustin, 2003; Underwood et al., 2006; Hirano et al., 2003; Held et al., 2003; Li et al., 2005; Rosso et al., 2005) have demonstrated the significant increase in information that is obtained from hyperspectral data sets. Analysis of these large data sets has required new and specialized approaches developed over the past decade (Roberts et al., 1998; Held et al., 2003; Schmid et al., 2004; Li et al., 2005). Spectral matching techniques can be used to identify species or vegetation types based on spectral data collected in the field (Underwood and Ustin, 2003), through laboratory analysis (Schmidt and Skidmore, 2003), or extracted directly from the images (Underwood et al., 2006). Several types of spectral libraries have been collected (Clark et al., 2003; Shepherd and Walsh, 2007), including a soils database for agricultural production (Shepherd and Walsh, 2002) and riparian wetland soils (Cohen et al., 2005). Developing spectral libraries is key to improving our capacity to utilize the full mapping potential from these new sources of data provided by airborne and advanced space-borne hyperspectral imagers.

The development of plant spectral libraries has not previously succeeded because of the large number of potential plant species that are required to characterize a terrestrial vegetation library. In addition, there has been no resolution on how to characterize the spectral variability expressed in changing phenological states and environmental conditions. However, wetlands, when stratified by biome, elevation, or latitude (e.g., temperate tidal wetlands) have limited numbers of species and genera, even considering world-wide distributions, which makes it feasible to develop a useful and functional spectral library for wetlands. In this study we collected spectral data for vegetation, soils, and other surfaces from four coastal wetlands associated with oil refineries in California and along the Gulf Coast of the United States in Texas and Mississippi. The presence of refineries in these wetlands provides possible sites of contamination, which will induce within-species variability in the data. Many oil refineries throughout the world are located in wetlands, estuaries, and deltas, therefore these conditions are frequently encountered and need to be part of a spectral library. As part of a larger study assessing the use of airborne hyperspectral imagery for detection of hydrocarbon pollution and heavy metal contamination, we collected an extensive spectral library for coastal wetland species and community types, across a broad range of bioclimatic, edaphic, and disturbance conditions. The spectral library collected at these four coastal wetland sites was used to delineate land cover and vegetation classes within a tidal brackish marsh located in the Sacramento delta, east of San Francisco Bay, associated with an oil refinery complex in Martinez, California. Airborne PROBE-1, a commercial high spatial resolution hyperspectral image data set was acquired at the Martinez site. A map of vegetation cover within the wetlands was produced based on the combined spectral signatures library and calibrated with field measurements from the site.

## 2. Methods

### 2.1. Site descriptions

Fieldwork to map individual species and obtain spectral measurements of the dominant plant species was conducted at five wetland sites associated with oil refineries (Fig. 1): the Chevron Port Arthur (Texas) Remediation Project (Clark Refinery); the Chevron Refinery in Pascagoula, Mississippi; the Chevron Refinery complex in Richmond, CA; and the Pacheco Creek wetlands (Fig. 2) associated with the Tosco Refinery and the Point Edith Wildlife Area in Martinez, California. Tidal wetland sites in California are typical of Pacific coastal salt marshes with *Spartina foliosa* (salt grass), *Schoenoplectus californicus* formerly *Scirpus californicus* (tule), *Schoenoplectus robustus* formerly *Scirpus robustus* (bulrush), Typha spp. (cattails), *Juncus arcticus* ssp. littoralis formerly *Juncus balticus* (common reed), *Distichlis spicata* (salt hay), *Salicornia virginica* (pickleweed) and other brackish water species distributed along gradients of tidal

Fig. 1. Oil refineries, and their shipping facilities throughout the world are often located in close proximity to important wetland ecosystems.

inundation and salinity (Zhang et al., 1996). Sites along the Gulf Coast are primarily intertidal wetlands, estuarine marshes, and some brackish/freshwater coastal wet prairie types. Intertidal wetlands here are also composed of pickleweed, salt hay, salt marsh bulrush, and needlegrass rush (*Juncus roemerianus*). Although *S. foliosa* is absent, *Spartina alternifolia* (saltwater cordgrass) occupies a similar dominant intertidal niche in coastal and eastern coastal salt marshes.

### 2.2. Collecting spectral measurements

Spectral measurements were made in the field from the canopies of plant species and mixed vegetation, soil, and various other surfaces (like paved roads), with the later used to validate the reflectance calibration provided with the imagery by Remote Measurement Services, LLC using the proprietary Hyperspectral Data Processing System (HyDaPS v/1.1) software by James Sokolowski. Eight bands were noisy and removed. All data collected were georeferenced using real-time differentially corrected GPS (Trimble PRO XRS) with 1 m accuracy, which allowed identifying specific pixels where field spectra were measured. A reconnaissance of all four sites was completed with the help of local experts, and sampling sites were stratified into representative zones. Major vegetation types and their dominant and subdominant species were identified. Plant samples were collected for all measured species for secondary identification. Relative species abundance categories for the major vegetation types were delineated. A series of stratified zones were identified and measured along transects which were sited to include identifiable gradients, primarily soil moisture content, distance to channels, elevation, and to a certain extent, salinity.

Spectrometer measurements (library samples) were obtained for all representative plant species, vegetation communities, and landuse types (Fig. 3). Measurements were acquired following standard hyperspectral measurements guidelines (Zomer et al., 1999). A GER 2600 (Spectra Vista Corp.) was used to measure reflectance from the canopies of monospecific stands, mixed species, and land cover types. The GER

Fig. 2. Wetlands closely associated with industrial sites, oil refineries, and hazardous waste sites at the Pacheco Creek research site (source: Google Earth).

Fig. 3. Collection of spectra above the canopy of salt marsh in Pascagoula, Miss., with the GER 2600.

measures the spectrum from 350 to 400 nm in the ultraviolet region, from 400 to 700 nm, the visible spectrum (at 1.5 nm bandwidths); blue is centered at 450 nm, green at 550 nm and red at 650 nm, the near-infrared region from 700 to 1500 nm, and the shortwave-infrared from 1500 to 2500 nm (at 11.5 nm). The GER 2600 Spectrometer was calibrated using a *Spectralon* (Labsphere, Inc.) reflectance panel (Fig. 4), an NBS standard for reference. All readings were obtained above the canopy of the species/plant community, in many cases requiring the use of a bucket truck to reach above and across large trees and highly contaminated sites and into the marsh or thicket. This height reach allowed measurement of canopy spectra from pure species and mixed communities and spectral gradations along ecotones.

Fig. 4. Calibrating the GER 2600 Spectrometer using a Spectralon (Labsphere, Inc.) reflectance panel, an NBS standard for reference. A dark cloth is used on the bucket to suppress scattered light.

In the case of grass fields, bare soil, or asphalt/cement calibration sites, either a transect or grid of sampling points was traversed. Representative leaf samples of major species were separately acquired at the sample sites and their reflectance and transmission were measured in a portable field lab using a LiCor Inc. integrating sphere with a known light source. Measurement of leaf spectra provides information about the biogeochemical properties that absorb energy in the 400–2500 nm wavelength range and separate this information from the canopy measurement that includes the scattering processes associated with canopy structure.

### 2.3. Data processing of field spectra

Spectral data output from the spectrometer was calibrated, and further analyzed using the CSTARS Spectral Analysis Management System (SAMS) software (available: http://cstars.ucdavis.edu). This software facilitates visualization and preliminary sorting and processing of their spectral signatures. Field spectra were evaluated and visually inspected for data quality, and categorized into vegetation categories. Mean spectra were calculated for a variety of vegetation category subsets, including both monospecific averages and various mixtures of plant species abundances. These synthetic (averaged) mean spectra ($n = 76$), were exported as data cubes into the Environment for Visualization of Images (ENVI; ITT Visual Solutions) software to facilitate their use as training data in analyses of the image data, including importing them into the ENVI spectral library. Likewise, the original spectra, i.e., unaveraged data ($n = 1336$), after screening for quality and errors, was exported as a data cube to ENVI. All spectra within the respective data cubes were collected into Regions of Interest (ROI) corresponding to the vegetation abundance categories measured in the field and used as training data in further analyses. Field spectra were projected in ENVI into a visualized $n$-dimensional data cloud ($n$-Dimensional Visualizer). Separation of the spectra along various axes was observed, and clusters of data points were identified and evaluated in terms of natural groupings (i.e., correspondence with species/vegetation abundance categories), which supported the hypothesis that spectral signatures could be used to identify species and/or vegetation types. Results from this analysis were used with a vegetation community analysis to classify and identify vegetation communities. All original spectra and community-averaged spectra from the five refinery areas were imported into ENVI as a single spectral library. The resulting wetland spectral library was used to classify the hyperspectral image data set for Pacheco Creek and compared to other classification techniques.

### 2.4. Remote sensing analysis

Airborne PROBE-1 hyperspectral image data (5 m resolution, 128 spectral bands with 12–13 nm resolution), of the Pacheco Creek research site was acquired during a flyover on July 17, 1998, as a part of the Geosat Committee's Hyperspectral Group Shoot, sponsored by a consortium of oil companies and commercial vendors. The data were provided as Level-1A reflectance cubes after conversion from radiance to reflectance, by Remote Measurement Services, LLC (Houston, Texas), the provider of this data. The 5 m pixel resolution PROBE-1 is composed of four discreet spectrometers, each having 32 bands with 12 bit DNs scaling from 0 to 4095. The basic pre-processing from radiance to reflectance included removal of the solar spectral profile, solar angle of incidence, and the scattering and absorptive effects of the Earth's atmosphere. In order to compare results to available multi-spectral remote sensing data, PROBE-1 bands were composited to simulate the six spectral bands of a Landsat Thematic Mapper (TM) data set. This 5 m resolution six-band Landsat simulated multi-spectral data set was classified using two common unsupervised classification algorithms; and two supervised approaches, for comparison with the hyperspectral analysis based on the spectral library.

### 2.5. Hyperspectral classification

The PROBE-1 data set of the Pacheco Creek site (Fig. 5) was transformed and smoothed to eliminate noise and reduce spectral dimensionality while retaining feature information using a Minimum Noise Fraction (MNF) (Green et al., 1988) transformation (a two step Principal Components Analysis) available in ENVI (Kruse et al., 1993). This 110-band MNF data set was classified using the Spectral Angle Mapper (SAM) algorithm in ENVI. SAM calculates the *n*-dimensional angle to match pixels to the reference (library) spectra (here, image derived MNF spectra of various species). This technique, when used on calibrated reflectance data, is relatively insensitive to illumination and albedo effects, primarily responding to spectral shape similarities and differences. SAM compares the angle between the reference spectrum vector and each pixel vector in *n*-dimensional space. Smaller angles represent closer matches to the reference spectrum.

## 3. Results and discussion

### 3.1. Developing the spectral library from field data

The wetlands spectral library from field data was comprised of spectra collected at all five sites, which were used as a set of reference spectra (Fig. 6), to delineate species and mixed communities at the Pacheco Creek site. The averaged spectra illustrate typical patterns in canopy spectra, with significant divergence in the shape of the spectral curve between plant species. Reflectance at 350 nm in the UV region is high in the end panels, probably because Rayleigh scattering was not fully calibrated. Across the visible, reflectance is low due to photosynthetic pigment absorptions except for the low peak in the green wavelengths. Reflectance is highest in the near-infrared between 700 and 1300 nm, due to lack of strongly absorbing materials in plants in this region of the spectrum. Nonetheless, shape differences between species are observed. A strong absorption feature is found around 1450 nm, caused by water in the canopy. There are smaller water absorptions around 970 nm and 1240 nm that are most evident in Typha and Phragmites spectra. The feature observed at 1800 nm is an instrument artifact. Species can be identified based on shape differences that are present across the spectrum. Regardless of which site the spectra were measured, different samples of the same species produced spectra within a limited range of variation. The consistency may have benefited from the measurements being made on mature canopies in discrete patches. High biomass conditions present at this time produced spectra with high near-infrared reflectance across most of the middle to late summer.

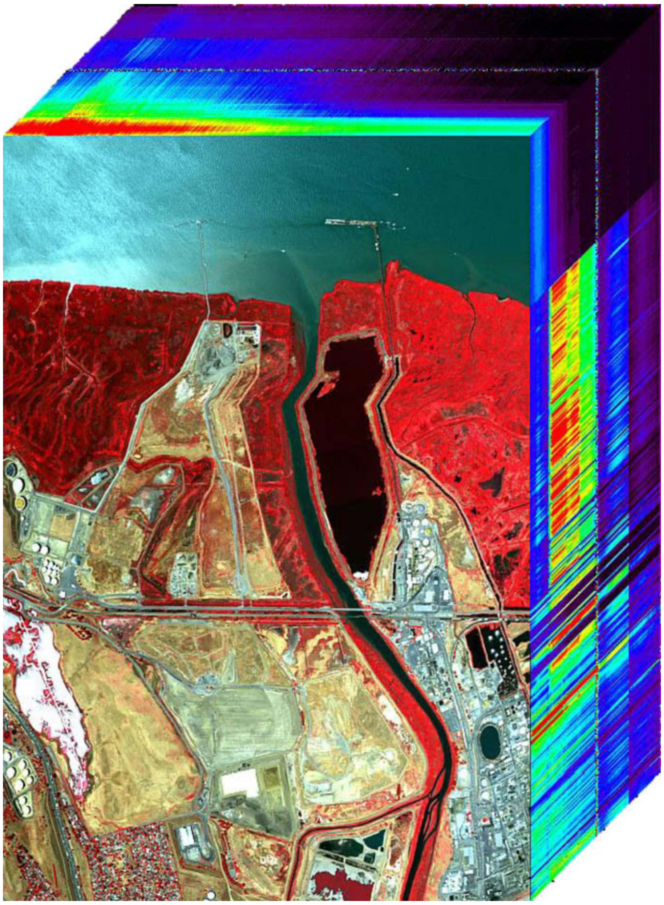

Fig. 5. PROBE-1 hyperspectral data cube of Pacheco Creek wetland site prior to georegistration (note bend in the oxidation pond, which required a 19 line displacement adding 18 pixels in the cross-track direction to correct). Image size is approximately 3 km by 6 km. Cover is a standard color infrared view with the spectra of the edge pixels shown in the *z*-direction. Colors are ordered black, blue, green, yellow, orange, red, from low reflectance to high reflectance.

Nonetheless, in the typha, cordgrass, and phragmites spectra, the data form two discrete groups of spectra, one with high reflectance and the other with lower reflectance. This difference is a response to the local environment, where healthy plant canopies have higher reflectance (particularly in the near-infrared) and plants exposed to petroleum contamination have a combination of reduced biomass (structural changes) and reduced pigment concentration (biochemical changes) (Ustin et al., 2004).

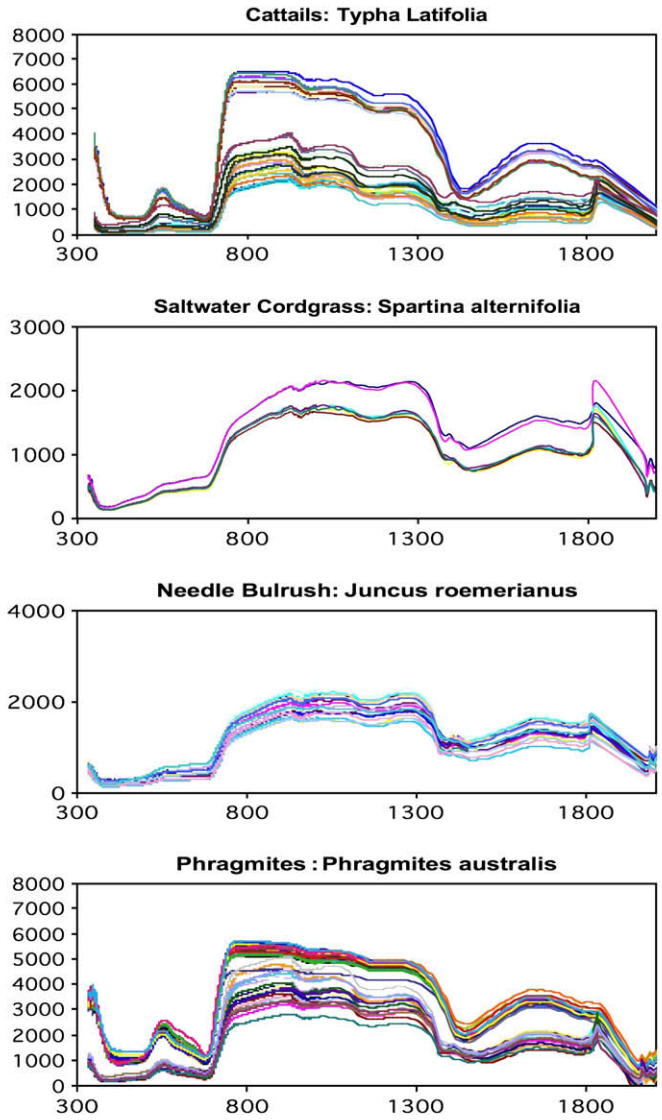

Fig. 6. Representative spectra for four wetland plant species, collected during field work at four marsh locations. *x*-Axis is wavelength in nm, and *y*-axis is % reflectance (×10 000).

Cordgrass and juncus have sparse canopies relative to healthy typha and phragmites, and consequently have higher reflectance in the red region (i.e., lower chlorophyll) and have lower reflectance in the near-infrared, illustrating how the differences in structure and chemistry affect the general trends in spectra of contaminated plants. Succulent species like pickleweed (not shown) have deep water absorption features compared to other wetland species.

### *3.2. Delineating wetland vegetation classes*

Vegetation communities were delineated into 56 classes based on species abundances, and the characteristic dominant and sub-dominate plant species. For purposes of building the spectral library, a good understanding of the species and plant communities at each site was needed to utilize fully the information content of the spectra. Intra-specific and intra-community variation were found across disturbance gradients. Phenomena included structural changes, reduced biomass, lower "greenness" and chlorophyll, chlorosis, and corresponding shifts across the spectral response curve. Methodological approaches to account for this variability, which can be used to assess stress are still to be resolved. Large sets of reference spectra may be needed to fully characterize this variability. However, in this study, the same species found at different sites had discernibly similar spectral signatures, indicating a potential for species level mapping without *a priori* knowledge of the species composition. Our study showed that attempts to map vegetation at the species level worked well for wetland types composed of spatial mosaics of monotypic species, and discrete community types. However, averaged spectra for highly heterogeneous mixed communities created confounding congruencies amongst closely related classes, which were difficult to delineate without corroboration from field data, or additional testing of spectral un-mixing and other spectral matching techniques.

### *3.3. Using the spectral library for classification of wetland vegetation*

High spatial resolution data provided significant variation amongst communities that were easily discernable (Fig. 7). General land cover types, such as industrial, barren, and wetland vegetation sites, were easily classified, even without using all of the spectral information in the data. The MNF transformation, a factoring method described above, orders the new bands by the proportional variance. Displaying three-band combinations highlights complex spatial patterns within the various stratified vegetation and landuse zones (Fig. 8). Distinct vegetation patterns are closely associated with channels within the wetland, consistent with species changes along micro-elevation gradients. Without either extensive field data collection or a spectral library, these patterns cannot be identified with composition and/or site condition.

A vegetation map (Fig. 9), based on the spectral library was applied to the full hyperspectral data set, which produced

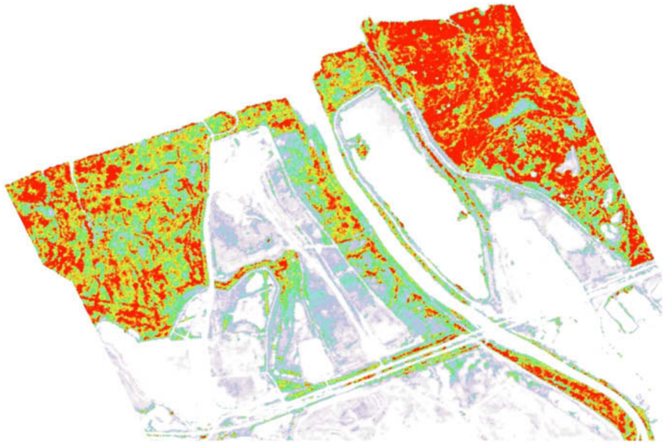

Fig. 7. Biomass and biochemical variation are readily discernable in the Normalized Difference Vegetation Index (NDVI) of the high spatial resolution data.

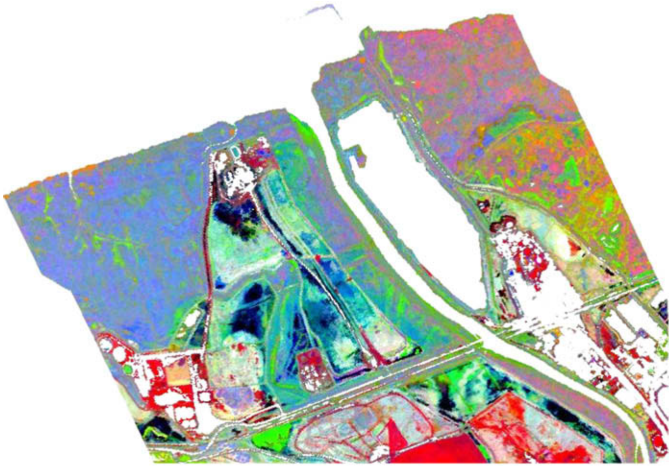

Fig. 8. Complex spatial patterning is evident in the MNF transformation, which retains the original spectral information in a small number of bands.

a map of the distribution of seven species within the marsh. In general, the hyperspectral data provided finer discrimination of species/vegetation types compared to the map obtained from the simulated six-band multi-spectral data set. This finding is similar to Underwood et al. (2007) who found that spectral resolution was more important for correct classification than spatial resolution, except in cases where high within pixel heterogeneity exceeded the pixel-to-pixel variance. For this study, a similar classification was produced from reference spectra extracted from the image (using GPS coordinates to identify species) as from field-measured spectra of those species. This correspondence is consistent with the patterns observed for spatial resolution and suggests that the averaging of the canopy spectra measured from the bucket truck provided a good representation of the image data.

Wider use of hyperspectral data requires improved methodologies and tools that facilitate and automate basic analyses and mapping that can be specifically applied to wetlands requirements. Both field and image methods for obtaining reference library spectra required complex processing and analysis. If a standard spectral library for wetland species/communities can be developed, it will aid resource managers by allowing them to utilize newer more powerful image analysis techniques while avoiding the data processing and expertise required to create the database. Shepherd and Walsh (2007) similarly concluded that key challenges in applying these technologies on a wider scale included: building human capacity in advanced science and technology-based approaches, development of low cost and rugged IR spectroscopy instrumentation, and development of decision support systems to help interpret spectroscopy data.

Fig. 9. Wetlands vegetation map derived with the combined spectral library and field based observations.

## 4. Conclusion

This study illustrates the potential for wetland assessment and inventory using advanced hyperspectral imagers, and applications for vegetation community monitoring. Currently, limitations of both data availability and cost remain, as do significant methodological and technical issues. However, this study highlights the advantages of wetland ecosystems for developing these methods, and the importance of developing spectral libraries specifically relevant to wetlands, across diverse biomes, eco-regions, and wetland types. Roberts et al. (1998) has argued a need for regionally specific spectral libraries for semi-arid ecosystems, Shepherd and Walsh (2007) for spectral libraries for agricultural and environmental management in developing countries, and Hirano et al. (2003) and Schmid et al. (2004) for wetlands. We likewise suggest that the compilation of wetland spectral libraries has intrinsic usefulness, as well as should proceed in anticipation of the wider availability of advanced high-resolution data from hyperspectral imagers, and their eventual space-based deployment.

In order to facilitate a global approach to applications of new advanced technologies for mapping and conservation of wetlands, a standardized classification system, similar to the FAO Land Cover Classification System (LCCS) (Di Gregorio and Jansen, 1998) for wetland communities should be adopted to make best use of the spectral libraries, and to facilitate a global remote sensing-based monitoring and assessment capacity. Additionally, collections of spectral libraries provide useful data beyond vegetation mapping, by providing a reference framework from which to compare physiology, plant condition, nutrient status, intra-specific and inter-specific phenotypic variation, and phenotypic expression of intra-specific varietal genotypic variation. In order to easily provide management relevant information products, standardized methodologies and approaches specifically relevant to wetlands need to be developed in tandem with data collection efforts. Additionally, it is advocated that efforts towards launching a space-borne high-resolution hyperspectral instrument for earth observation be supported and promoted. Developing an advanced earth monitoring capability, particularly for high-spatial/spectral resolution hyperspectral data, to the global research community will make a significant contribution to the conservation and protection of wetlands and other terrestrial ecosystems.

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